

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

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 (CO₂), carbon monoxide (CO), methane (CH₄), chlorofluorocarbons (CFCs), and nitrous oxide (NO_x) 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 CO₂ 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.

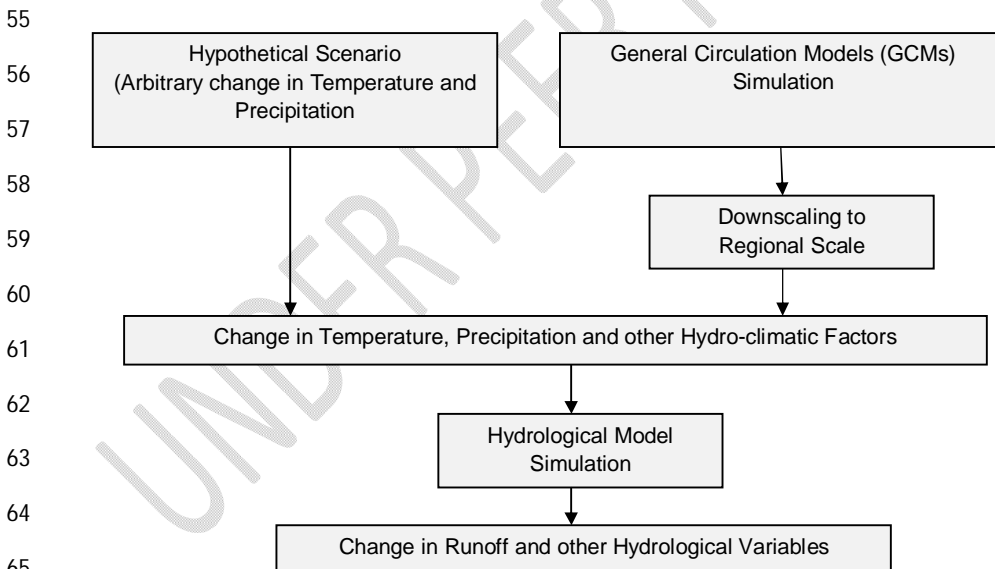
Water is an indispensable resource for sustaining all forms of life on earth. Changes in the water cycle, driven by climate change, have significant impacts on water resources due to their sensitivity to changing climatic conditions. These impacts are manifested through three visible signals of climate 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. The changing climate conditions can have severe impacts on the hydrological cycle, which can potentially threaten human societies that depend on

35 water resources for agriculture, hydropower production, and ecosystems. Hence, it is crucial to
36 provide decision-makers with reliable information about the possible future changes in the
37 hydrological cycle to help them formulate effective strategies for mitigation and adaptation.

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

48 2. MATERIALS AND METHODS

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



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

67 2.1 Hydrological modeling for climate change impacts study

68 Hydrological models have been used to simulate hydrological regimes since the 1960s, with the
69 development of different types of models, including conceptual, lumped, and physically-based
70 distributed models. With the advancements in computer technology, these models have improved
71 significantly, allowing for the application of more complex models at higher resolutions in a shorter

72 amount of time. Furthermore, hydrology has become more interdisciplinary, particularly with climate
73 change science, as changes in the climate can have both direct and indirect impacts on the
74 hydrological cycle, which in turn can affect the global and local climate. While the connection between
75 hydrology and climate science is now widely acknowledged, coupling the two is still a relatively young
76 discipline. However, given the increasing awareness of climate change, there is now a greater
77 demand for simulations that can predict potential hydrological changes under future climate
78 conditions.

79 Studies have explored the effects of climate change on various aspects of the hydrological cycle,
80 such as flood frequencies (Cameron, 2006), runoff (Bergstrom et. al., 2001), soil moisture
81 (Mavromatis, 2012), groundwater levels (Goderniaux et. al., 2009), evaporation (Kay and Davies,
82 2008), and water quality (Wilby et. al., 2006). However, these studies mainly focus on either large-
83 scale climate change impacts or projections at low temporal resolutions such as seasonal or annual
84 changes. Studies on regional impacts and extreme events such as floods and droughts are limited
85 due to the coarse spatial and temporal scales of climate model simulations. These scales do not
86 match the required regional scale for analyzing daily water resource variations. A fundamental
87 problem is the lack of standardized procedures for post-processing climate model outputs for
88 hydrological impact analyses. The resulting hydrological simulations' uncertainty has not been fully
89 evaluated due to limited computer power, which hinders further investigations.

90 **2.2 Modeling for Climate Study**

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

93 **2.2.1 Roles of GCMs in Climate Change Study**

94 The first global climate models (GCMs) were introduced by Phillips (1956) to simulate average,
95 synoptic-scale (i.e., 104–106 km² spatial scale), and atmospheric circulation patterns for specified
96 external forcing conditions. Over time, various atmospheric GCMs were developed to simulate
97 average, large-scale, atmospheric circulation (e.g., Holton, 1992). Some of the most widely used
98 GCMs include the Canadian Climate Center (CCC) model, the Geophysical Fluid Dynamic Laboratory
99 (GFDL) model, the Goddard Institute for Space Studies (GISS) model, the National Center for
100 Atmospheric Research (NCAR) model, the Oregon State University (OSU) model, and the United
101 Kingdom Meteorological Office (UKMO) model, among others.

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

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

112 **2.2.2 Gaps between Climate Modeling and Hydrologic Modeling**

113 The atmospheric components of GCMs are highly advanced, utilizing many layers to simulate
114 atmospheric conditions. However, despite identical atmospheric forcing, parameterizations in current
115 GCMs often fail to provide accurate predictions for many hydrological variables. As a result, gaps

Comment [DI1]: Insert one space between lines 111-112

Comment [DI2]: I recommend a justify text format from line 113 to 121

116 exist between hydrologic and climate modeling due to limitations in GCM simulations. These gaps can
117 be attributed to several factors, including:

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

122 2.2.3 Recent Research Developments and Achievements

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

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

135 2.2.4 Dynamic Downscaling (DD)

136 The process of dynamical downscaling, also known as nested RCM approach, involves utilizing
137 regional climate models (RCMs) for specific regions with boundary conditions derived from GCM
138 simulations. This approach was first applied by Dickinson et al. (1989) in the late 1980s for climate
139 change studies. RCMs, also called Limited-Area Models (LAMs), produce highly resolved spatial and
140 temporal climate information, with a grid resolution of approximately 0.22-0.44° (~25-50 km) and a
141 time step size of six hours (Mearns et al., 2003). The coarse-grid GCM simulation output is used for
142 initial and lateral boundary conditions, which is called a "one-way nesting approach." While most RCM
143 studies implement the one-way mode without feedback from RCM to GCM, two-way nesting with
144 feedback from RCM simulations back to the GCM is an alternative (Lorenz and Jacob, 2005; Foley,
145 2010; Bowden et al., 2011; Chan et al., 2012).

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

157 2.2.5 Statistical Downscaling

158 In statistical downscaling, the relationships between large-scale atmospheric predictor variables and
159 local meteorological series are established (Kim et al., 1984; von Storch et al., 1993). The
160 classification of statistical downscaling methods can be based on the techniques used or the predictor

161 variables selected (Wilby and Wigley, 1997; Rummukainen, 1997). Commonly used predictors include
162 free atmospheric variables such as geopotential heights (Bardossy and Plate, 1992; Wilby, 1995) and
163 surface patterns such as sea level pressure (Karl et al., 1990).

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

169 **3Development of Macroscale Hydrologic Models (MHM)**

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

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

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

185 **4Use of Hypothetical Scenarios**

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

191 As a result of the challenges in using GCMs to drive hydrologic models, hydrologists have resorted to
192 using simple methods to modify present conditions. To estimate the impacts of hypothetical climate
193 change on hydrological behavior, various climate change scenarios have been developed and widely
194 adopted. For instance, predictions for "double CO₂" conditions have become a standard approach in
195 the field (Loaiciga et al., 1996).

196 The procedure for estimating the impacts of hypothetical climate change on hydrological behavior
197 typically involves several stages. First, hydrologists determine the parameters of a hydrological model
198 in the study catchment using current climatic inputs and observed river flows for model validation.
199 Second, the historical time series of climatic data is perturbed according to some climate change
200 scenarios, such as adding $\Delta T = +1, +2, +4$ for temperature or multiplying precipitation values by $(1 +$
201 $\Delta P / 100)$. Third, the hydrological characteristics of the catchment under the perturbed climate are
202 simulated using the calibrated hydrological model. Finally, the model simulations of the current and
203 possible future hydrological characteristics are compared. This general procedure has been widely
204 adopted by hydrologists to estimate the impacts of hypothetical climate change on hydrological
205 behavior (e.g., Loaiciga et al., 1996).

Comment [DI3]: I recommend to use top-down in similitude to bottom-up

206 **5 Uncertainties in the Modeling Chain**

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

220 To overcome the challenge of producing a variety of different projections when using climate model
221 simulations for hydrological studies, a possible solution is to apply several model simulations together,
222 referred to as "ensemble simulations" (Giorgi, 2006; Teutschbein and Seibert, 2010; Ehret et al.,
223 2012). This method involves the use of multi-model approaches, which have two key advantages:
224 first, the spread of individual ensemble members covers a more realistic range of uncertainty, and
225 second, the ensemble median may fit observations better (Teutschbein and Seibert, 2010). By
226 combining multiple simulations, it is possible to generate a more comprehensive and accurate
227 representation of the projected hydrological changes, reducing the influence of uncertainties
228 introduced by individual models and improving the reliability of the final simulations.

229 **6. SUMMARY AND CONCLUSIONS**

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

237 The challenges faced by both communities are clear.

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

248 **REFERENCES**

- 249 1. Arnell NW. Data requirements for macroscale modeling of the hydrosphere, *Macroscale*
250 *Modeling of the Hydrosphere*. IAHS Publ. 1993;214:139-149.

- 251 2. Bardossy A and Plate EJ. Space-time model for daily rainfall using atmospheric circulation
252 patterns, *Water Resource*. 1992;28:1247–1260.
- 253 3. Bergstrom S, Carlsson B, Gardelin M, Lindstrom G, Pettersson A and Rummukainen
254 M. Climate change impacts on run-off in Sweden – assessments by global climate models,
255 dynamical downscaling and hydrological modeling. *Climate Research*. 2001;16:101–112.
- 256 4. Beven KJ. *Rainfall-runoff modeling: the primer*. John Wiley & Sons; 2011 Nov 29.
- 257 5. Bowden JH, Otte TL, Nolte CG and Otte MJ. Examining Interior Grid Nudging Techniques
258 Using Two-way Nesting in the WRF Model for Regional Climate Modeling, *J Climate*, 2011,
259 25(8), 2805–2823.
- 260 6. Cameron D. An application of the UKCIP02 climate change scenarios to flood estimation by
261 continuous simulation for a gauged catchment in the northeast of Scotland, UK (with
262 uncertainty), *Journal Hydrology*, 2006, 328(1–2), 212–226.
- 263 7. Chan S, Kendon E, Fowler H, Blenkinsop S, Ferro CT, and Stephenson D. Does increasing
264 the spatial resolution of a regional climate model improve the simulated daily precipitation?
265 *Climate Dynamics*, 2012, 1–21.
- 266 8. Christensen JH, Boberg F, Christensen OB, and Lucas Picher P. On the need for bias
267 correction of regional climate change projections of temperature and precipitation, *Geophys*
268 *Res Lett*, 2008, 35(20), L20709.
- 269 9. Dickinson RE, Errico RM, Giorgi F and Bates GT. A regional climate model for the western
270 United States, *Climatic Change*, 1989, 15(3), 383–422.
- 271 10. Ehret U, Zehe E, Wulfmeyer V, Warrach-Sagi K and Liebert J, HESS Opinions “Should we
272 apply bias correction to global and regional climate model data? *Hydrol Earth Syst Sci*, 2012,
273 16(9), 3391–3404.
- 274 11. Foley AM. Uncertainty in regional climate modeling: A review *Prog Phys Geog*, 2010, 34(5),
275 647–670.
- 276 12. Foley JA, Costa MH, Delire C, Ramankutty N and Snyder P. Green surprise? How terrestrial
277 ecosystems could affect earth’s climate, *Front Ecol Environ*, 2003, 1(1), 38–44.
- 278 13. Giorgi F. Regional climate modeling: Status and perspectives, *J Phys IV*, 2006, 139, 101–
279 118.
- 280 14. Glantz MH and Krenz JH. *Human Components of the Climate System*. Int: K.E. Trenberth,
281 *Climate System Modeling*, 1992, University Press, Cambridge, pp. 27-49.
- 282 15. Goderniaux P, Brouyère SH, Fowler JS, Blenkinsop, Therrien R, Orban P and Dassargues A.
283 Large scale surface–subsurface hydrological model to assess climate change impacts on
284 groundwater reserves, *J. Hydrol*, 2009, 373(1–2), 122–138.
- 285 16. Graham LP, Andreasson J, Carlsson B. Assessing climate change impacts on hydrology from
286 an ensemble of regional climate models, model scales and linking methods - A case study on
287 the Lule River basin. *Climatic Change*, 2007a, 81(Supplement), 293–307.
- 288 17. Graham LP, Hagemann S, Jaun S and Beniston M. On interpreting hydrological change from
289 regional climate models, *Climatic Change*, 2007b, 81(Supplement), 97–122.
- 290 18. Holton JR. *An Introduction to Dynamic Meteorology*, 3rd ed., 1992, Academic, San Diego,
291 CA.
- 292 19. Houghton JT, Jenkins GJ and Ephraums JJ. *Climate Change. The IPCC Assessment*,
293 Cambridge University Press, 1990.
- 294 20. IPCC (2007), *Climate Change, The Physical Science Basis, Contribution of Working Group I*
295 *to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited
296 by S Solomon, D Qin, M Manning, Z Chen, M Marquis, KB Averyt, M Tignor and HL Miller.
297 Cambridge University Press, Cambridge, UK, and New York, USA, 2007.
- 298 21. Jarsjo J, Asokan S M, Prieto C, Bring A and Destouni G. Hydrological responses to climate
299 change conditioned by historic alterations of land-use and water-use, *Hydrol Earth Syst Sci*,
300 2012, 16(5), 1335–1347.

- 301 22. Karl T R, Wang WC, Schlesinger ME, Knight RW and Portman D. A method of relating general
302 circulation model simulated climate to observed local climate. Part I: Seasonal statistics, *J.*
303 *Climate*, 1990, 3, 1053–1079.
- 304 23. Kay AL and Davies HN. Calculating potential evaporation from climate model data: A source
305 of uncertainty for hydrological climate change impacts, *Journal of Hydrology*, 2008, 358(3–4),
306 221–239.
- 307 24. Kay AL, Davies HN, Bell VA and Jones RG. Comparison of uncertainty sources for climate
308 change impacts: flood frequency in England, *Climatic Change*, 2009, 92(1), 41–63.
- 309 25. Kim JW, Chang JT, Baker NL, Wilks DS and Gates WLP. The statistical problem of climate
310 inversion: determination of the relationship between local and large-scale climate, *Monthly*
311 *Weather Rev.* 1984, 112, 2069–2077.
- 312 26. Kite GW, Dalton A and Dion K. Simulation of streamflow in a macroscale watershed using
313 general circulation model data, *Water Resources. Res.* 1994, 30, 1547–1599.
- 314 27. Liston GE, Sud YC and Wood EF. Evaluating GCM land surface hydrology parameterisations
315 by computing river discharges using a runoff routing model, application to the Mississippi
316 Basin, *J. Appl. Meteorol.* 1994, 33, 394–404.
- 317 28. Loaiciga, H. A., Valdes, J. B., Vogel, R., Garvey, J. and Schwarz, H., Global warming and the
318 hydrologic cycle, *J. Hydrol.* 1996, 174, 83–127.
- 319 29. Lobell D, Bala G, Mirin A, Phillips T, Maxwell R and Rotman D. Regional Differences in the
320 Influence of Irrigation on Climate, *J Climate*, 2009, 22(8), 2248–2255.
- 321 30. Lorenz P and Jacob D. Influence of regional scale information on the global circulation: A two-
322 way nesting climate simulation, *Geophys Res Lett*, 2005, 32(18), L18706.
- 323 31. Mavromatis T. Changes in exceptional hydrological and meteorological weekly event
324 frequencies in Greece, *Climatic Change*, 2012, 110(1), 249–267.
- 325 32. Mearns LO, Giorgi F, Whetton P, Pabon D, Hulme M and Lal M. Guidelines for use of climate
326 scenarios developed from regional climate model experiments, Data Distribution Centre of the
327 Intergovernmental Panel on Climate Change, 2003. [online] Available from: [http://www.ipcc-](http://www.ipcc-data.org/guidelines/dgm_no1_v1_10-2003.pdf)
328 [data.org/guidelines/dgm_no1_v1_10-2003.pdf](http://www.ipcc-data.org/guidelines/dgm_no1_v1_10-2003.pdf)
- 329 33. Phillips NA. The general circulation of atmosphere: a numerical experiment, *Q. J. R. Meteorol.*
330 *Soc.* 1956, 82, 123–164.
- 331 34. Puma MJ and Cook BI. Effects of irrigation on global climate during the 20th century, *J*
332 *Geophys Res*, 2010, 115, D16120.
- 333 35. Rummukainen M. Methods for statistical downscaling of GCM simulation, SWECLIM report,
334 Rossby Centre, SMHI, Norrköping, Sweden, 1997.
- 335 36. Sausen R, Schubert S and Dumenil DA. A model of river runoff for use in coupled atmosphere-
336 ocean models, *J. Hydrol.*, 1994, 115, 337–352.
- 337 37. Teutschbein C and Seibert J. Regional Climate Models for Hydrological Impact Studies at the
338 Catchment Scale: A Review of Recent Modeling Strategies, *Geography Compass*, 2010, 4(7),
339 834–860.
- 340 38. Teutschbein C, Wetterhall F and Seibert J. Evaluation of different downscaling techniques for
341 hydrological climate-change impact studies at the catchment scale, *Clim Dynam*, 2011, 37(9-
342 10), 2087–2105.
- 343 39. Varis O, Kajander T and Lemmela R. Climate and water: from climate models to water
344 resources management and vice versa, *Climatic Change*, 2004, 66(3), 321–344.
- 345 40. von Storch H, Zorita E and Cubash U. Downscaling of global climate change estimates to
346 regional scales: An application to Iberian rainfall in wintertime, *J. Climate* 1993, 6, 1161–1171.
- 347 41. Vorosmarty CJ, Moore B, Grace AL, Gildea MP, Melillo JL, Peterson BJ, Rastetter EB and
348 Steudler PA. Continental scale models of water balance and fluvial transport: an application to
349 South America, *Global Biogeochem. Cycles*, 1989, 3, 241–256.

- 350 42. Wilby RL and Wigley TM L. Downscaling general circulation model output: a review of
351 methods and limitations, *Progress in Physical Geography*, 1997, 21, 530–548.
- 352 43. Wilby RL, Dawson CW and Barrow EM. SDSM - a decision support tool for the assessment of
353 regional climate change impacts, *Environ Modell Softw*, 2002, 17(2), 145–157.
- 354 44. Wilby RL, Whitehead PG A, Wade J, Butterfield D, Davis RJ and Watts G. Integrated
355 modeling of climate change impacts on water resources and quality in a lowland catchment:
356 River Kennet, UK, *J Hydrol*, 2006, 330(1- 2), 204–220.

UNDER PEER REVIEW