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Assessing Climate Change Impacts at River Basin Scale by Integrating Global Circulation Models with Regional Hydrological Simulations

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Abstract: The sensitivity of Europe to climate change has a distinct north– south gradient with the projections from Global Climate Models indicating that southern Europe will be the more severely affected. Average global predicted precipitation demonstrate an increase during the 21st century in the Northern Hemisphere and particularly at mid-high latitudes, however, at lower latitudes, such as the Mediterranean region, year to year fluctuations in precipitation appear to have an obvious decreasing trend. The impacts of these climate variations is bound to affect all water related sectors, such as water supply, irrigation systems, renewable energy sources and industrial production, as well as ecosystems. This paper initiates the application of a downscale procedure by coupling refined scale Global models, known as Regional Climate Models, with spatial distributed hydrology models. The dynamically downscaled climatic data are further downscaled at the catchment scale. The simulation of the results of the applied methodology on a transboundary river basin demonstrates a future 14.5% and 24.1% diminution of the runoff for the B1 and A1B emission scenarios respectively, as well as the emergence of extreme events such as floods and droughts during the 50 year simulation period.

Key words: Climate change, Global Circulation Models, Downscaling, Catchment hydrology.

1. INTRODUCTION

Climate simulation is conducted at a global scale with the use of Global Climate Models, also known as General Circulation Models (GCMs), and is based on the representation of the physical laws governing the atmosphere and the circulation and behaviour of the oceans using mathematical equations. These are derived from the latest advances in fluid dynamics, thermodynamics and chemical interactions. However, these non-linear partial differential equations can only be solved using approximate numerical solutions with the latter being very sensitive to the correct setting of initial boundary equations. Thus, the complexity of the climatic processes and interactions necessitate an integrated approach provided by the coupling of atmosphere-ocean general circulation models (AOGCM) with components dedicated to sea-ice, land-surface and chemical transport modelling (IPCC 2000; Wang and Mysak 2000; IPCC 2007).

The results obtained from the GCMs are considerably useful in evaluating potential climate changes at a global scale. However, due to the GCMs coarse spatial resolution, local land surface characteristics are ignored during the simulation procedure. To minimise the uncertainties from the use of climatic projections of global climate models in catchment hydrological models, the modelling procedure should use downscaling techniques at the stage where output from global models are converted to regional corresponding climatic data (Christensen et al., 2005). Such downscaling can be both temporal and spatial, and can be approached by both statistical (Hewitson, 1996; Wood et al. 2004) and dynamical methods (Mearns at al., 2003). Finding the best methods for downscaling is currently a high priority research area (Kumar et al., 2011).

The present study aims to assess climate change impacts on the flow regime of an internationally shared river basin, namely the Mesta/Nestos basin, by using the coupling of refined scale General Circulation Models, known as Regional Climate Models (RCMs), namely CLM, with spatial distributed hydrology models, namely MODSUR-NEIGE (modélisation des transferts de surface - neige). The proposed methodology initiates the integration of dynamically downscaled climatic data with regional spatial conditions.

2. THE REGION UNDER STUDY

The canvas of this study is the Mesta/Nestos river basin, one of the fourteen transboundary river basins in South Eastern Europe (Ganoulis et al., 2000). It has been designated as a demonstration river basin in the framework of the UNESCO programme HELP (Hydrology for Environment, Life and Policy) (Ganoulis et al., 2008; Skoulikaris et al. 2009a). The river's catchment area of 6,218 km^2 as well as the perennial stream's length of 255 km are almost equally shared between the upstream and downstream countries of Bulgaria and Greece respectively, Figure 1. The headwaters are located at the highest reliefs of the Balkans, namely the Mussala peak (2,925m) in the Rila mountains and the Vihren peak (2,915m) in the Pirin mountains. The runoff water from several affluents in the Bulgarian part of the basin enters Greek territory and after some 120 km spreads over a delta situated on the Aegean Sea coast of Northern Greece (Skoulikaris et al. 2009b).

Figure 1. The internationally shared basin of the Mesta/Nestos River

The Mesta/Nestos river basin is characterised by not having a single climatic type, due to the interaction between the trajectories of the weather systems, since the basin's orientation is from East to West and North to South, and by its complex topography, since it spreads among the highest mountain of the region and the sea level (Bank of Greece, 2011). Thus, within just a few dozen kilometres, the climate can change from coastal Mediterranean to practically alpine in the mountainous parts. In the latter, the temperature is low in winter and moderate in summer, while in the lowlands the winter is mild and the summer dry and hot.

These climatic differences result in uneven rates of evapotranspiration and precipitation distribution over the basin as a whole. In the Bulgarian part, the annual rainfall is approximately 810 mm/year, with prolonged snow cover in the upper altitudes. In these areas low temperatures and high levels of precipitation are dominant during the winter (Grunewald et al. 2010). The snow is of enormous importance for the run-off/flow regime and the irrigation possibilities in the valleys and the delta (Grunewald et al. 2008). In the Greek part of the basin, the mean annual rainfall is 790 mm, however, the high summer temperatures, for example in July the temperature ranges from 23.3^{o}C to 25.9^{o}C, foster and accelerate the evapotranspiration process.

According to Moutafis (1991), the mean annual runoff gathered in the Bulgarian part of the basin in 1972 was equal to 47.20 m^3/s, while the water flow entering Greece was 39.43 m^3/s. A more recent analysis of gauge data revealed that the total water volume which enters Greece is

1,123 million cubic meters, which is equivalent to 35.59 m^3/s (Mimides et al. 2007). A further reduction of the incoming water volume has also been estimated by Ganoulis et al. 2007.

3. DYNAMIC DOWNSCALE OF GLOBAL CLIMATE MODELS

GCMs are typically based on a three-dimensional representation of the ocean and the terrestrial biosphere over a grid which covers the globe (Hulme and Viner, 1998, Viner 2002). A horizontal resolution of between 2.5 and 7.5 degrees, with 10 to 20 vertical layers in the atmosphere and sometimes as many as 20 underwater layers in the oceans comprise the conceptual structure of the grids. By adding the time dimension to the three spatial dimensions, these models can be considered as four dimensional.

In this study, the possible effect of climate change on river hydrology has been assessed using results from the ECHAM5/MPIOM coupled models developed by the Max Planck Institute for Meteorology in Hamburg. The ECHAM5 model (Roeckner et al. 2003) uses a T21 Gaussian grid with a spatial resolution equivalent to 5.6° longitude × 5.6° latitude and 19 atmospheric layers (L19). It is coupled with the MPIOM ocean-sea ice component (Roeckner et al. 2006; Jungclaus et al. 2006). MPIOM is a simplified equation model (C-Grid, z- coordinates, free surface) using hydrostatic and Boussinesq fluid hypotheses. In standard configuration it has 40 vertical levels, with 20 in the upper 600 m. The horizontal resolution of MPIOM gradually varies between a minimum of 12 km close to Greenland and 150 km in the tropical Pacific. The ECHAM5/MPIOM model has been adopted by the Intergovernmental Panel on Climate Change (IPCC) as one of the models used for the simulation of the SRES scenarios of the Fourth Assessment Report (AR4).

The cell size resolution of 5.6°x5.6° of the horizontal dimension of the ECHAM5 model was a dissuasive factor in adopting its climatic projections to catchments of a few hundred kilometers, Figure 2. However, the results obtained from the specific model were used to trigger the simulation procedure of a Regional Climate Model (RCM), namely CLM. The Climate Local Model (CLM) is a non hydrostatic European regional climate model (Rockel et al. 2006) with spatial resolutions approximately equal to 20x20 km, and whose boundaries, idem forcing, conditions are provided by the ECHAM5/MPIOM model at time intervals of 6 hours. According to Mearns at al. (2003), this coupling results in a physical dynamical downscaling, where the GCMs output data are used as forcing conditions to dedicated RCMs.

The CLM regional climate model covers the west European region including the Baltic Sea and the greater part of the Mediterranean Sea. For the European region two simulation datasets were produced to investigate IPCC emission scenarios: one covers the past climate, i.e. from 1960 to 2000, and the other covers predictions until 2100, Table 1. The climate of the 21st century was modelled based on the A1B and B1 IPCC climate scenarios. Scenario A1B is linked to three and scenario B1 to two realisation runs respectively of the 20th century climate.

Table 1.Synopsis of the CLM climate model characteristics

Data compilation	*Model and Data Group (M&D) at MPI for Meteorology, Hamburg*
Model	*CLM 2.4.11 (Climate mode of the Local Model of the DWD)* *Dynamic model; drive: ECHAM5, non-hydrostatic*
Model region	*Europe*
Simulation period	*from 1960 to 2100*
IPCC emission scenarios	*A1B, B1 (from 2001)*
Resolution	*0.165° (data stream 2), 0.2° (data stream 3); approx. 20 km*
Structure	*Rotated model grid (data stream 2 = DS2) or* *Regular lat/lon grid (data stream 3 = DS3);*
Data format	*netCDF or ASCII format*

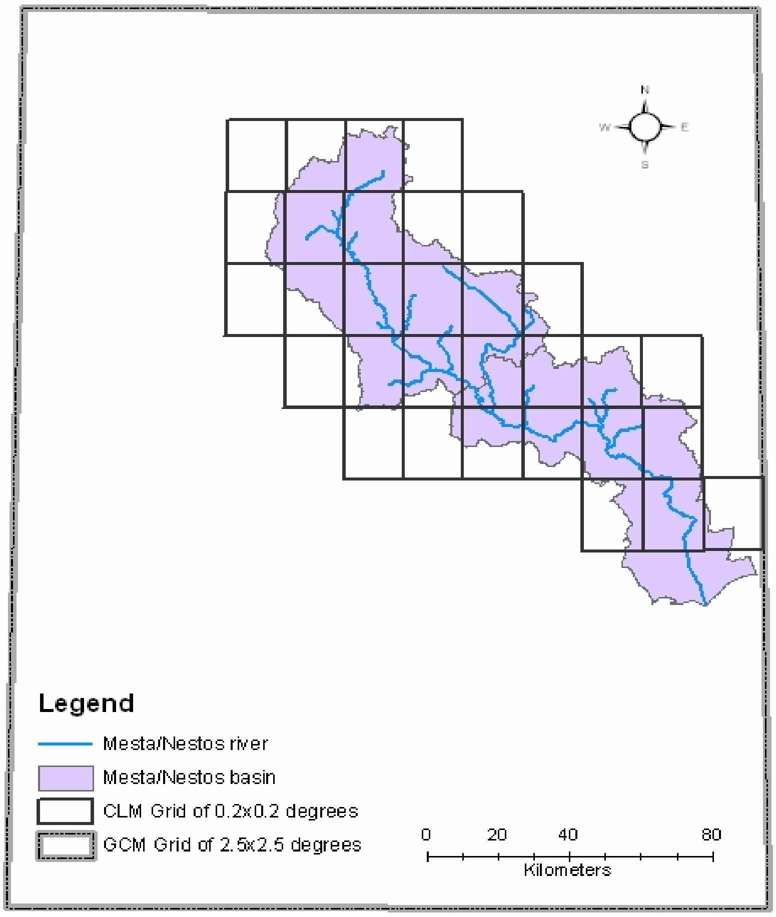

Figure 2. Geometric coverage relationship between the cells of a GCM of 2.5o square cells (external grey dotted square) and a RCM of 0.2o square cells (internal black squares)over a water basin a few hundred km2in size, such as the Mesta/Nestos river basin.

4. HYDROLOGIC DOWNSCALE

The simulation of the Mesta/Nestos basin for different hydrological conditions powered by the CLM climatic results was conducted with the use of the MODSUR-NEIGE hydrologic model. The MODSUR (modélisation des transferts de surface) model (Ledoux et al., 1989) has successfully been applied in many basins of varying scales, e.g. the Seine and Rhone basins in France, the Maritza basin in Bulgaria, and of varying hydrogeological settings (Golaz et al., 2001; Habets et al., 1999; Skoulikaris et al., 2010). It has also been coupled with atmospheric (Ledoux et al., 2002; Habets et al. 2008) and agricultural (Ledoux et al., 2007) models. The NEIGE component of the MODSUR-NEIGE model simulates the snow cover regime on the principle of “degree days” (USACE, 1956; Rango and Martinec, 2007) using an approach which distinguishes snow melting processes between forested and non forested areas.

The MODSUR-NEIGE model is a spatial distributed model and its operation is based on a grid of quadtree structure where each node of the nest can be subdivided into up to four quadrants, i.e a grid's cell can be connected to cells equal in size, or to cells four times smaller or larger. Based on this fundamental rule, the Mesta/Nestos basin grid construction was accomplished by manipulating a Digital Elevation Model (DEM) taken from the Shuttle Radar Topography Mission (SRTM) at a 100 m resolution, with the model grid consisting of square cells ranging from 250 to 2000 m in size.

The topographic characteristics such as runoff directions, drainage network, altitudes and slopes were extracted from the DEM and integrated to each cell of the model spatial grid. The association of the climatic data obtained by the CLM in the form of daily rainfall, temperature and evapotranspiration with each cell of the grid, was conducted with the use of spatial distribution methods. More specifically, the mesh of 20x20 km of the CLM data was disaggregated to the more refined grid of the hydrology model. The water regime was computed for each grid cell using a system of four reservoirs allocating the rainfall in storage, infiltration, evaporation and surface runoff (Ganoulis et al. 2010). Figure 3 presents the panorama of the two step downscaling procedure: 1) dynamic downscale from the global to the regional scale and 2) hydrological downscale to the catchment scale.

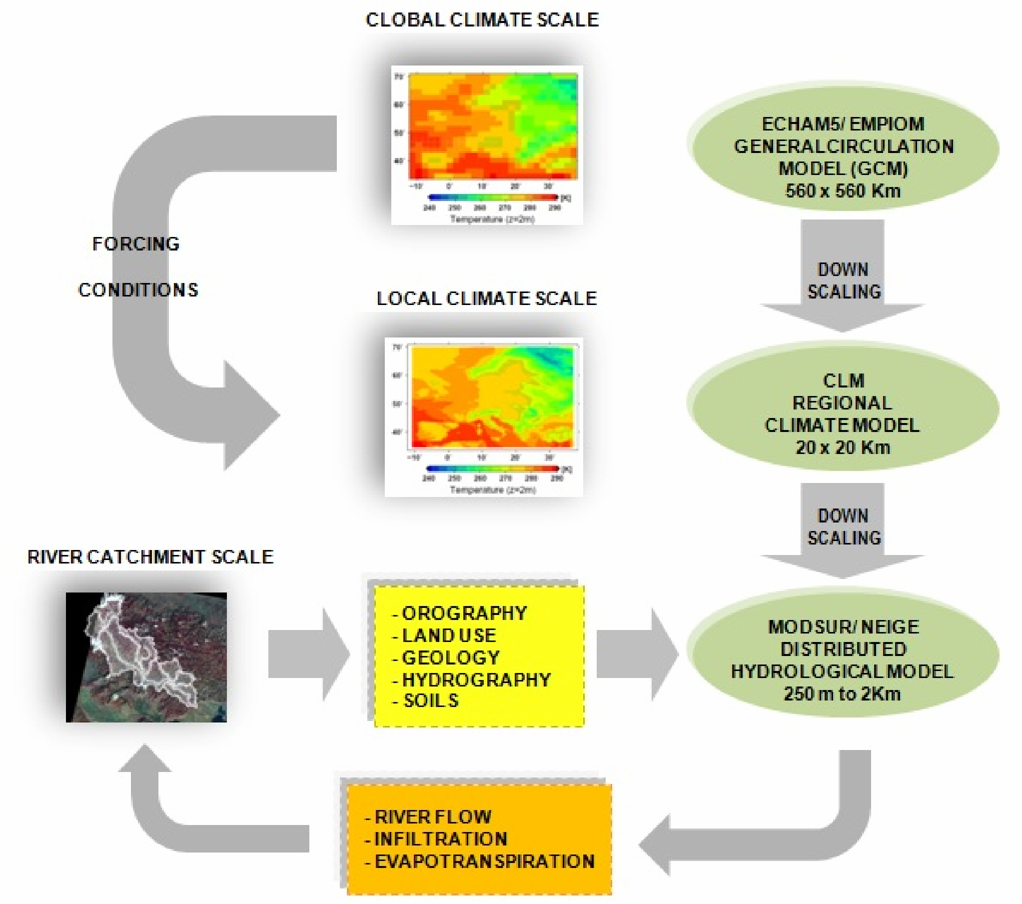

Figure 3. Cascade of downscaling procedures for the integration of global climate variants to river catchments' scale

5. RESULTS OF SIMULATION

A large number of studies of the effect of climate change on river flow have been published and were summarized in IPCC (2007); however only a few global-scale studies have used runoff simulated directly by climate models (IPCC, 2007; Kumar et al., 2011). At a regional scale, Skoulikaris (2008) reviews those studies related to climate change impacts on the water regime of the Greek river basins and examines potential impacts on a transboundary river basin. Most of these studies use a catchment hydrological model driven by climate scenarios based on climate model simulations.

The impacts of the A1B and B1 emission scenarios are assessed in this study for 50 years, from 2025 to 2075. The balanced development of fossil and non-fossil energy sources described in A1B scenario coincides with an augmentation of 369.40 to 717.00 ppm of CO_2 by the end of the year 2100. The relevant increase for the B1 scenario, which introduces clean and resource-efficient technologies, is up to 549.00 ppm (IPCC, 2000). The results produced by the implemented methodology are compared with a "reference" runoff sequence, namely Ref. scenario. This artificial time series was created by duplicating and projecting in the future a stable past flow (January 1970 to December 1995), which is representative of the average conditions of flow during the contemporary period.

The outcome from the simulation results coincides with the projections of the GCMs for the Mediterranean basin about future water availability and the changes in extreme events. According to the IPCC (2007), the regions most prone to an increase in drought risk are those at the lowest altitudes, where the highest increase in irrigation water demand is projected. More specifically, in southern Europe (south of 47°N), runoff is projected to decrease by 0–23% by the 2020s and by 6–36% by the 2070s.

The outputs from the present work clearly demonstrate the decrease of the mean annual river runoff for both A1B and B1 climatic scenarios in comparison with the Ref. scenario, Figure 4. The mean runoff was calculated to be 15.60 m^3/s for the Ref. scenario, and to be slightly lower at 13.55 m^3/s in the case of the B1 scenario, with the reduction of the river flow being greater at 11.90 m^3/s in the case of the A1B scenario.

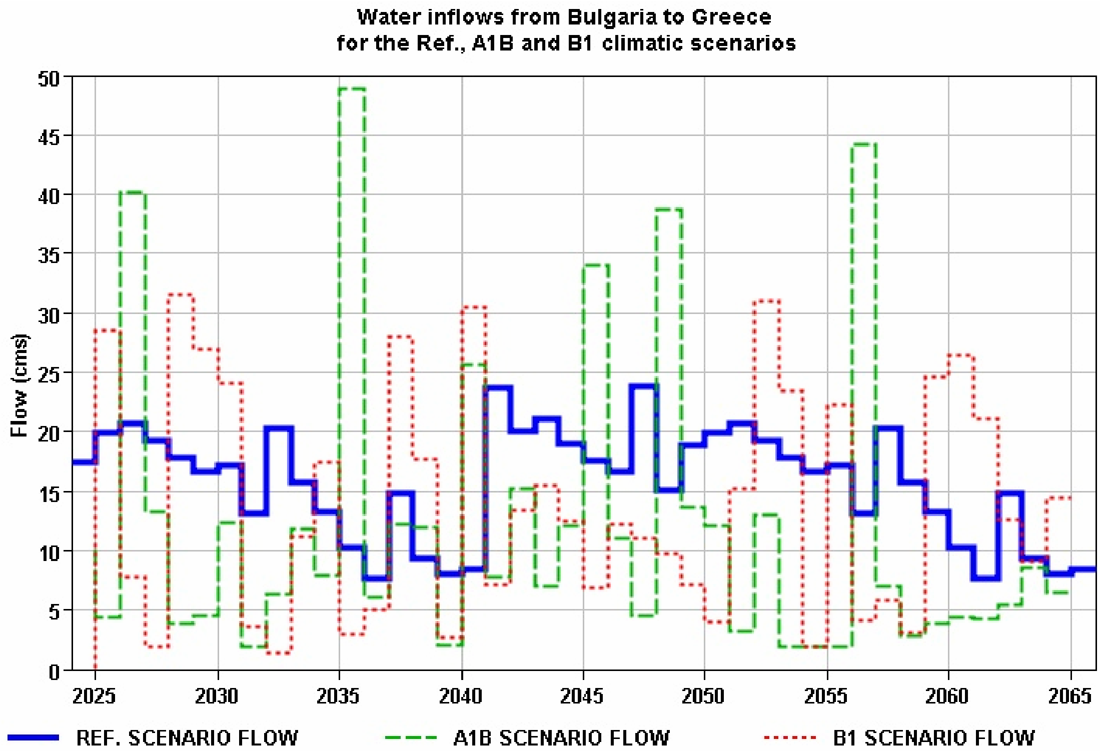

Figure 4. Comparison between the Ref. and the A1B and B1 climatic scenarios for the runoff entering Greece from Bulgaria for a 50 years period

Despite the average flow reduction, more extreme events of floods and droughts both in terms of timing and frequency are projected for the simulation period. The maximum runoff is predicted to be 48.80 m3/s and 31.40 m3/s in the A1B and B1 scenarios respectively, while the observed flows reflected by the Ref. scenario never exceed 23.80 m3/s. These extremes occur more than once in both scenarios. On the other hand, phenomena of extended scarcity are obvious since minimum water flows are dominant in the decades 2030-2040 and 2050-2060 for the B1 and A1B scenarios respectively. It was observed that flow seasonality increases, with higher flows in the peak flow season and lower flows during the low-flow season coupled with extended dry periods.

6. CONCLUSIONS

A twofold downscaling procedure was used for the estimation of future river runoff according to the A1B and B1 emission scenarios. Climate data derived from the ECHAM5/MPIOM climate model was initially used as boundary conditions for the downscaling of climatic variables in the 20x20 km CLM regional climate model. The second downscale approach was based on the potential of the spatial distributed hydrology model MODSUR-NEIGE to allocate the precipitation, temperature and evapotranspiration data of the regional climatic model over the catchment region by taking into account the topographic, geologic and land use characteristics. The hydrological model simulates daily river flows with a spatial grid resolution ranging from 250 m to 2 km. The outputs demonstrate that climate change results in a significant decrease of the Mesta/Nestos river flow with consequences for hydroelectric and agricultural production. It is thus possible that the agricultural demands for water during the irrigation period, which coincides with the warmest period of the year, will not be able to be met.

REFERENCES

Bank of Greece, 2011. Environmental, economic and social impacts due to climate change in Greece. Report; 546pp.

Christensen, J.H., Carter, T.R., Rummukainen, M., Amanatidis, G., 2005. Evaluating the performance and utility of regional climate models: the PRUDENCE project. Clim. Change; 81: 1-6.

Habets, F., Etchevers, P., Golaz, C., Leblois, E., Ledoux, E., Martin, E., Noilhan, J., Ottlé, C., 1999. Simulation of the water budget and the river flows of the Rhone basin. J. Geophys. Res.; 104: 31145–31172.

Hewitson, B., 1996. Climate downscaling: Techniques and application. Climate Res.;7: 85–95.

Hulme, M., Viner, D., 1998. A climate change scenario for the tropics. Clim. Change; 39: 145-176.

IPCC, 2000. Special Report on Emission Scenarios. Cambridge University Press, 570 pp.

IPCC, 2007. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 979 pp.

Jungclaus, J.H., Botzet, M., Haak, H., Keenlyside, N., Luo J.-J., Latif, M., Marotzke, J., Mikolajewicz, U., Roeckner, E., 2006. Ocean circulation and tropical variability in the coupled model ECHAM5/MPI-OM. Journal of Climate; 19: 3952-3972.

Ganoulis, J., Murphy, I. L. Brilly, M., 2000. Transboundary Water Resources in the Balkans: Initiating a Sustainable Co-operative Network. NATO ASI SERIES, Partnership Sub-Series 2: Environmental Security; 47: 254pp.

Ganoulis, J., Skoulikaris, H., Monget, J.M., 2008. Involving Stakeholders In Transboundary Water Resources Management: The Mesta/Nestos "HELP" Basin". Water SA Journal; 34: 461-467.

Ganoulis, J., Skoulikaris, Ch., 2010. Integrating hydraulic, hydrology and environmental economy models for the protection and sustainable use of transboundary water resources, In: Environmental Hydraulics, Taylor & Francis Ltd, London, 49-60.

Golaz, C., Etchevers, P., Habets, F., Ledoux, E. Noilhan, J., 2001. Comparison of two hydrological simulations of the Rhone basin. Physics and Chemistry of the Earth; 25: 461-466.

Grunewald, K., Scheithauer, J., Monget, J-M., Brown, B., 2008. Characterisation of contemporary local climate change in the mountains of southwest Bulgaria. Climatic Change; 95: 535-549.

Grunewald, K., Scheithauer, J., 2010. Landscape Development and Climate Change in Southwest Bulgaria (Pirin Mountains). Springer, 2010, 161pp.

Kumar, A., Schei,T., Ahenkorah, A., Caceres Rodriguez, R., Devernay, J.M., Freitas, M., Hall, D., Killingtveit, A., Liu, Z., 2011. Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Cambridge University Press, 82pp.

Ledoux, E., Girard, G., de Marsily, G., Deschenes, J., 1989. Spatially distributed modeling: Conceptual approach, coupling surface water and ground water in Unsaturated flow hydrologic modeling - theory and practice. NATO ASI Series S 275: 435–454.

Ledoux, E., Etchevers, P., Golaz, C., Habets, F., Noilhan, J., Voirin, S., 2002. Regional simulation of the water budget and riverflows with ISBA-MODCOU coupled model: Application to the Adour and Rhone basins in Mathematical models of large watershed hydrology. V. P. Singh and D. K. Frevert, eds., Chapter 8, Water Resources Publications, Littleton, Colo.

Ledoux, E., Gomez E., Monget, J.M., Viavattene, C., Viennot, P., Ducharne, A., Benoit, M., Mignolet, C., Schott, C. Mary, B., 2007. Agriculture and groundwater nitrate contamination in the Seine basin. The STICS–MODCOU modelling chain. Science of The Total Environment; 375: 33-47.

Mearns, L.O., Giorgi, F., Whetton, P., Pabon, D., Hulme, M., Lal, M., 2003. Guidelines for Use of Climate Scenarios Developed from Regional Climate Model Experiments. DDC of IPCC TGCIA.

Mimides, Th., Kotsovinos, N., Rizos, S., Soulis C., Karakatsoulis, P., Stavropoulos, D., 2007. Integrated runoff and balance analysis concerning Greek-Bulgarian transboundary hydrological basin of River Nestos/Mesta. Desalination; 213: 174–181.

Moutafis, N., 1991. Possibilities for further Development of Hydroelectric Projects in Greece. Conference Proceedings: "Crisis on the Country's Electrical Energy Production?". Technical Chamber of Greece, June 18-19 1991.

Rango, A., Martinec, J., 2007. Revisiting the degree-day method for snowmelt computations. Journal of the American Water Resources Association; 31: 657-669.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., Manzini, E., Rhodi, A., Schlese U., Schulzweida U., Tompkin A., 2003. The atmospheric general circulation model ECHAM 5. Part I: Model description. MPI-Report 349.

Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U., Schulzweida, U., 2006. Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model. Journal of Climate; 19: 3771-3791.

Skoulikaris, Ch., 2008. Mathematical Modelling Applied to the Sustainable Management of Water Resources Projects at a River Basin Scale: the Case of the Mesta/Nestos. PhD Thesis, Aristotle University of Thessaloniki, Greece, 291pp.

Skoulikaris, Ch., Ganoulis, J., Monget, J.M., 2009. Integrated modelling of a new dam: a case study from the "HELP" Mesta/Nestos River. 18th World IMACS Congress and MODSIM09 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, 4050-4056.

Skoulikaris, Ch., Ganoulis, J., Monget, J.M., 2009. Impact of Climate Change on River Water Flow: The Case of the Transboundary Mesta/Nestos River between Bulgaria and Greece. 33rd International Association of Hydraulic Engineering & Research (IAHR) Biennial Congress, Vancouver, British Columbia, August 9-14, 2009, 1108-1115pp.

Viner, D., 2002. A qualitative assessment of the sources of uncertainty in climate change impacts assessment studies: A short discussion paper. Advances in Global Change Research; 10: 139-151

U.S. Army Corps of Engineers, 1956. Snow Hydrology. Pub. U.S. Department of Commerce Office of Technical Services, No. PB 151660, 437 pp.

Wang, Z., Mysak, L.A., 2000. A simple coupled atmosphere-ocean-sea ice-land surface model for climate and paleoclimate studies. J Clim.; 13: 1150-1172.

Wood, A. W., Leung, L. R., Sridhar, V., Lettenmaier, D. P., 2004. Hydrologic Implications of Dynamical and Statistical Approaches to Downscaling Climate Model Outputs. Clim. Change; 62: 189–216.