

## Virtually experiencing future climate changes in Central America with MRI-AGCM: climate analogues study

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### Abstract:

Twenty-four simulations were carried using the Meteorological Research Institute-Atmospheric General Circulation Model (MRI-AGCM) to predict the late 21st century climate under scenario A1B of the Special Report on Emissions Scenarios. Future climate analogues were identified for Central American capital cities using a recently developed nonparametric method. We used MRI-AGCM3.2H with a horizontal resolution of approximately 60 km, three convection schemes, four sea surface temperature distributions, and two initial conditions. Thus, the total ensemble size was 24, with a simulation period of 25 years. Most of the future analogues are at lower latitudes than their target cities, or near biological diversity and endemism hotspots like coral reefs and mangrove forests. Projected seasonal variations in surface air temperature and rainfall in Panama City were similar to the present-day climate of Soc Trang, located at the mouth of the Mekong River in Vietnam. The nonparametric method introduced in this study for identifying climate analogues can be utilized for impact assessments under a changing climate.

**KEYWORDS** climate analogue; climate change; surface air temperature; rainfall; nonparametric method; Central America

### INTRODUCTION

Although many developments have been made in the field of climate modeling, local- to regional-scale climate change projections are associated with large uncertainties (e.g. Knutti *et al.*, 2010; Fischer *et al.*, 2012). The difficulty in projecting surface air temperature (SAT) and rainfall on a regional scale is expected to obscure early indicators of climate change over the next two decades (e.g. Mahlstein *et al.*, 2011, 2012; Hawkins *et al.*, 2014), making it difficult to project how future climate change will affect human activities (Hallegatte *et al.*, 2007). By the end of the 21st century, SAT is projected to depart from present-day SAT (1980–2009) by several degrees (Fischer *et al.*, 2012).

Central America is situated between the tropical Pacific and Atlantic oceans, which greatly influence its climate. In

this region, the thermal differences between the continents of North and South America and the Pacific and Atlantic oceans are significant determinants of hydroclimatic conditions (Nakaegawa *et al.*, 2014c). The climates of Central America and the Caribbean are influenced by the inter-tropical convergence zone (ITCZ), a narrow band with intense rainfall, and by El Niño-Southern Oscillation (ENSO) (El Niño is associated with dry conditions and La Niña with wet conditions), leading to intense regional variability in rainfall. Due to proximity to the oceans, annual ranges in SAT throughout the region are usually slight, and rainfall is apparently the most dominant hydroclimatological component (e.g. Taylor and Alfaro, 2005; Nakaegawa *et al.*, 2014b); the migration and the annual cycle of synoptic structures forms the mean climates in this region. Moreover, the tropics will be extremely susceptible to climate change due to the earliest emergence of unparalleled climates, and tropical species are especially affected by slight climate changes with the tropics supporting most of the planet's species (Mora *et al.*, 2013). Already, the SAT increase due to increasing greenhouse gas concentrations has been responsible for the extinction of two frog species (the stubfoot frog, *Atelopus* and the golden toad, *Incilius periglenes*) in Costa Rica by creating favorable conditions for the pathogenic *Batrachochytrium dendrobatidis* fungus (Pounds *et al.*, 2006). According to Giorgi (2006), Central America should be considered a hotspot (a region highly sensitive to the effects of climate change) due to projections of reduced rainfall and intensification of rainfall variability (Nakaegawa *et al.*, 2014a). For Panama in particular, climate change may have severe economic impacts (Fábrega *et al.*, 2013). This diversity of impacts from climatic changes in Central America suggests knowing how local-scale future climates change under a global warming is important.

It is of scientific interest to explore how to convey a future climate at a target place to public, policy makers, and stake holders, and to scientists who study animals, health, and water, in a way that allows people to virtually experience the new climate. One possible way to achieve this is climate analogues. Climate analogues, also referred to as space-for-time substitutes, are areas where the present-day climatic conditions resemble past or future environments in another location based on climatic factors (e.g. Williams *et*

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*al.*, 2007; Ramírez-Villegas *et al.*, 2011). It has been applied to global (Arnbjerg-Nielsen *et al.*, 2015) and many local regions such as Australia (Webb *et al.*, 2013; Nakaegawa *et al.*, 2017) and Japan (Ishizaki *et al.*, 2012) but not Central America. Most climate analogues are deterministic and show one-to-one correspondence between a target and an analogue city. Because future climate projection involves factors of uncertainties such as the climate model itself, internal variability, and greenhouse gases emission scenarios, the climate analogue should be shown as probabilistic by incorporating these uncertainties. Hibino *et al.* (2015) recently addressed this issue in climate analogues and demonstrated probabilistic geographical distributions of climate analogues by incorporating three factors of uncertainties using a non-parametric method. The aim of this work was to provide an opportunity for better virtual experience of climate change using climate analogues for capital cities in Central America with quantification of the uncertainties in future climate projections. The climate analogues in the present study were obtained by identifying a city with a present-day climate similar to that predicted for a target city in the future.

Twenty-four simulations of the Meteorological Research Institute-Atmospheric General Circulation Model (MRI-AGCM; Mizuta *et al.*, 2012) were carried out for present-day and future climates to reflect uncertainties in climate projections. The three factors of uncertainties treated in this study include projected future sea surface temperatures (SSTs) and convection schemes in the model itself and internal variability as natural features of atmospheric flow. The locations of the future climate analogues for Central American capital cities were identified using the nonparametric method recently developed by Hibino *et al.* (2015).

## METHODS

The procedure to search for climate analogues was a two-step process. First, we projected the future climate of the seven capitals in Central America. Then, we calculated a similarity score comparing each target city with locations all over the world and chose the locations with the maximum similarity scores, both globally and within the American continents. Climate analogues are identified with 0.5° horizontal resolution due to the restricted observation dataset. Therefore, target cities and climate analogue cities in this study represent the 0.5° grid box including the cities, not the cities themselves. More details of this method are given in Text S1.

### Future climate projection

Future climate data were obtained from ensemble MRI-AGCM simulations for present and future climates. The MRI-AGCM captured the present-day climates well (e.g. Mizuta *et al.*, 2012; Nakaegawa *et al.*, 2014c) compared to those of atmosphere-ocean GCM participating in phase 3 of the Coupled Model Intercomparison Project (CMIP3; Meehl *et al.*, 2007) because the MRI-AGCM is forced with observed SSTs but CMIP3 models simulate SSTs with inherent biases. Another factor in the outperformance of the MRI-AGCM is the horizontal resolution of the MRI-AGCM which is two to three times finer than those of

CMIP3 models. Nevertheless, the MRI-AGCM results may have inherent biases that do not reflect observational data. We use Equation (S1) to overcome biases embedded in the AGCM data (for more details, see Text S1). To avoid uncertainties due to differences between scenarios and between models, we performed all future climate simulations for the late 21st century (2075–2099, 25 years) using scenario A1B (Intergovernmental Panel on Climate Change (IPCC), 2000) from the Special Report on Emissions Scenarios (SRES) in the MRI-AGCM3.2H model, which has a grid spacing of about 60 km. Relative to the present day (1979–2003, 25 years), global mean SST is projected to rise 2.17°C by the late 21st century.

Our multi-ensemble included three convection schemes (see Text S1 for details): the Yoshimura scheme (YS; Yoshimura *et al.*, 2015), the Arakawa–Schubert scheme (AS; Randall and Pan, 1993), and the Kain–Fritsch scheme (KF; Kain and Fritsch, 1993).

In addition, four different multi-model projected SST distributions were considered. The uncertainties derived from the internal variability of the climate system were calculated by comparison of two simulations with distinct initial conditions. Thus, 24 ensemble experiments were conducted covering three convection schemes, four SST distributions and two initial conditions, each with a 25-year integration period, yielding 600 years of climate projections. Four SST distributions were obtained by applying a cluster analysis for multi-model projected changes in SST using CMIP3. M, C1, C2, and C3 represent a mean of future SST projections. There were local differences in the multi-model projected changes in SST among the four (Table S1). Climatological annual projected changes in SST averaged over the domain as shown in Figure 1 range from 1.95°C to 2.14°C. Each cluster had its own spatial patterns of the projected changes in SST between the Pacific Ocean and the Caribbean Sea. The projected changes in SST in the Caribbean Sea were small to large and those of the Pacific Ocean are different, from small to large. More information about the characteristics of the model for the simulations can be found in Text S1.

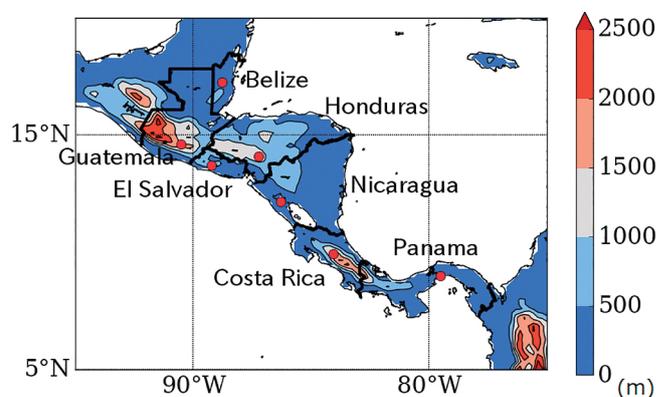


Figure 1. The seven capitals in Central America targeted for climate analogues. Detailed information about the capitals is listed in Table SII

*Climate analogues*

We evaluated the similarity of climates by comparing the monthly time series of SAT and rainfall for each sample year (see Text S2 for details). The locations of the climate analogues, where present-day climates are similar to the future climates of the target capitals on a monthly mean time-scale, can be identified in a probabilistic, but not deterministic, manner by making use of the 600-year modeled data. For this purpose, a new method for identifying climate analogues was used. The root mean square difference ( $\Delta^{1/2}$ ) of monthly-mean SAT and rainfall between the present-day and future climates was used as the metric. We calculated the similarity score, as defined by Equations (S3) and (S4), using this metric. The similarity score accounts for the uncertainties in climate analogues stemming from future climate projections.

*Study area*

We selected seven target capitals in Central America for climate analogues, which are listed in Table SII and geographically depicted in Figure 1. An overview of the present-day climates for each capital is provided in Figure S1. These present-day climates are influenced by the tropical Pacific and Atlantic oceans, the continents of North and South America, ITCZ, ENSO, and others as mentioned in the Introduction section. There are two common features of the climates of the seven capitals: small annual ranges of SAT and distinct wet and dry seasons. The small annual ranges of SAT is due to the two oceans nearby, while distinct wet and dry seasons are due to the migration of the ITCZ.

The period for future climate analogues is the same period used in future climate simulations, i.e. from 2075 to 2099. The projected annual mean changes in SATs was about 2.5°C across the seven capitals which was slightly higher than those of SSTs (Figure S1). The maximum annual change was found in Managua (Nicaragua) about 3.0°C and the maximum monthly changes occurred in May (Figure S1e). Rainfall in the future climate is projected to decrease in the northern six capitals almost all through the year. This decrease can be explained by the enhancement of local Hadley circulation inducing the descending flows in the subtropics due to active convections in the Tropics under global warming conditions. This is why Central America emerges as one of the primary Hot-Spots (Giorgi, 2006). In contrast, rainfall in the future climate is projected to increase only in Panama because convection is projected to be activated.

We also explored climate analogue cities for capitals of Caribbean countries adjacent to Central America to determine similarities and differences in climate analogues between the two areas that share the Caribbean Sea and are located at similar latitudes.

**RESULTS**

*Central America*

Figure 2 shows the best climate analogue cities for the seven target capitals based on a global search. Green arrows indicate similarity scores from 0.1 to 0.3 while gray arrows show scores under 0.1. All cities have green arrows except Panama City, which had the lowest score.

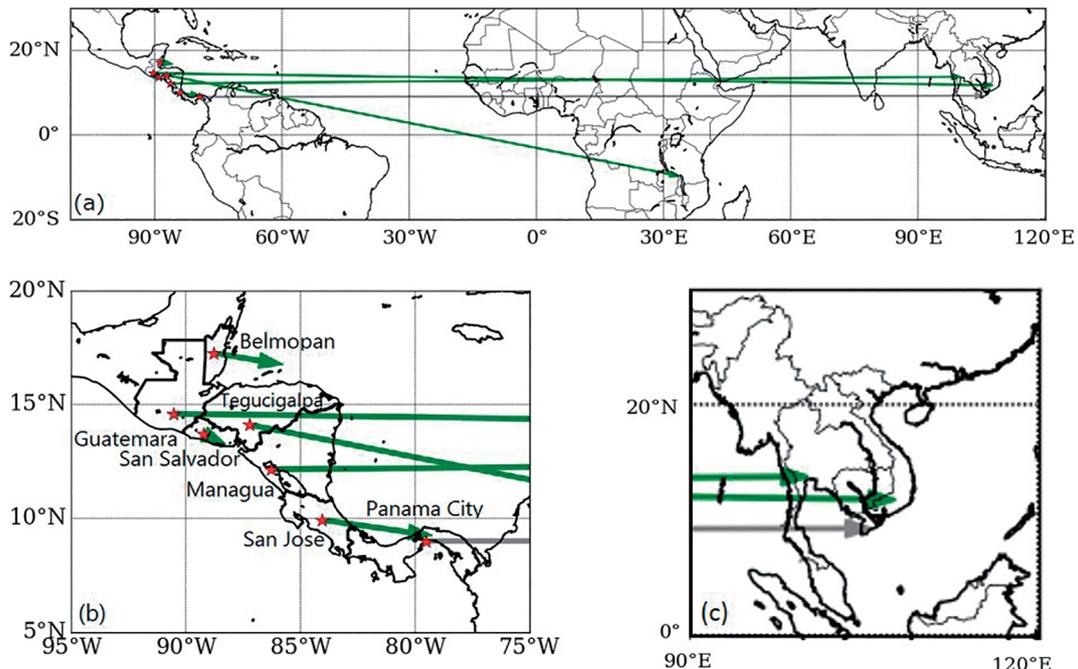


Figure 2. The optimal climate analogue cities for the seven target capitals based on a global search: (a) global distribution and enlarged view for (b) Central America and (c) Indochina Peninsula. The starting point and arrowhead of each vector represent a target capital and its climate analogue city, respectively. The color of each arrow indicates the locations' similarity score: 0.0 to 0.1 are represented by gray, 0.1 to 0.3 by green

We found climate analogue cities with high similarity scores outside Central America for Guatemala (Guatemala) and Managua (Nicaragua) in Vietnam (Figures S2a and S2e), and for Tegucigalpa (Honduras) in Thailand (Figure S2c). Although it had a low similarity score, Panama City also had a climate analogue, Soc Trang, located at the mouth of the Mekong River in Vietnam (Figure 2). Total, SAT, and rainfall similarity scores for Panama City were 0.01, 0.230, and 0.197, respectively (Figure S3), which could be interpreted to mean that no useful analogues exist for climate change assessment (Figure S2g). Williams *et al.* (2007) suggested that people in hotter regions such as Panama would experience a future climate that does not have a present-day parallel. Despite these challenges, a climate analogue city with a low similarity score can be used as a general guide.

The climate analogues for two target capitals, San Salvador (El Salvador) and Belmopan (Belize), fell within Central America, in El Salvador and Roatan, Honduras (Figures 2b, S2d, and S2b). Present-day Colon, on the Caribbean coast of Panama, was identified as the climate analogue of San José, Cost Rica. Future seasonal variations in SAT and rainfall in San José, Cost Rica, were identical to present-day conditions in Colon, Panama, within the uncertainty of the climate projection (Figures S2f and S4).

Figure 3 shows the climate analogues within Central America for each 0.5° grid point. Most of the cities (Guatemala, Tegucigalpa (Honduras), Managua (Nicaragua)) move toward the equator or near hotspots under future climate conditions, though Panama City is an exception. Panama City's low similarity score suggests a novel climate during the late 21st century (Williams *et al.*, 2007; Hibino *et al.*, 2015).

#### Caribbean countries

No climate analogues for the locations in Caribbean countries except for a grid in Puerto Rico were identified with a total score greater than 0.1 (Figure 3). Small island countries are not represented by land area at the scales of observations and the model grid, leading capitals in the Lesser Antilles to have a maximum SAT similarity score of zero. The target capitals in the Caribbean countries have hot climates even in the present day. Thus, future increases

in SAT may lead to a novel hot climate for which there is no present-day analogue (Williams *et al.*, 2007). Grand Cayman Island was selected as a climate analogue city for four grid points or target capitals. This identification is due to the low elevation of Grand Cayman Island, where the highest point is 18 m and, therefore, SAT is higher than at other grid points or target capitals. Elevation is a key factor for identifying a climate analogue city in the capitals of both Caribbean and Central American countries. Some target sites enter a novel climate in the late 21st century, denoted by grid points with no arrow in Figure 3; they all have hot climates at the present time.

## DISCUSSION

Two climate analogue candidates for San Jose were identified by projecting future climates with different convection schemes and SST distributions, namely La Cruz de Rio Grande, Nicaragua, and Honiara on the northwestern coast of Guadalcanal Island, Solomon Islands (Table I). Among all target-analogue combinations, Colon had the highest similarity score, 0.12 seen in Figure 2. For the YS and AS schemes, three quarters of ensemble projections with different SST distributions yielded Honiara in the Solomon Islands as the best climate analogue for San Jose, while the KF scheme identified La Cruz de Rio Grande in Nicaragua. For the other capitals (Panama City, Guatemala, Tegucigalpa (Honduras), Belmopan (Belize), San Salvador (Salvador), and Managua (Nicaragua)), similar patterns were found.

Figure 4a highlights seasonal variations in the multi-convection-scheme ensemble mean SAT and rainfall values projected for San Jose, Costa Rica under four different future SST distributions. Uncertainty in future SAT is about 0.4°C and the difference in SAT between the present-day and future climates is greater than 2°C. On the other hand, projected changes in SST of C3 in Central America is the second highest among the 4 projected changes in SST (see Table SI). The convection-scheme ensemble mean projected changes in climatological annual mean SATs of C3 are highest among the 4 projected changes in SST; C3 shows the highest projected changes in SAT in the 4 projected

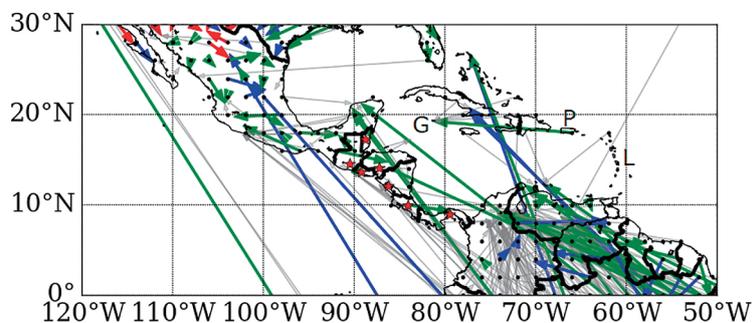


Figure 3. The best climate analogue cities for all 0.5° grid points, based on a search confined to the Americas. The starting point and arrowhead of each vector represent a target capital and its climate analogue city, respectively. The color of each arrow indicates the locations' similarity score: 0.0 to 0.1 are represented by gray, 0.1 to 0.3 by green, 0.3 to 0.5 by blue, and 0.5 to 1.0 by red. Red stars represent the seven capitals and 0.5° grid points. G, L, and P represent Grand Cayman Island, the Lesser Islands, and Puerto Rico respectively

changes in SST for each of YS and S (see Table SIII). Higher dependence of the convection scheme on the SAT than that of the projected changes in SST is often seen in land areas (Endo *et al.*, 2012). Therefore, this uncertainty stems primarily from the uncertainty due to the spatial pattern in the projected changes in SST and secondarily from the uncertainties due to the projected changes in SST and convection schemes. On the other hand, uncertainty in future rainfall is large, especially during the early rainy season from May to September, when the difference exceeds 100 mm month<sup>-1</sup>.

Seasonal variations in the multi-convection-scheme ensemble mean SAT and rainfall values for San Jose, Costa Rica, exhibit smaller uncertainty in future SAT, with approximately the same increase in SAT under each of the three convection schemes (Figure 4b). Future rainfall uncertainty is especially great during the early rainy season (June to October), even in qualitative terms, such as a change in sign. Table I shows that the optimal climate ana-

logue city varies with changes in both the spatial distribution of SST and the convection scheme. This result stresses the importance of analyzing factors of uncertainties in climate analogues under future climate projections. In this regard, the method for identifying climate analogue cities introduced in the present study is useful, because it allows quantification of the uncertainties in climate analogue results along with mapping of the degree of similarity (Figures 5, S1f, and S3).

### CONCLUSION

Equivalent to six hundred years, 24-member × 25-year ensemble simulations were carried out with MRI-AGCM3.2H to project the late 21st century climate using SRES A1B; then, climate analogues for the seven capital cities of Central America were identified by a recently developed nonparametric method. One of the key features of this method is the quantification of uncertainties for future climate analogue cities: internal variability, convection scheme, and spatial patterns of the projected changes in SST. Three climate analogue cities were found in Central America during a global search, while the other four, which had low total similarity scores, were found on other continents: three in Asia and one in Africa. A novel climate, one that has not yet been experienced in any area, is projected for target capitals with very low similarity scores.

Most of the future analogues are at lower latitudes than their target cities, or near hotspots, with Panama City being a notable exception. Seasonal variations in SAT and rainfall for Panama City in the future climate are similar (identical to within the uncertainty of the climate projection) to present-day values at Soc Trang, located at the mouth of the Mekong River, Vietnam. No analogue cities for the capitals of Caribbean countries except for the grid in Puerto Rico were identified with similarity scores greater than 0.1.

The method introduced in this study allows us to explore

Table I. Optimal climate analogue cities for San Jose selected using each ensemble. C1, C2, and C3 represent cluster means of future changes in SST projected by CMIP3 model ensembles using cluster analysis, while M represents a multi-model ensemble mean of future climate changes in SST projected by CMIP3 model ensembles used in cluster analysis. YS, AS, and KF represent the Yoshimura, Arakawa-Schubert, and Kain-Fritsch schemes, respectively. L and H represent La Cruz de Rio Grande, Nicaragua, and Honiara, Solomon Islands, respectively

Convection Scheme	Spatial pattern of future changes in SST			
	M	C1	C2	C3
YS	H	H	L	H
AS	H	H	H	L
KF	L	L	L	H

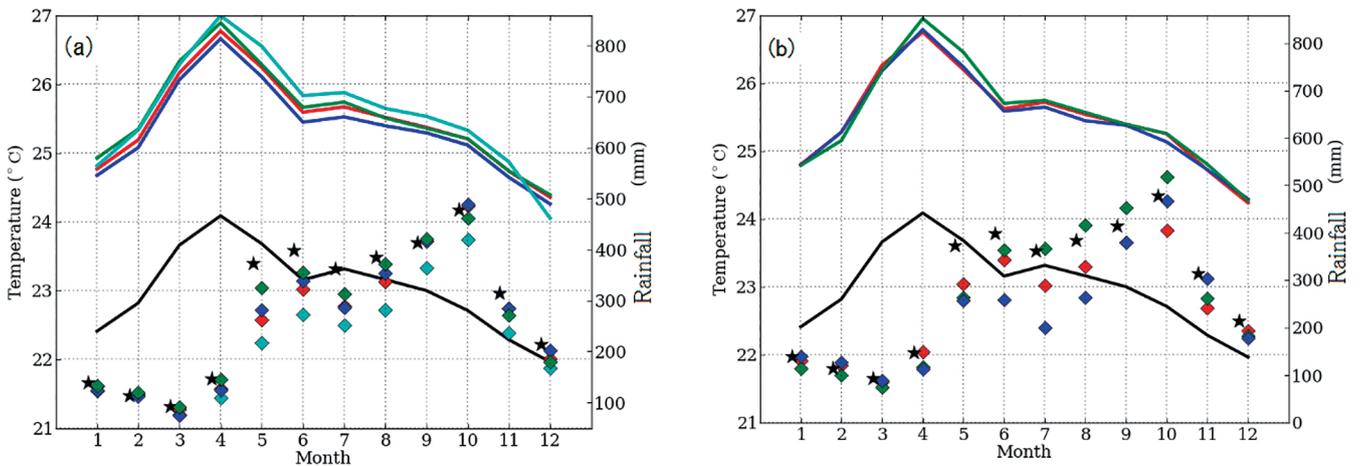


Figure 4. Seasonal cycles of surface air temperature (SAT; lines) and rainfall (symbols) in San Jose, Costa Rica: (a) multi-convection-scheme ensemble for each of the four different future sea surface temperature (SST) scenarios: red, blue, green, cyan, and black represent the M, C1, C2, and C3 projections and present-day observations, respectively; (b) multi-SST ensemble for three convection schemes: red, blue, green, and black represent YS, AS, KF, and present-day observations. See Table I and the methods section for details about the experimental design

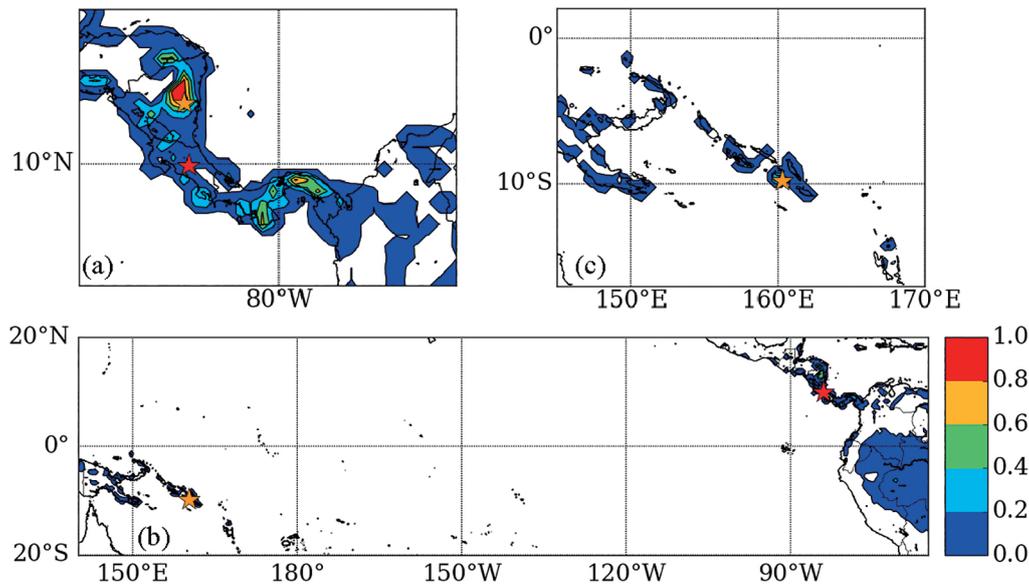


Figure 5. Geographical distribution of normalized total similarity scores of climate analogues for San Jose, Costa Rica: (a) cluster C2 mean of future changes in SST under the Kain-Fritsch scheme (C2, KS in Table II), (b) cluster C1 mean of future changes in SST using the Yoshimura scheme, and (c) enlarged view showing the climate analogue city in (b). Red and orange stars represent target and climate analogue cities respectively. The best scores for (a) and (b) were 0.24 and 0.19 respectively. The total similarity score displayed was normalized to the best total score for each scheme

the effects of regional future climate projections while considering the uncertainty of those projections in a quantitative manner. Additionally, the method is applicable to several impact assessment factors such as the likelihood of health risks, zones susceptible to inundation and the location of areas appropriate for farming. Quantification of uncertainties gives policy makers a scientific option for making knowledge-based decisions. In the present study, only one emission scenario was used (SRES A1B) and, therefore, the reliability of various climate change scenarios was not compared. Moreover, we did not attempt to account for all possible models and factors of uncertainties in this study (Ishizaki *et al.*, 2012), and suggest that they should be addressed in future works.

This study focuses on the region of Central America and Caribbean countries; therefore it lacks global-scale generality. However, it provides distinct region-specific information about future climate changes and pave the way to solving region-specific problems emerging as a primary scientific task.

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#### SUPPLEMENTS

- Text S1. Simulation method
- Text S2. Climate analogue method
- Table SI. Local features of cluster mean projected changes in climatological annual mean SST around Central America
- Table SII. The seven Central American capitals targeted for climate analogues in this study
- Table SIII. Projected changes in climatological annual mean surface air temperature at San Jose for each combination
- Figure S1. Present-day seasonal cycle of surface air temperature and rainfall in the seven capitals and in identified climate analogue cities
- Figure S2. Seasonal variations in SAT and rainfall at the target capital of Panama City, Panama, and an identified climate analogue city
- Figure S3. Map of normalized similarity scores for climate analogues of Panama City, Panama
- Figure S4. Map of total similarity scores for climate analogues of San Jose, Costa Rica

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