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Hydroclimate projections for Panama in the late 21st Century

José Fábrega[1], Tosiyuki Nakaegawa[2], Reinhardt Pinzón[1], Keisuke Nakayama[3], Osamu Arakawa[2] and SOUSEI Theme-C Modeling Group[2]

[1]*Centro de Investigaciones Hidráulicas e Hidrotécnicas, Universidad Tecnológica de Panamá, Republic of Panamá*
[2]*Climate Research Department, Meteorological Research Institute, Japan*
[3]*Dept. of Civil and Environmental Engineering, Kitami Institute of Technology, Japan*

Abstract:

This work analyzes hydroclimate projections in Panama toward the end of the 21st century by employing the MRI-AGCM3.1 model. Understanding the impact of climate change on water resources is fundamental for a number of economic activities in Panama (i.e. Panama Canal operation, hydropower generation, and agriculture). Therefore, it is important to assess hydroclimatic impacts in specific basins using reliable Atmospheric Global Circulation Models (AGCMs) validated against actual field data. A 20-km mesh experiment was developed by using time-sliced analysis for current (1979–2002) and future (2075–2099) periods. Uncertainty in climate projections were addressed by completing 60-km mesh AGCM ensemble experiments at three additional lower boundary conditions. Four regions in Panama were selected for detailed analysis: from east to west, Bocas del Toro, Veraguas, Panama Canal and Darien. Projections show significant precipitation increases from May and July to December for all regions except Bocas del Toro. In this region, a decrease in precipitation is expected between April and August. Total runoff for all regions followed the changes in precipitation as expected. Due to net radiation increases, projected evaporation did not appear to be affected by precipitation changes.

KEYWORDS Panama; hydroclimate projections; MRI-AGCM3.1; precipitation; evaporation; total runoff

INTRODUCTION

Panama has extensive water resources that determine a great deal of its economic activity (Espinosa *et al.*, 1997). It has the second largest amount of water in Central America with a volume of 52.437 m^3 per capita (Comisión Centroamericana de Ambiente y Desarrollo, 2005). Geographically, Panama is located between the western tropical Atlantic Ocean and the eastern tropical Pacific Ocean, stretching from 7°12'07" to 9°38'46"N and 77°09'24" to 83°03'07"W (Autoridad Nacional del Ambiente (ANAM), 2011). The Panamanian climate is dictated by its position, orientation, narrowness, the influence of the inter-tropical convergence zone and ocean-atmosphere interactions (Empresa de Transmisión Eléctrica S.A. (ETESA), 2007). For the 1971–2002 period, Panama had an annual average precipitation of 2924 mm (220.8 km^3) and a annual average runoff of 1764 mm (133.2 km^3), translating to a runoff coefficient of 60.3% (Programa Hidrológico Internacional, 2008). Panama is divided into three pluviometric regions: Pacific, Atlantic and Central. The Pacific region has a dry season running from December to April, and a wet season from May to December. For the Atlantic region, precipitation continues throughout the year (ETESA, 2007). This precipitation feeds 500 rivers in 52 watersheds (ANAM, 2011), which in turn deliver water to either the Pacific or Atlantic. Pacific watersheds represent a larger water resource and have longer main streams than those of the Atlantic watersheds (ANAM, 2011).

Besides agriculture and drinking water uses, water resources are considered an important economic asset in Panama. For example, the Panama Canal Watershed composed mainly of the Chagres River provides the necessary water for the transit of vessels to the Panama Canal, which represents about 8% of Panama GDP. Also, in terms of energy production, hydropower accounts for 50% of the installed electrical capacity in the country (Secretaria de Energía, 2012). Therefore, the effects of climate change on hydroclimate should be considered for long term economic planning.

In terms of agriculture, Ruane *et al.* (2011) demonstrated that Panama corn yield is expected to increase slightly over the 21st century due to accelerated development of the crop. Climate change is becoming an obstacle to a faster decline in Chagas disease in Panama, since changes in land use and climate might increase the risk of human contact with Chagas vectors (Gottdenker *et al.*, 2011). Finally, long-term reduction of coral growth rates in the Panamanian Pacific is an example of climate change impacts on coastal systems (Guzman *et al.*, 2008). With respect to precipitation, by employing long-term data from six meteorological stations around the Panama Canal, Nakayama *et al.* (2012) found an incremental increase in a simple precipitation intensity index, also suggesting an increase in the frequency of strong precipitation events in Panama. Espinosa *et al.* (1997) employed a rainfall-runoff hydrological model to evaluate various scenarios of water resource availability in three river basins (La Villa, Chiriquí, and Chagres) using 20-year records of meteorological data, temperature increments of 1 or 2°C and precipitation changes of 115 and 120% for the Pacific and Atlantic watersheds, respectively. They found that river discharge in the Pacific watersheds (La Villa and Chiriquí) would be the most affected under the increased temperature and precipitation scenarios.

Projections from dynamical coupled general circulation

Correspondence to: Tosiyuki Nakaegawa, Climate Research Department, Meteorological Research Institute, 1-1 Nagamine, Tsukuba, Ibaraki 305-0052, Japan. E-mail: tnakaega@mri-jma.go.jp

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models (GCMs) have not been used because their horizontal resolution is generally about 100 to 400 km, corresponding to an area larger than the entire area of the Panama Canal, and for some cases larger than the entire country, Recently, projections from a high horizontal resolution AGCM with a 20 km mesh size became available for impact projection studies for large river basins (e.g. Nakaegawa and Vergara, 2011; Nakaegawa *et al.*, 2012, 2013) and may provide a means to project hydroclimates in a small country such as Panama. The present work analyzes hydroclimate projections in Panama toward the end of the 21st century.

METHODOLOGY

Study regions

The four regions targeted in this study are shown in Figure 1 which is divided into Total Runoff Integrating Pathways with a horizontal resolution of 0.5° (TRIP; Oki and Sud, 1998). Large river basins for each of these regions are shown in Table SI. These basins cover about 43% of Panama. Basins from the Bocas del Toro and the Panama Canal regions discharge to the Atlantic Ocean while corresponding basins in the Veraguas and Darien regions discharge to the Pacific Ocean.

These regions represent major areas of Panama. Bocas del Toro, the closest region to Costa Rica, includes the provinces of Chiriquí and Bocas del Toro, and the Ngöbe-Buglé comarca. A comarca is an administrative geographical division composed mainly of an indigenous population. The Veraguas region represents the provinces of Herrera, Los Santos, Coclé and Veraguas. It is located roughly in the middle of the country. The Panama Canal region comprises the Colon province and the west section of the Panama province. The two major panamanian cities at both ends of the Panama Canal (Panama and Colon) are located in this region. Finally, the Darien region includes the Darien province and the east section of the Panama province. The other two comarcas are located in Embera-Wounaan and Kuna Yala, a region along the border with Colombia that is less populated.

MODEL, EXPERIMENT, AND DATA

Model

The model employed was the Meteorological Research

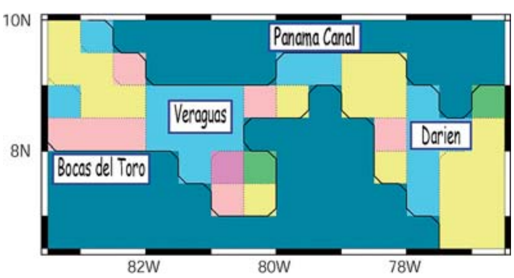

Figure 1. Four regions in Panama targeted in this study based on TRIP (Oki and Sud, 1998): Bocas del Toro, Veraguas, Panama Canal, and Darien. Colors except for dark blue represent different basins.

Institute (MRI) AGCM version MRI-AGCM3.1 The Japan Meteorological Agency (JMA) first developed the model for operational short-term numerical weather prediction with a 60-km mesh; the MRI improved the original version for long-term climate simulations by implementing a semi-Lagrangian scheme in a dynamical core, allowing longer time steps in numerical integrations. This model has a 20 km horizontal resolution corresponding to a linear Gaussian Grid (T_L959), which indicates a triangular truncation 959 with a transformed 1920 × 960 grid cells in a spherical projection. The vertical resolution is given by 50 layers up to 0.1 hPa.

Atmospheric variables in the 20 km-mesh AGCM were related to land-surface elements, employing a new version of the Simplified Biosphere (SiB; Hirai *et al.*, 2007). SiB predicts soil surface and canopy temperatures by solving radiation and heat transfer balance equations, and water content and temperature in soils by solving Richards and thermal diffusion equations, respectively. It also diagnostically determines sensible and latent heat fluxes, and surface, subsurface and total runoff, the latter a summation of the components reaching a river stream. Evaporation in this study is defined as the summation of evaporation from ground surface, grass, and canopy, and transpiration from vegetations. A more complete explanation of the 20-km mesh AGCM can be found in Mizuta *et al.* (2006).

Experiment

A 20-km mesh AGCM experiment was performed by using time-sliced analysis for the present and future. For the present (1979–2002), we employed observed monthly sea-surface temperatures (SSTs) values and sea-ice concentration. For the future (2075–2099), the Coupled Model Intercomparison Project, phase 3 (CMIP3) multi-model ensemble (MME) dataset was employed to define SST values as the sum of the MME mean of SST change values and current SST values (Mizuta *et al.*, 2008). The simulations made by the CMIP3 were developed under scenario A1B of the Special Reports on Emissions Scenarios (SRES).

Uncertainty in climate projections was addressed by completing 60-km mesh AGCM ensemble experiments. In these simulations, the same CMIP3 MME mean as that employed in the 20-km mesh AGCM experiment was used, along with three additional lower boundary conditions: CSIRO, MIROC, and MRI. For each lower boundary condition, three-initial-condition ensemble experiments were performed, with total ensemble size 15: 1 × 3 for the current climate and 4 × 3 for the future climate.

In the future climate projection analysis, we upscaled and downscaled hydroclimate variables with 0.5 degree horizontal resolution as seen in Figure 1; by spatial averaging for the 20-km and interpolation for the 60-km mesh models, respectively. The same mesh size allows us to compare results and to quantify the uncertainties in future climate projections.

Data

Observed precipitation datasets were obtained from the Tropical Rainfall Measuring Mission (TRMM) Product 3B42 (Adler *et al.*, 2000). The horizontal and temporal resolutions of these data are 0.25° and 3 hours, respectively. This dataset is validated against gauge-based observations in Document S1. In addition, we used CMIP3 MME to quantify the uncertainties in hydroclimate projections due to different model structures because Panama is small compared to the horizontal resolution of CMIP3 models, and one grid shift results in distinct modifications of climatic change impacts in Panama. Then, annual mean hydroclimatological values for 2075–2099 from SRES A1B in CMIP3 MME were used for the future climate; those for 1975–1999 from the 20th Century Climate in Coupled Models experiment as a part of CMIP3 (Meehl *et al.*, 2007) were used as the present climate.

RESULTS

Validation of precipitation

Climatological mean precipitation in the four regions of Panama in this study was simulated with the 20-km mesh AGCM and then compared with that of TRMM 3B42 (see Document S1 and Figure S1). The large amounts of precipitation characterizing Panama in TRMM 3B42 were captured by the 20-km mesh AGCM; daily mean precipitation over 50% of the country is above 7 mm day^{-1} with the other 50% receiving between 4 to 7 mm d^{-1}. Bocas del Toro and Veraguas showed the largest amount of precipitation, while the Panama Canal and Darien showed the lowest.

Table I presents the validation of mean current precipitation with the 20-km and 60-km mesh AGCM experiments for the four regions. Annual mean precipitation in the 20-km mesh AGCM corresponded well to TRMM3B42, within an error of 20% for all regions except the Panama Canal where the annual mean precipitation was 27% underestimated. For Darien, the 20-km mesh AGCM slightly overestimated annual mean precipitation by 4%. Within the seasonal cycle, the temporal correlation was very similar for all regions, with values from 0.84 to 0.91. The standard deviation ratio was in the range of 0.61 to 0.66 with the exception of Darien.

The 60-km mesh AGCM underestimated annual mean precipitation for all regions by 17 to 39% except Darien (ratio of 1.00). Temporal correlations were very similar to those obtained for the 20-km mesh experiment. With the exception of Veraguas, RRMSEs were greater for the 60-km AGCM than for the 20-km mesh AGCM; a result expected due to the larger mesh size employed. In general both the 20-km and 60-km mesh AGCM experiments capture current precipitation well.

Climatological annual mean projection

Figures 2a to 2c show the future hydroclimate projections for precipitation, evaporation and total runoff in the 20-km mesh AGCM. Future precipitation appears to increase for all regions by at least 5%, with the exception of some areas of the Bocas del Toro region. It should be pointed out that increments greater than 15% were projected for the most populated areas in Panama, located next to the Panama Canal. Evaporation should also increase across the country. Finally, total runoff showed that approximately 50% of the areas in Panama do not have statistically significant changes (Figure 2c). However, consistent with precipitation projections, the areas in the Bocas del Toro region with lower precipitation (Figure 2a) also have lower total runoff projections.

Figures 2d to 2f show the consistency of changes in sign between the 20-km mesh AGCM and the 4 multi SST 60-km mesh AGCM simulations, with a value of four representing a consistent change and a value of one an inconsistent change. Evaporation and precipitation results appeared to be consistent over half of the country, with values of 4 (the greatest on the scale used) for evaporation and 3–4 for precipitation. Defining robustness as a measure of how well a process works if assumptions are changed, we employed the consistency of changes in sign as a measure of robustness for the statistically significant results of figures 2a to 2c. For evaporation, these results confirm predictions made by the AGCM simulation. The statistically significant precipitation increases projected (Figure 2a) are confirmed to be robust in Figure 2d for almost all areas, except for some areas in the Bocas del Toro. For total runoff, in most areas, the statistically significant changes in the 20-km mesh AGCM showed low robustness, with the exception of selected spots in Veraguas and Darien (see Figure 2c and 2f).

Table I. Validation of area-mean precipitation in the current climate simulation for the four regions. Annual mean ratio (simulation/observation), temporal correlation of seasonal cycles of monthly mean values between the simulation and the observation, the variation ratio of seasonal cycles measured with standard deviation of monthly mean values (simulation/observation), and relative root mean square error (RRMSE). All units are non-dimensional.

Model horizontal resolution	Annual ratio	Seasonal cycle		
		Temporal correlation	Standard deviation ratio	RRMSE
(a) 20-km				
Bocas del Toro	0.84	0.88	0.66	0.31
Veraguas	1.18	0.88	0.65	0.34
Darien	1.04	0.84	0.48	0.39
Panama Canal	0.73	0.91	0.61	0.38
(b) 60-km				
Bocas del Toro	0.66	0.89	0.62	0.43
Veraguas	0.83	0.90	0.65	0.33
Darien	1.00	0.88	0.34	0.43
Panama Canal	0.61	0.94	0.50	0.49

Future change in precipitation, evaporation, and total runoff

Figure 3 presents projected climatological regional monthly means of hydrological variables (precipitation, evaporation and total runoff) in Panama under the future climate. For Bocas del Toro, precipitation is expected to decrease from April to August, with June being the month with the maximum negative change. A similar trend was observed for total runoff with an even greater negative change in June (Figure 3a). Evaporation changes were small but statistically significant for all months, and did not appear to be affected by changes in precipitation because increases in net radiation by 6.5 W/m^2 due to greenhouse gases could supply enough energy for evaporation. Increases in longwave and shortwave radiations accounts for about 50% of increase in net radiation respectively.

In Veraguas, future projections indicate precipitation increases for most of the rainy season (July–December). For this region, total runoff was projected to increase from August to December. For evaporation, there were no appreciable changes, and in most cases no statistically significant differences.

Future projections showed greater precipitation intensity for Darien during the period ranging from May to December. This behavior is very similar to that observed for total runoff; not only in qualitative terms, but also in quantitative terms. Therefore, considering the difference in scale between both variables (precipitation is consistently 4 to 6 mm higher than total runoff all year around), it appears that the precipitation increase for this region is captured by the total runoff component.

The Panama Canal region projections showed precipitation increases from May to December. As for other regions, total runoff followed the changes in precipitation very closely. Evaporation was fairly constant during the year, with a small reduction in December being statistically insignificant.

Future projections presented in Figure 3 showed precipitation increases starting between May and July to the end of the year for all regions, with the exception of Bocas del Toro. In this region, a decrease in future precipitation is expected between the months of April to August. Since these behaviors occur at the rainy seasons of all the regions, total yearly precipitation for all the regions but Bocas del Toro also increased. Total runoff for all cases followed the trends seen in precipitation as expected. Future evaporation did not appear to be affected by future precipitation changes and increased by about 0.2 to 0.3 mm/d for all months due to

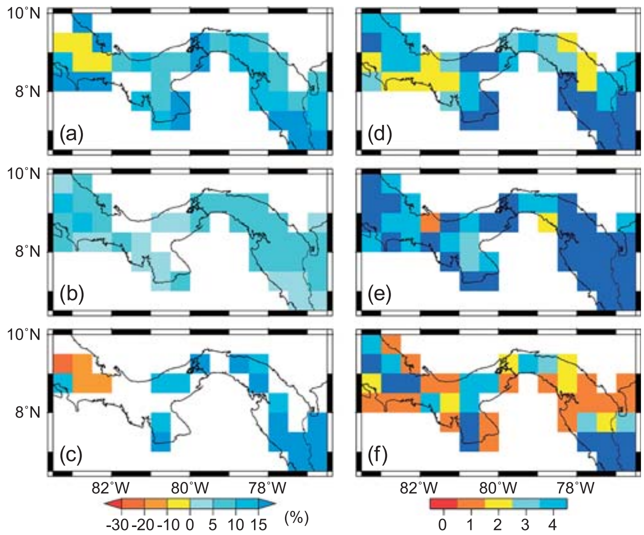

Figure 2. (left; a–c) Climatological annual mean hydrological variable changes (%) in the future climate relative to the current. Areas statistically significant at 95% level are colored. (right d–f) The number of consistent changes in sign comparing the 4 multi-SST 60-km mesh AGCM ensemble simulations with the 20-km mesh AGCM. A value of four represents consistent changes between the 20-km mesh model and the 4 multi-SST 60-km mesh AGCM, while one represents inconsistent changes. (a) and (d): precipitation; (b) and (e): evaporation; (c) and (f) total runoff.

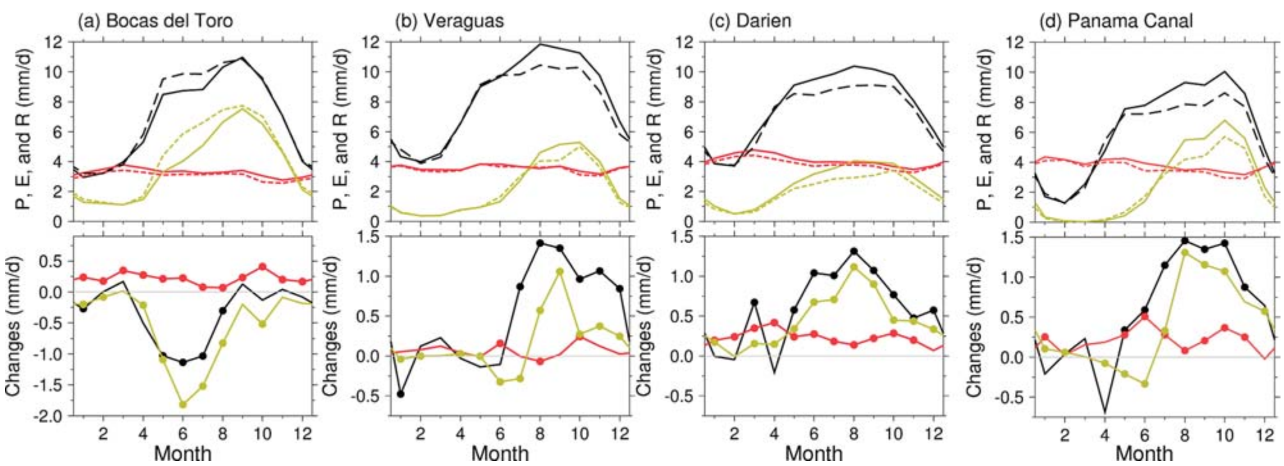

Figure 3. (top) Regional mean seasonal variation in precipitation, evaporation, and total runoff under current (dashed) and future (solid) climates and the change between current and future climates (bottom panels). Black, red, and green lines denote precipitation, evaporation, and total runoff (mm/d), respectively. Circles represent statistically significant changes at 95% level.

increased net radiation. These increases correspond well with increases in net radiation if evaporation consumes almost all increased net radiation. Figure 3 also demonstrates that projected precipitation changes during the rainy season were statistically significant at 95% level for all variables. Insignificant changes were observed during the dry season, while projected evaporation and total runoff changes were statistically significant for both seasons in general.

DISCUSSION

Future variation in precipitation, evaporation and total runoff were projected on a monthly basis for the four regions in Panama. In terms of precipitation, this appears to increase for all regions by at least 5%, with the exception of some areas of the Bocas del Toro region. Results were statistically significant in many months and indicate a consistent temporal behavior between precipitation and total runoff, with small positive increments in evaporation. Espinosa *et al.* (1997) employed the rainfall-runoff hydrological model to project future river discharge at the end of 21st century in three important rivers in Panama (La Villa, Chagres and Chiriquí). They assumed temperature increases of up to 2°C combined with precipitation changes of up to ±15% for the Chiriquí and La Villa rivers and up to ±20% for the Chagres basin. River discharge under these scenarios varied by basin location and according to the direction of change in precipitation (increase/decrease). River discharge was projected to decrease by up to 40% when precipitation decreased for both basin locations. For precipitation increases, total runoff was projected to increase by up to 50% in the Chagres river basin. The Pacific basins under the precipitation increase scenarios showed total runoff decreases of up to 35% from November to April and increases of up to 40% for May to October. Compared to previous work, our results indicate that scenarios with precipitation decreases and temporally constant rates of change, such as used in Espinosa *et al.* (1997), are unreasonable and increases in precipitation does not lead to total runoff increase, as seen in Figures 2c and 3. Therefore, the hydroclimate projections in the present study may be more reliable.

Multi-model projections are widely recognized as essential since different model structures project different future climates. IPCC reports present future projections with multi-models, as do most scientific articles such as Kitoh *et al.* (2012) and Nakaegawa and Vergara (2010). This reflects the fact that, without multi-model projections, we cannot project future climates in a scientific manner. We quantified the uncertainties in hydroclimate projections using the 60-km mesh AGCM ensemble; however at 4 models, it was smaller than the total number of CMIP3 MME (24). In order to quantify the uncertainty on a country scale, we compared total runoff changes with global- and country-scale means of surface air temperature, precipitation, and evaporation (Figure S2). Due to the very coarse horizontal resolutions of CMIP3 models, Panama is only represented in 15 out of the 24 models, and by a single grid. The total runoff changes were small in the present study but are very large in some CMIP3 models. Large air temperature increases of 3°C tend to lead to total runoff decreases. The total runoff changes showed a very strong linear relationship to local precipitation changes but not to global changes. Local evaporation did not show any consistent changes or have any relationship to the total runoff. Although the models used in the present study reproduce the current climate well and have high reliability, and thus the projections with quantified uncertainty may be reliable, one should acknowledge the larger uncertainty in the CMIP3 MME, especially for impact assessments.

As we mentioned earlier, water in Panama is an economic resource in various productive activities. The Panama Canal region for example, showed a statistically significant increase in precipitation and total runoff (up to 1.5 mm/day for precipitation and slightly less for total runoff) for the months of May to December (Figure 3d). These results trend to indicate more water may be available for the Panama Canal in the future. The results are important not only for Panamanian policy makers, but also for international trade. For example during 2011, the Panama Canal had a total of 12914 transits events for large vessels with a total gross tonnage of 369,845,400 (Autoridad del Canal de Panamá, 2012). According to the Secretary of Energy, Panama has an estimated total hydropower potential of 2383 MW of which 1826 MW is in Bocas del Toro (provinces of Chiriquí and Bocas del Toro; Secretaría de Energía, 2012). In this region, precipitation is projected to decrease all year with a maximum decrease of nearly 2 mm/day in June (Figure 3a). This situation might reduce the hydropower potential and suggests that it should be evaluated in more detail for this region. Agriculture and biodiversity conservation are important in all regions in Panama. The changes in precipitation and total runoff projected for all regions should be considered in order to assess the hydroclimate impact on soil erosion, possible flooded areas, harvest time changes for crops, and adaptation capacity of some species.

Finally, we stress that results from this study were made by employing an SRES A1B scenario under specific validation conditions. Any scenario with assumptions different from this will lead to different projections. Further, future climate projection analysis was made with 0.5 degree horizontal resolution and only precipitation was validated, since no reliable estimates of actual evaporation and total runoff are available. While we employed 118 observation stations to validate our TRMM data and these stations are widely distributed in the Panama region, they provide lower coverage of the Darien region and some areas (mountains) of the Bocas del Toro region.

SUMMARY

The present work analyzed hydroclimate projections for Panama at the end of the 21st century by employing the MRI-AGCM3.1 for precipitation, evaporation and total runoff. The AGCM experiment was developed by using time-sliced analysis for current and future climates. For the current period (1979–2002), we employed observed monthly sea-surface temperatures (SSTs) values and sea-ice concentration. For the future climate (2075–2099), the CMIP3MME dataset was employed to quantify the uncertainty in climate projections, since the 60-km mesh AGCM ensemble experiments do not include uncertainties stemming from model structure or multi-model.

Climatological annual mean hydroclimate projections in the 20-km mesh AGCM under the future climate showed a precipitation increase for all regions by at least 5%, with the exception of some areas of the Bocas del Toro. The consistency in sign change between the 20-km mesh AGCM and the 4 multi SST 60-km mesh AGCM simulations was also analyzed: evaporation and precipitation projections appeared to be robust over half of the country. This was not the case for total runoff (see Figure 2).

Monthly mean projections indicate that precipitation increases are projected to start between May and July and to terminate the end of the year for all regions, with the exception of Bocas del Toro where a decrease in precipitation is projected between April and August. Seasonal variations in total runoff changes follow the changes in precipitation for all regions as expected. Evaporation does not appear to be affected by precipitation changes, but instead is likely to be controlled by increased net radiation stemming from greenhouse gas increases and small cloud cover.

We chose SRES A1B in this study since it is widely used for climate projection and impact assessments; there are other SRES: A2 (business as usual), B1, and B2. These different scenarios may lead to future climates different from our results. In addition, the 5th phase of CMIP employs Representative Concentration Pathways (RCPs; Moss *et al.*, 2010) which describe only radiative forcing. Future hydroclimate projection under the RCPs is required in a further study.

Understanding the impact of climate change on water resources is fundamental for a number of economic activities in Panama. The operation of the Panama Canal, hydropower generation, agriculture, and sustainability of the rapid economic development of Panama in recent years has depended on an efficient and scientific management of water resources. Therefore, it is important to assess impacts in specific basins using reliable hydroclimate projections.

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SUPPLEMENTS

SOUSEI Theme-C member list
Document S1.
Figure S1. Geographical distributions of annual mean precipitation in Panama
Figure S2. Changes in area-mean total runoff in Panama
Table SI. Major basins within the four regions under study

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