First Projection of Climatological Mean River Discharges in the Magdalena River Basin, Colombia, in a Changing Climate during the 21st Century

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Abstract:
This study projects the river discharge in the Magdalena River basin, Colombia, considering projected climate conditions for the 21st century, by using a 20-km-mesh atmospheric global climate model and a 0.5°-mesh global river routing model under a greenhouse gas emission scenario. The climatological annual mean river discharges along the main stream of the Magdalena River do not change significantly, however precipitation, evaporation, and total runoff into the river show statistically significantly changes over most of the Magdalena River basin. By the end of the 21st century, the projected climatological monthly mean river discharge at Puerto Berrio decreases statistically significantly in April, October, and November (P < 0.05), compared to current values, whereas it shows a distinct increase for June through August, thereby reducing the present bimodality of its seasonal variation. Minimum climatological monthly mean river discharge in February could be lower at the end of the 21st century than in the current condition. These results should help increase the awareness of the changing river discharge in the Magdalena River basin, and prepare adaptation strategies to face these challenges.

KEYWORDS Magdalena River; climate change; river discharge; Colombia; 20-km mesh GCM

INTRODUCTION

Colombia sits at the tropical inter-convergence zone and has a mountainous terrain over the western part of the country. These factors have contributed to a significant endowment of fresh water. The major rivers in Colombia have discharges of more than 2000 mm/year each, and annual water availability per capita there is among the highest in the world, although this availability is unevenly distributed. Also, abundant water supplies have contributed to the development of a power sector, largely based on hydropower (82% of water delivered to the grid in 2007 was hydro generated (MME, 2008)). The river with the largest discharge where most fresh water withdrawals take place is the Magdalena River, which flows into the Caribbean Sea; therefore, its river basin is socio-economically crucial for Colombia (NC-Colombia, 2001).

By the end of the 21st century, the climatological annual mean river discharge in Colombia is projected to increase 12% above current levels; the maximum discharge is projected to increase by 30%, whereas seasonal variability is projected to decrease by 5%, according to a hydrological projection based on the second assessment of the Intergovernmental Panel for Climate Change (IPCC; NC-Colombia, 2001). A climate projection from a multiple-model ensemble of 8 atmosphere-ocean global climate models (AOGCMs) used in the 4th assessment of the IPCC showed that many glaciers may completely disappear in the tropical Andes in the next few decades, which will reduce the natural regulation of river discharges and may result in a seasonal scarcity of water for drinking, agriculture, and hydropower production (Bradley et al., 2006). Climate changes may also affect water supply from páramos, a high-altitude neotropical ecosystem (IDEAM, 2004) that provides most of the fresh water to cities located in the Colombian Andes, including its capital Bogota. These projections use the coarse horizontal resolution of around 280 km of the AOGCMs, but higher resolution atmospheric GCM is required to examine the distribution of the climate changes within Colombia or river basins. A super-high-resolution atmospheric GCM with a horizontal grid size of about 20 km (20-km AGCM; Mizuta et al., 2006) projected that surface air temperature in Colombia will increase by 1.5 to 2.5°C by the end of the 21st century, especially in the mountains and central regions, where most of the operational hydropower capacity is located. It also projected that annual precipitation will decrease and its variability will increase (Vergara, 2005).

The present study examines the projected river discharges of the Magdalena River basin for a changing climate during the 21st century. This is a socio-economically important region in Colombia, and the location of one of the largest hydropower plants, Betania, with 540 MW nominal capacity. Previous studies did not show projections for individual river basins, and the results from the 20-km AGCM have not yet been examined for impact assessments in Colombia.

METHODS

River Basin

The Magdalena River basin was diagrammed for this study using a global digital river routing dataset from Total Runoff Integrating Pathways (TRIP; Oki and Sud, 1998) with a horizontal resolution of 0.5° (Figure 1). The river has a main stream length of more than 1500 km and basin areas of 0.26 million km² at Calamar in the lower basin and 0.08 million km² at Puerto Berrio in the middle basin. The
Cauca River basin, the largest tributary basin, is located in the Cauca valley between the Cordillera Central and Oriental ranges in the western part of the Magdalena River basin.

Model

The models used in this study are the 20-km AGCM for future climate projection and a river routing model for future river discharge projection. The 20-km AGCM has a horizontal resolution of triangular truncation 959 with a linear Gaussian grid (T\_L\_959), corresponding to a grid size of about 20 km, and it has 60 vertical layers, with the model top at 0.1 hPa. The land surface model used is the new version of the Japan Meteorological Agency Simplified Biosphere (SiB; Ohizumi and Hosaka, 2000), and incorporates vegetation, snowpack, and soil processes coupled with the atmospheric components of the 20-km AGCM. SiB predicts soil temperature and moisture content and diagnostically computes the surface and subsurface runoff (hereafter referred to as total runoff), which are inputs for the river routing model described in the next paragraph. For a further description of the 20-km AGCM, please see Mizuta et al. (2006).

The Global River flow model using TRIP (GRiVET; e.g. Nakaegawa and Hosaka, 2008) was used as the river routing model. GRiVET predicts the river water storage in the river channel forced with the total runoff from SiB and diagnostically computes the river discharge. The river discharge is assumed to be proportional to the river water storage in GRiVET (see Oki and Sud (1998) for details). The proportionality constant has the same dimension as velocity, called the effective velocity, and was set to 0.4 m/s in this study (see Kitoh et al. (2008a) and Nakaegawa and Hosaka (2008) for rationality).

Experiment

We performed 3 time-sliced simulations: for the present, the near future, and the end of the 21st century climate simulations. We used the observed monthly sea-surface temperatures (SSTs) and sea-ice concentrations for the current climate simulation (1979–2003), and the SSTs projected by the Coupled Model Intercomparison Project, phase 3 (CMIP3) multi-model ensemble (MME) dataset for the near future (2015–2035) and end of the 21st century (2075–2099) climate simulations. The boundary SST data were prepared by superimposing 3 components: the linear trend in the MME SSTs, the future change in the MME SSTs between the current and projected climate simulations, and the detrended observed SST anomalies for the period 1979–2003 (Mizuta et al., 2008). Future sea-ice concentrations were obtained in a similar fashion. The 20-km AGCM simulation in this study and CMIP3 simulations used for preparing the boundary data were performed under scenario A1B of the Special Report on Emission Scenarios (SRES). The river discharges were computed with GRiVET by inputting the total runoff's obtained in these simulations. Details of the experiment are described in Kitoh et al. (2009).

Data

Tropical Rainfall Measuring Mission (TRMM) Product 3B42 was used as observed precipitation. Observed climatological monthly mean river discharges provided by the Global Runoff Data Center (http://www.bafg.de/GRDC/EN/Home/homepage_node.html) were used to validate the model simulation of river discharge under current climate conditions.

RESULTS

Reproducibility

Climatological mean precipitation in the Magdalena River basin is reproduced in the 20-km AGCM with the statistically-significant spatial correlation value of 0.4, but it is about 35% overestimated (see Figure S1 and Document S1). Although the climatological annual mean river discharge and amplitude of the seasonal variation are overestimated, the seasonal variations at Puerto Berrio and Calamar in the Magdalena River basin are fairly well captured in the current climate simulation (see Figure S2 and Document S1 for details). This level of reproducibility allows a future projection according to the discussion about the global model’s reproducibility in Kitoh et al. (2008a, 2008b) and Ben-Zvi and Givati (2008). However, the seasonal variation at La Pintada in the Cauca River basin is not captured probably due to the steep and complex topography, and a climatological monthly mean projection is not applied there.

Climatological annual means

The projected increases in the climatological global mean surface air temperature by the 20-km AGCM simulations are 0.93 K in the near future and 2.73 K at the end of the 21st century. The change in the climatological global mean...
surface air temperature at the end of this century is slightly lower, by about 0.4 K, than the change of the CMIP3 multi-model ensemble (MME) mean. The change in the climatological annual mean precipitation in the Magdalena River basin is projected to be 1% in the near future climate and 2% at the end of the 21st century, which is almost the same as the CMIP3 multi-model ensemble mean at the end of the 21st century, 2.5% ± 1.3%. The projection for Colombia is almost the same as that by Vergara (2005) with previous version of the 20-km AGCM simulation.

We determined the geographical distributions of the projected percent changes in climatological annual mean precipitation, evaporation, total runoff, and river discharge at the end of the 21st century (Figure 2). The changes in each grid box for all but river discharge are basin-mean values of all grid values upstream in each basin from a specific grid box. These basin-mean values allow a comparison with the projected changes in river discharge. By the end of the 21st century, there are statistically significant increases ($P < 0.05$, Student’s $t$-test) in the projected climatological annual mean precipitation in most areas of both the Magdalena and Cauca River basins, and decreases in a few parts of the middle and upper Magdalena and Cauca River basins (Figure 2a). The climatological annual mean evaporation increases compared to the present climatology in almost all areas ($P < 0.05$) and exceeds a 6% increase in some areas (Figure 2b). The increases in climatological annual mean evaporation are due to both the increase in the climatological annual mean downward longwave radiation and the dependence of the Bowen ratio on the surface air temperature. The climatological annual mean total runoff shows decreases rather than increases in many areas of both basins (Figure 2c) because of the significant large increase in climatological annual mean evaporation. The changes in climatological annual mean river discharge show a geographical pattern similar to that of the climatological annual mean total runoff, but with less area showing statistically significant changes (Figure 2d). There were no statistically significant changes along the main stream of the Magdalena River basin. Similar patterns of change were observed in the simulation for near future climate conditions, but the changes are not statistically significant for most areas of the two basins because of small secular changes and large interannual variability.

Climatological monthly means

The projected climatological monthly means of hydrological variables at Puerto Berrio at the end of the 21st century and their changes relative to present values are depicted in Figure 3. The projected climatological monthly mean precipitation shows a distinct increase over present-day values from March to August, except for April (Figure 3b), which explains the future reduction of the bimodality of the variation in climatological monthly mean precipitation (Figure 3a). The climatological monthly mean evaporation is higher by about 0.3 mm/day from the present climatology throughout the year. The changes in both the climatological monthly mean river discharge and total runoff have smaller amplitudes than that of the climatological monthly mean precipitation, and have almost the same seasonal variations. The projected climatological monthly mean river discharge is significantly lower ($P < 0.05$) than present values in April, October, and November, resulting in a reduced maximum climatological monthly mean river discharge in October (compare with Figure S2a). The minimum climatological monthly mean river discharge in February by the end of the

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Figure 2. Geographical distribution of projected climatological annual mean percent changes in (a) precipitation, (b) evaporation, (c) total runoff, and (d) river discharge at the end of the 21st century. Except for river discharge, values for each grid box are basin-mean values of all grid boxes upstream of a specific grid box. White lines delimit regions with statistically significant changes ($P < 0.05$) compared to current values and the characters L and H at center of closed innermost contours denote the insignificant and significant areas. No white line is clearly distinguished in panel (b) since almost all areas are statistically significant for evaporation.
Climates are projected to decrease for the Magdalena River climatological annual mean river discharges under future is in the medium range of the CMIP3 projections. The change in the future climate simulations used for this study basin and to increase for the Atrato River basin (light yellow the climatological monthly mean river discharge, only for only for the increases in January, February, and July, and in climatological mean precipitation at Puerto Berrio are found to decrease in April, October, and November (\(P < 0.05\)). The minimum climatological monthly mean river discharge in February may decrease below that of the present climatology. The climatological monthly mean river discharge in the valley of the bimodality (June–August) may increase, thereby reducing the bimodality by the end of the 21st century. These changes stem from changes in the climatological monthly mean precipitation. At Calamar, the severity of both drought and flood river discharge at monthly time-scales may increase at the end of the 21st century. In the near future, a statistically significant change in the monthly means of river discharge at Puerto Berrio suggests a more severe drought and flood river discharge. These results suggest an increasing need for adaptation to future hydrological cycles to reduce the likely flooding and the impact of seasonal variations on the operation and maintenance of water reservoirs for power and freshwater supply. Our results should raise the awareness of the changing river discharges in the Magdalena River basin and highlight the need for awareness and early adaptation efforts to the likely consequences of climate impacts on the hydrological cycle in Colombia.

The climatological annual mean river discharge of the Magdalena River is projected to decrease by the end of the 21st century, whereas the climatological annual mean river discharge at the Colombian national level was projected to increase by 12% above the current climatology (NC-Colombia, 2001). Such a large projected increase in the present study is confined to the Atrato River basin. The 5% decrease in the amplitude of seasonal variation in river discharge in this previous study is qualitatively consistent with the projections at Puerto Berrio in the present study, but not with those at Calamar.

CONCLUSION

We first projected the river discharge in the Magdalena River basin under future climate conditions using the 20-km AGCM and the 0.5° version of GRiVET under the SRES A1B scenario. The changes in climatological annual mean river discharge by the end of the 21st century are statistically significant (\(P < 0.05\)) only in some areas of the Magdalena and Cauca River basins. The projected changes in climatological annual mean river discharge in the near future are not statistically significantly for most of both the Magdalena and Cauca River basins owing to the small secular change and large interannual variations.

By the end of the 21st century, the climatological monthly mean river discharge at Puerto Berrio is projected to decrease in April, October, and November (\(P < 0.05\)). The minimum climatological monthly mean river discharge in February may decrease below that of the present climatology. The climatological monthly mean river discharge in the valley of the bimodality (June–August) may increase, thereby reducing the bimodality by the end of the 21st century. These changes stem from changes in the climatological monthly mean precipitation. At Calamar, the severity of both drought and flood river discharge at monthly time-scales may increase at the end of the 21st century. In the near future, a statistically significant change in the climatological monthly mean river discharge at Puerto Berrio is only found for the projected decrease in October.

DISCUSSION

The climatological global mean surface air temperature change in the future climate simulations used for this study is in the medium range of the CMIP3 projections. The climatological annual mean river discharges under future climates are projected to decrease for the Magdalena River basin and to increase for the Atrato River basin (light yellow color in Figure 1), which is bordered on the West by the Magdalena River basin as shown in Figure 2d. This contrast is also projected by the CMIP3 MME projections (Milly et al., 2005). This agreement shows that the projections in this study are probably spatially robust, although we may need to consider additional information about robustness at 0.5°-scale.

The projections at the monthly time-scale revealed slightly less severe but statistically significant flood river discharges and slightly more severe drought river discharge at Puerto Berrio by the end of the 21st century compared to the current conditions; predictions for Calmar show slightly more severe droughts and flood river discharge. These results suggest an increasing need for adaptation to future hydrological cycles to reduce the likely flooding and the impact of seasonal variations on the operation and maintenance of water reservoirs for power and freshwater supply. Our results should raise the awareness of the changing river discharges in the Magdalena River basin and highlight the need for awareness and early adaptation efforts to the likely consequences of climate impacts on the hydrological cycle in Colombia.

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Water resource availability, power supply and flood disasters under future climate conditions should be evaluated at the local scale rather than at the basin scale as Kim et al. (2010) evaluated, since water use differs with location and, as demonstrated in this study, projections vary with location even within a basin. However, even a 20-km resolution cannot accurately represent the very steep and complex topography of the Cordillera Central and Oriental ranges. In addition to the 20-km AGCM simulations, downscaling of future climate simulations projected by CMIP3 AOGCMs, with coarse horizontal resolutions of 20-km or finer, will permit the application of an MME method to reinforce projections of river discharge, especially at local scales such as the Magdalena River basin.

Moreover, projections of river discharges should include finer time resolutions such as daily to sub-monthly time-scales, as short-time-scale hydrological phenomena such as flash-floods and low flows can have devastating effects on human activities and ecosystems. Following the present study, after daily river discharge simulated under current climate conditions is validated against observations, probability analysis for floods and drought should be performed including a wider coverage for basins that are relevant for water and power supply.

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SUPPLEMENT

S1. Supplementary document about reproducibility of Precipitation and figures are included in Supplement 1.

REFERENCES


