3 Impacts of climate change on ecosystem hydrological services of Central America

Water availability

Pablo Imbach, Bruno Locatelli, Juan Carlos Zamora, Emily Fung, Lluis Calderer, Luis Molina and Philippe Ciais

Introduction

Climate change and land use change are predicted to be the two main drivers of global biodiversity alterations (Sala *et al.* 2000). The effects of climate change on biodiversity are manifested at different scales, from genes (i.e. generating mutations and simplifying gene pools) to species (i.e. extinctions and range modifications) and ecosystems (i.e. community composition and distribution changes). These effects influence ecosystem functions and processes, for instance changes in the abundance and composition of plant species may influence water cycle, nutrient and carbon dynamics, trophic interactions and disturbance regimes (Chapin III *et al.* 1997; Diaz *et al.* 2004).

Ecosystem functions are linked to the provision of ecosystem goods and services when human values are considered (de Groot *et al.* 2002; MEA 2005). Many authors have highlighted the value of these ecosystem services for sustainable development, globally (Costanza *et al.* 1997) or locally (Lutz *et al.* 2000; Woodward and Wui 2001; Pattanayak 2004). Terrestrial ecosystems provide an array of watershed services, for instance the regulation of hydrological flows, benefiting agriculture, drinking water users, energy production, or transportation (Costanza *et al.* 1997; MEA 2005).

Watershed services are of outmost importance in many developing countries where water is a crucial development issue, such as Central America (Locatelli *et al.* 2010). According to (UNDP 2006), around 20 percent of global population lives without access to potable water. Nicaragua being the second poorest country in Latin America provides a good example, where only 49 percent of the rural population has access to this resource and high water-related mortality is observed (CONAPAS 2006). Potential conflicts in the future could be expected due to freshwater use and access, given pressures from population growth and water use demand (i.e. for irrigation and industry; UNFPA 2006).

The degradation of ecosystems and the associated loss in the provision of ecosystem services are major threats for human well-being (MEA 2005). Knowing about the impacts of climate change on the ecosystems hydrological functions is necessary to inform policy makers about the risks induced by climate change and support their decisions about adaptation to future changes (Scholze *et al.* 2006).

In this chapter we aim at assessing changes in ecosystem hydrological services under future climate scenarios and impacts on per-capita water availability for main watersheds of Mesoamerica. We used several climate change scenarios and a biogeography model to project a range of potential changes in the provision of ecosystem services while accounting for uncertainty from climate models and future emission scenarios. These results could be used as the basis to assess the vulnerability to climate change, at the national and regional scale, of important economic sectors relying on hydrological services (i.e. agriculture, power generation, drinking water).

Previous studies in Central America

Climate change scenarios

Changes in atmospheric concentration of greenhouse gases since the beginning of the industrial revolution have modified the natural dynamics of the global climate. The range of potential future storylines suggests that the trend will continue and in most scenarios further increase. The development of future climate scenarios relies, generally, on three components:

- the historical and future emissions of greenhouse gases and aerosols into the atmosphere (emission storylines);
- (ii) the simulation of climate models accounting for global warming as a result of changes in radiative forcing (the energy balance between the radiant energy received by the Earth from the Sun and radiated back to space) associated to concentration trends of these greenhouse gases and aerosols (radiative effects) and to land use changes (biophysical effects); and
- the regional climate change resulting from this forcing.

Emission storylines and the future increase in greenhouse gases and changes in aerosols depend on the evolution of several socio-economic parameters (i.e. population, land use or technology) as well as climate policy efforts to meet radiative forcing targets. The IPCC (Intergovernmental Panel on Climate Change) has developed a range of storylines or “emission scenarios” up to the year 2100 (IPCC 2000), which were used to force climate models (referred as SRES for Special Report on Emission Scenarios). These storylines framed emissions scenarios used to simulate future climate in IPCC Fourth Assessment Report (IPCC 2007) and set the basis for the representative concentration pathways (RCP) (and resulting radiative forcing) used to simulate climate scenarios with the latest generation of climate models for its Fifth Assessment Report (IPCC 2013). The current generation of global climate models (GCMs; or general circulation models) integrate atmosphere, ocean and terrestrial processes and simulate climate trends at large scales. The recent 5th IPCC Assessment is based on GCM simulations from the fifth phase of the Coupled Model Intercomparison Project using RCP of greenhouse gases (Rogelj *et al.* 2012) that include effects of climate policy scenarios for the twenty-first century on emissions while the previous assessment used emission scenarios that did not account for future effects of mitigation and adaptation policies. Differences in climate scenarios between the 4th and 5th IPCC reports indicate, for example, a median global temperature increase of 2.4°C for 2090–2099 under RCP 4.5 (used in this study) and SRES B1 scenarios (3.4°C and 3.9°C for A1B and A2, respectively). RCP 4.5 median temperatures also rise faster until 2050 compared to SRES B1 (Rogelj *et al.* 2012). Given uncertainties in future emissions of greenhouse gases as well as in climate modeling efforts, it is important to assess future climate uncertainties when evaluating potential impacts of climate change. Furthermore, assessments of climate trends, for example based on weather stations or satellite data, allows for comparing these in future simulations with historical observations.

Weather station data and satellite observation allow comparing recent observed trends with the projected changes in future climate. Although, human caused changes in climate are difficult to detect and attribute from natural climate variability, trends in key climate variables have been already observed in Central America. Aguilar *et al.* (2005), for example, found an increase in temperature and precipitation intensity based on weather station data in the last half of the 20th century across the region. Malhi and Wright (2004) found a similar trend in temperature and an increase in annual mean precipitation in some parts of northern Central America. The authors also highlight the difficulty in discerning trends in precipitation across tropical areas due to high inter-annual variability.

A consistent drying signal in Central America's future climate is found across the existing range of climate scenarios, showing a general decrease in precipitation and an increase in temperature (Neelin *et al.* 2006). At the seasonal scale this trend could further reduce precipitation and length of the mid-summer drought (a period of reduced precipitation within the rainy season; Magaña *et al.* 1999), particularly in the central part of Central America (Rauscher *et al.* 2008). The increased temperature signal under future scenarios is consistent across global climate models while the change in precipitation shows higher disagreement with positive and negative anomalies depending on the model (Imbach *et al.* 2012). The expected magnitude of change in climate makes the region a climate change hotspot among tropical areas (Giorgi 2006) where mean temperature will move outside its historical variability envelope relatively sooner than other land areas (Hawkins and Sutton 2012; Mora *et al.* 2013).

The spatial configuration of the region, a topographically complex narrow strip of land, requires downscaling of global climate models into high resolution scenarios. But only a small set of downscaled scenarios are available so far. Karmalkar *et al.* (2011) developed downscaled scenarios (0.22° or ~25 km) using the PRECIS (Providing Regional Climates for Impacts Studies) model derived from HadRM3, the Hadley Centre Regional Climate Model (Jones *et al.* 2004). Nakaegawa *et al.* (2013a) used MRI (Meteorological Research Institute model of Japan) to develop scenarios at 60 and 180 km, with an ensemble of realizations, as well as one simulation at 20 km. Both authors found improvements in simulating high resolution precipitation (compared to global simulations) with a wet/dry bias in the dry/wet seasons with PRECIS (MRI results focused on upper atmosphere dynamics that are out of our scope). Under high emission scenarios (A2; 2070–2100) Karmalkar *et al.* (2011) found higher warming during the wet season (relative to the dry season). Precipitation showed larger reductions during the wet season, and during the dry season over areas influenced by orographic precipitation (Pacific watershed). Nakaegawa *et al.* (2013b) found an increase in maximum 5-day precipitation and number of consecutive dry days with consistent changes over the Yucatán Peninsula and Guatemala (for consecutive dry days only).

Hydrological modeling

The Mapped Atmosphere Plant Soil System (MAPSS) model (a brief description is provided in the methods section) has been previously calibrated and water balance and leaf area index (LAI) outputs validated with historical observations for Mesoamerica (Imbach *et al.* 2010). The runoff output was validated against long-term average runoff from a set of catchments (n = 138) that covered the regional gradient of precipitation, elevation, catchment size and forest land cover. This model satisfactorily predicted annual runoff (with an under-estimation of 12%) and the prediction of seasonal stream discharge was also well reproduced in 78 percent of the catchments. The absolute runoff at the monthly time scale had a lower performance, with a satisfactory prediction only over 48 percent of the catchments, probably due to model lack of capacity to simulate aquifers recharge and discharge processes across seasons. The LAI output was validated against two long-term average LAI maps from remote sensing sources. The model under-represents LAI values in the northern part of the region and over-represents LAI in the southern part (Costa Rica and Panama) that could lead to potential biases when modeling water balance. These differences are probably related to, besides model bias, high-cloud coverage that reduces the LAI algorithm performance from remote sensing sources. The authors recommended using MAPSS output values at the annual scale for further applications in Mesoamerica. Based on the same model setup, Imbach *et al.* (2012) analyzed uncertainties of discharge and vegetation distribution, under a range of future climate scenarios (average climate for 2070–2099) providing the starting point of the analysis presented here.

Hidalgo *et al.* (2013) used VIC (variable infiltration capacity), a macro-scale hydrological model, to assess impacts of climate change on Central American hydrology with special focus on drought prevalence. The model simulates hydrological variables from the surface (i.e. surface runoff, soil moisture, base flow) and energy balance near the surface (i.e. to derive evapotranspiration) using daily climate data. The model has a parameterization for soils, vegetation and snow distribution (not relevant for our study area), that was calibrated using and automatic procedure. Contrary to MAPSS the VIC model has a prescribed mosaic of vegetation, including disturbed land cover types (i.e. agriculture) but can assess transient changes (MAPSS estimates long-term average conditions).

Both VIC and MAPSS produced similar results, with water availability being *likely* reduced across most of the region (>61% of Mesoamerica; Imbach *et al.* 2012) and drought frequency increases (Hidalgo *et al.* 2013). Imbach *et al.* (2012) also assessed associated changes in ecosystems and found *likely* reductions in leaf area index and increased evapotranspiration (the later in southern Mesoamerica) coincident with runoff reductions.

Water availability indicators at coarse scales

Several indicators have been developed to assess water availability at coarse scales. The water scarcity index (WSI) is simply defined as the fraction of total annual runoff available per capita (i.e. m^3 per capita) and helps distinguish climatic from human causes (i.e. poor infrastructure). The indicator was applied to multiple countries and used to categorize yearly water availability as: *no stress*, *stress*, *scarcity* and *absolute scarcity* (>1700, 1700–1000, 1000–500 and <500 m^3 per capita, respectively; Falkenmark 1989). It is commonly used at country level assessments and tends to under estimate water scarcity for smaller populations. WSI cannot capture differences of water requirements due to different lifestyles (linked to the intensity of use of the resource) or seasonal limitations on the resource (Brown and Matlock 2011).

Other indexes were developed to account for different human requirements (drinking, sanitation, bathing and food preparation needs) indicating a minimum water requirement of 50 liters per person per day (Gleick 1996). The *social resource water stress/scarcity index* evaluates the capacity of a society to adapt to changes in water availability, using indicators such as the Human Development Index as a weighing factor for adaptive capacity (Ohlsson 2000). The *ratio of annual water withdrawals to water availability* (Water Resources Vulnerability Index) has also been used in countries facing severe water scarcity (withdrawals exceed 40% of the annual supply; Brown and Matlock 2011). Other indexes account for different uses of available water—for example, rain-fed agriculture (the *Water Poverty Index*; Salameh 2000) versus domestic and industrial uses of urban and rural population (Vörösmarty *et al.* 2005), which allows for partitioning water between differentiated users and supply sources. Arnell (2004) presented a country level assessment, at global scale, combining WSI at the catchment scale to quantify population exposed to water availability changes (improving or deteriorating) under future climate scenarios. They only produced aggregated data over the whole Mesoamerican region (comprising Central America and southern Mexico) without distinguishing between countries, whereas we seek here to produce regionally detailed estimates.

Methods

Study area

Central America comprises seven countries (from south to north, Panama, Costa Rica, Nicaragua, Honduras, El Salvador, Guatemala and Belize) that bridge South and North America. It is a topographically complex strip of land where the Central American cordillera (reaching over 4000 masl) separates the Caribbean Sea and the Pacific Ocean by just over 60 km in some places. The region has a tropical climate with a dry season between December and May, when the rainy season begins until December with two peak months in June and September (Magaña *et al.* 1999). The region has a high inter-annual variability in precipitation leading to alternating periods of extreme rainfall regimes (Hastenrath and Polzin 2013).

Central America has approximately half (51% in 2008) of its population (42.5 million in 2010) living in poverty and 26 percent in extreme poverty with Costa Rica and Honduras showing the lowest (19%) and highest (69%) values respectively (CEPAL 2011). Water resources distribution is highly variable across the region and determined by climate and weather variability, human settlements, industry, and agricultural development (CEPAL 2011). Water demand is higher in the Pacific relative to the Caribbean watershed although the later has higher water availability (CEPAL 2011). The agricultural sector has the largest demand in Honduras, Guatemala, Costa Rica and El Salvador (between 54% and 83% of total water extracted) while in Panama and Belize extraction is dominated by the industrial and municipal sectors (66% and 89% respectively; CEPAL 2011).

The MAPSS hydrology and vegetation model

Hydrological ecosystem services, specifically water balance (i.e. runoff quantity) were evaluated for different climate change scenarios (under RCP 4.5) using a model that estimates the equilibrium between water balance and potential vegetation (Neilson 1995). The MAPSS model used in this study belongs to the group of soil–vegetation–atmosphere transfer (SVAT) models that are commonly used to simulate ecosystem functioning (i.e. Krinner *et al.* 2005) under changing climate conditions. A mechanism-based approach (such as the one used in MAPSS) is useful to assess changes in ecosystems types (Yates *et al.* 2000) and functions under changing environmental (e.g. climate change) conditions (Sitch *et al.* 2008). On the other hand, statistical models (i.e. Holdridge 1947) allow modeling vegetation based on the observed match between different climates and vegetation types but cannot account for the effects of new conditions (e.g. new climates or elevated CO_2) that have no current analog, which precisely will prevail over Central America (Williams *et al.* 2005). Approaches similar to the one used here have been used to assess changes vegetation type (Neilson 1995), ecosystems carbon stocks (Kindermann *et al.* 1996; Dargaville *et al.* 2002) and water cycles (Neilson 1995).

MAPSS simulates the vegetation distribution and structure (LAI) and precipitation partitioning (into runoff, soil moisture change and evapotranspiration) under a given climate (Neilson 1995). Potential vegetation cover in equilibrium with climate is modeled with a maximum LAI that can be supported based on soil texture, depth and climate input data (precipitation, temperature, wind speed and vapor pressure). Trees, shrubs and grasses compete for humidity and radiation and equilibrium conditions evaluated (for example, as the tree canopy closes grasses disappear). It has been successfully used at high resolution for continental areas (a full model description is given by Neilson 1995).

MAPSS works at monthly time steps and calculates a leaf area index for each life form (trees, shrubs and grasses) and stomatal conductance to upscale transpiration of the ecosystem canopy and soil water dynamics (Neilson 1995). Precipitation is intercepted depending on total monthly precipitation and vegetation coverage (LAI). Through fall precipitation (reaching the soil layer) is divided into surface runoff or soil infiltration (depending if the soil is saturated or unsaturated). There are three soil layers where these processes occur, with grasses being able to transpire water from the top layer while trees and shrubs also from the intermediate layer. The third, and deep layer is used for base-flow that later becomes runoff. Potential evapotranspiration (PET) increases with LAI. While stomatal conductance decreases as soils get drier and as the atmospheric demand for water increases (PET). PET is based on an aerodynamic turbulent transfer model calibrated by Neilson (1995). The effect of elevated CO_2 can be evaluated by modifying water use efficiency of the vegetation (see Imbach *et al.* 2012 for an example in Mesoamerica).

The model is run in loops until the annual water balance of trees and shrubs and the monthly water balance for grasses reach equilibrium conditions, defined by the fractional coverage of each type of vegetation that maximizes transpiration on each grid point depleting most of the available water.

The advantage of MAPSS is that it accounts for feedbacks between changes in vegetation type and LAI on the soil water balance, which can produce non-linear equilibrium states, that could explain runoff changes under changing climate conditions in Mesoamerica (Imbach *et al.* 2012). The limitations of MAPSS are twofold. First, MAPSS does not account for aquifers water storage (∅s), assuming that this term is negligible at the annual scale. Second, MAPSS does not calculate explicitly the horizontal water flow within a catchment, as influenced by soil, climate and topography (i.e. Gómez-Delgado *et al.* 2011), but the limited data availability for our regional-scale assessment would make the use of such an explicit hydrology model impractical. Further, neglecting routing processes remains a good approximation in Central America, given the relatively small size of catchments in this region, and the monthly time steps used.

We also acknowledge that one limitation of our approach that we consider potential vegetation only, over a study area which has significant areas with pastures and agriculture (DeClerck *et al.* 2010). At the annual scale over this region, however, Imbach *et al.* (2010) found no model bias related to the cultivated fraction of each catchment, suggesting that current land use has no dramatic effect on simulated water availability for long term averages at the regional scale.

Climate change scenarios

We constructed regional climate change scenarios, using the reference climate data from the WorldClim 1.4 database (www.worldclim.org; Hijmans *et al.* 2005) at 30 seconds spatial resolution (~1 km^2), that provides monthly average precipitation, maximum and minimum temperature for the 1950-2000 period. Future climate scenarios are from CMIP5 for RCP 4.5 that accounts for an intermediate global radiative forcing (or emission scenarios). We used future scenarios from 19 GCMs from CMIP5.[1] Downscaled climatologies for each GCM was obtained as monthly 20-year averages for 2050 (2041–2060) and 2070 (2061–2080). The downscaling method is a simple approach known as the "delta method" where coarse resolution climate anomalies (GCM modeled difference between future and reference climate conditions) are added to the high resolution climatology (WorldClim 1.4 in our case).

Runoff and water availability

We estimated historical runoff based on the results from the above-mentioned MAPSS model calibrated by Imbach *et al.* (2010), as explained above, as well as future changes in water balance under average climate conditions in 2050 (2041–2060 average) and 2070 (2061–2080 average) under the studied scenario (RCP 4.5). Previous work from Imbach *et al.* (2012), using the same model setup, chose longer term climate scenarios (2070–2099) from a previous GCM dataset (CMIP3) and three scenarios (A2, A1B and B1).

We selected a runoff change threshold of 20 percent in order to assess the likelihood of impacts across the range of climate scenarios (Imbach *et al.* 2012). The likelihood of change was estimated as the fraction of the 19 GCM+MAPSS model runs showing runoff change above 20 percent (Mastrandrea *et al.* 2010). A change was considered as *likely* when runoff increased or decreased of at least 20 percent in more than 66 percent of the model runs. This procedure allowed showing both the magnitude of changes in runoff and the uncertainty from climate change scenarios.

We also calculated water availability at the catchment scale (300 catchments in total) using the WSI indicator (see the introduction to this chapter) with the catchment database from (Lehner *et al.* 2008; available from hydrosheds.cr.usgs.gov). This index was selected since the data for its estimation was available at the catchment scale covering the region of study. The WSI was calculated by aggregating total annual runoff for each catchment and its total population count from GRUMPv1 (Global Rural Urban Mapping Project; CIESIN *et al.* 2011). Mean runoff under future climate conditions was estimated as the median value from model runs using all the GCMs. We also excluded catchments smaller than 100 km^2 because these small watersheds often import water from neighboring larger catchments.

Results

Climate scenarios

Mean temperature anomalies for RCP 4.5 (average of the 19 GCMs) range between 2.2–1.4°C and 2.6–1.8°C for 2050 and 2070 respectively (1.8°C and

2.2°C mean values for the region shown in Figure 3.1a), with larger anomalies in northwest part of the region relative to the southern part of the study area.

Mean precipitation anomalies for 2050 for RCP 4.5 (average of 19 GCMs) show increased or decreased precipitation depending on the location considered in the Mesoamerican region. Most of the northern region (from Guatemala to Nicaragua) presents an average decrease of precipitation up to 10% yr^{-1} while the southern countries (Costa Rica and Panama) show increased precipitation in similar magnitudes (Figure 3.1b). A precipitation increase occurs in the CMIP5 models over all four trimesters of the year in the southern part. In the northern part, mean annual precipitation decrease is explained by large decreases between June - August during the wet season, whereas small rainfall increases are observed during other months. A comparison of temperature and precipitation anomalies with previous studies based on AR4 scenarios and CMIP3 models (i.e. Imbach *et al.* 2012) is out of the scope of this study, given different radiative forcing trajectories between SRES (AR4) and RCP (AR5) scenarios, different number of GCM realizations and, different model versions. Mean annual anomalies of precipitation over the northern part of the region show relatively higher inter-model agreement relative to southern countries. We found *likely* negative precipitation anomalies for most of Guatemala, Honduras, Nicaragua (northern part) and El Salvador, and *likely* positive precipitation anomalies over Panama. Nicaragua and Costa Rica show negative and positive mean anomalies respectively, although with higher model disagreement on the anomaly sign (Figure 3.1b).

Population density and water balance

The least populated areas are usually located towards the Caribbean coast, including northern Guatemala, Belize, eastern Honduras and Nicaragua and eastern Panama. Belize and El Salvador are the least and most densely populated countries respectively (Figure 3.2). Areas with high population density are on the Pacific side, western Honduras and central areas of Costa Rica. Costa Rica and Panama have a relatively higher mean annual runoff (>1000 mm) across most of their territory (see Imbach *et al.* 2010) including areas with high population density. Contrastingly, Guatemala and Honduras have a large fraction of their most populated areas with lower water availability (mean annual runoff <500 mm).

We found that runoff is *likely* to decrease in 81 percent of Central American countries in 2050 (89% in 2070), following a general drying trend over the region (Figure 3.3). Runoff is *likely* to decrease by at least 20 percent in over 50 percent of the region in 2050 (71% in 2070) and *likely* to increase over only 2 percent of the area. Country percentages show that El Salvador has the largest area exposed to *likely* runoff reductions (of at least 20%) followed by Belize, Costa Rica, Guatemala, Nicaragua, and Honduras (Table 3.1). Honduras has 33 percent of its area exposed to *likely* runoff reductions. As expected, the areas of *likely* runoff reductions (>20%) are larger in 2070 than in 2050, particularly for Honduras and Nicaragua (Table 3.1).

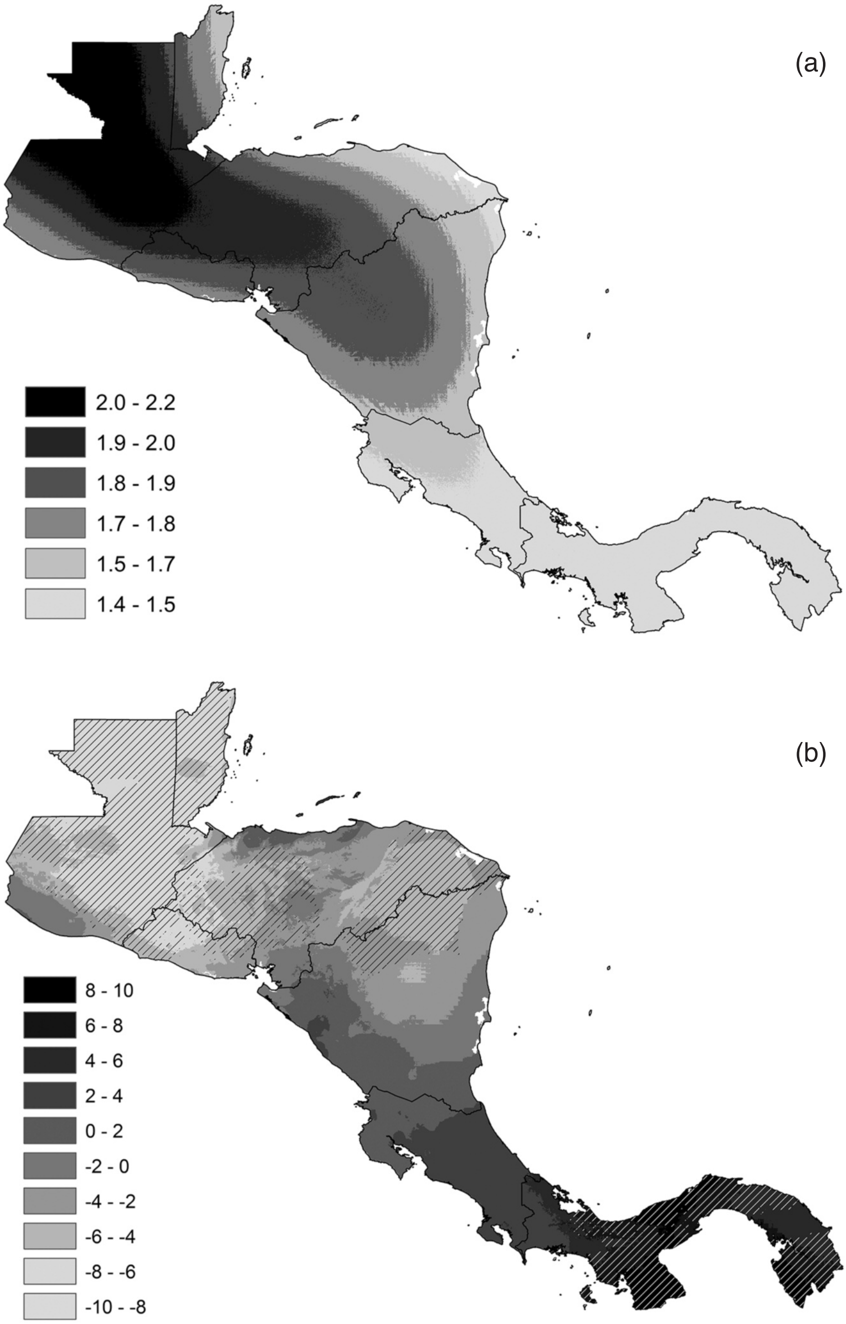

Figure 3.1 (a) Mean temperature and (b) precipitation anomaly (19 GCMs). Dashed areas show *likely* (>66%) model agreement on the anomaly sign.

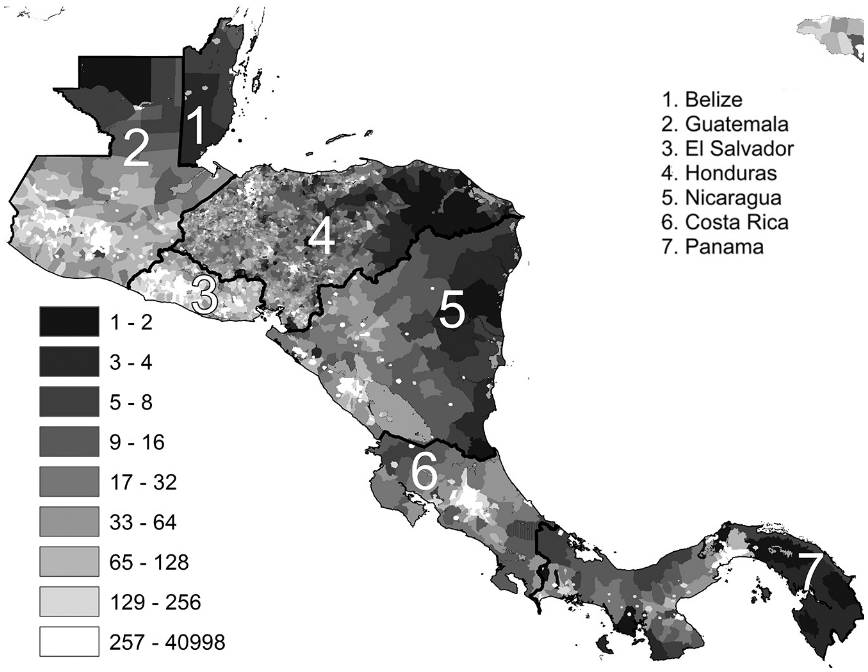

Figure 3.2 Population density (population count per 1 km^2 pixel).

Water availability under reference climate conditions (1950–2000) show *scarce* conditions over Honduras in Aguán, Cangrejal, Choluteca and Chamelecón (*absolute scarcity*) river basins. Guatemala (María Linda) and El Salvador (between Jiboa and Chilama river basins) show *stressed* basins. Nicaragua (between Tamarindo and Brito river basins) and Panamá (between San Juan Díaz and Pacora river basins) have both *scarce* and *stressed* basins near capital cities. Guatemala also shows limited resources within the Mopán and Hondo river basins (Figure 3.4a). Basins with limited resources hold 5.5 million people (around 15% of the total population, including inhabitants in Mexico who share basins with Guatemala). Around 1 million people live in *absolute scarcity* conditions in the Chamelecón (Honduras) and Mopán-Hondo (Guatemala) river basins, although the later holds a lake that could improve resource availability (not accounted for in this study).

Current *scarce* resource availability remains unchanged under mid-twenty-first-century climate in Choluteca, parts of the Tamarindo–Brito and Juan Díaz–Pacora basins (in Nicaragua and Panama respectively). The Chamalecón basin persists under *absolute scarcity* and the Aguán and Cangrejal basins join this category in the future (Figure 3.4b). The Ulúa, Lempa, Banderas, Grande de Sonsonate, Paz and Atitlan river basins move from the *no stress* to the *stressed* category encompassing

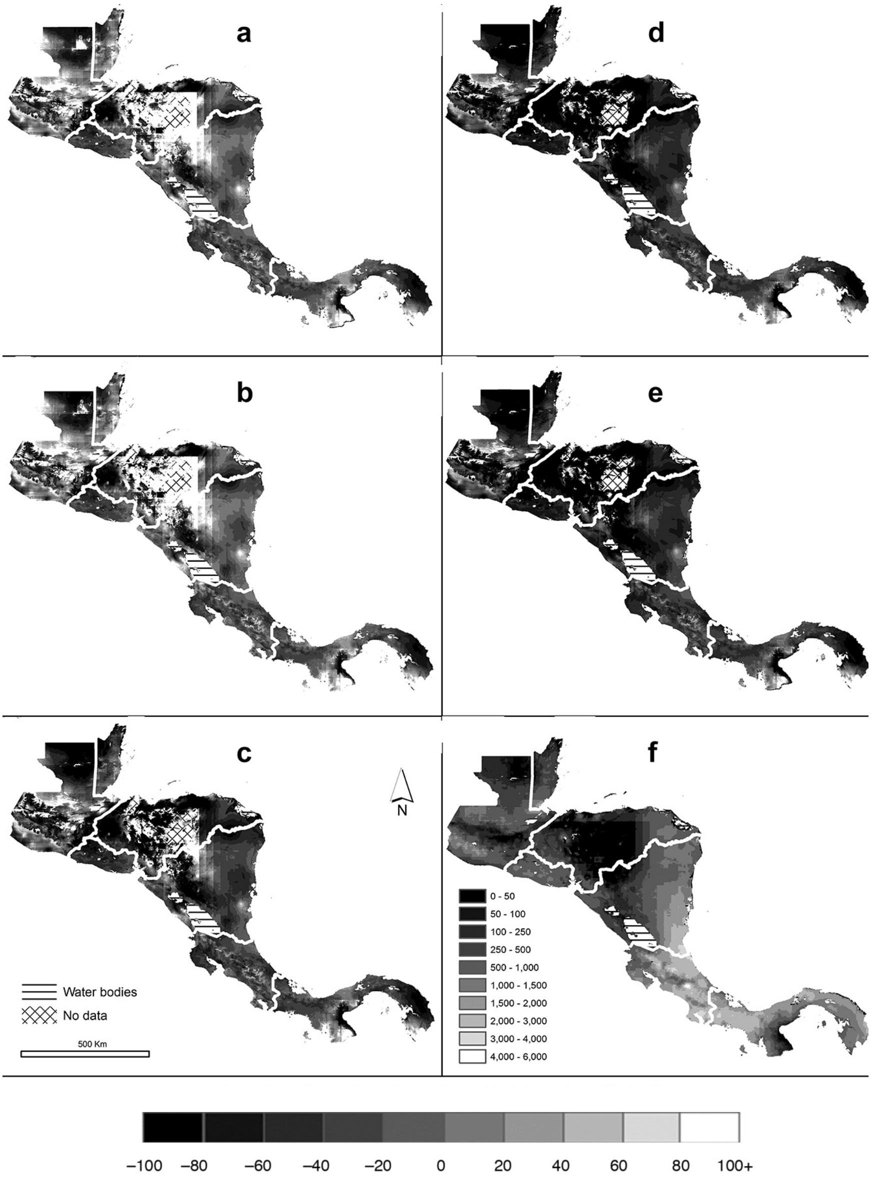

Figure 3.3 Change in annual runoff (%) for the (a) maximum, (e) minimum, and (d) 25th, (c) 50th, and (b) 75th percentile values of the projected climate conditions in 2050 for the downscaled CMIP5 ensemble of 19 GCM models (all for the RCP 4.5 scenario), compared with (f) the reference period (1950–2000) (mm).

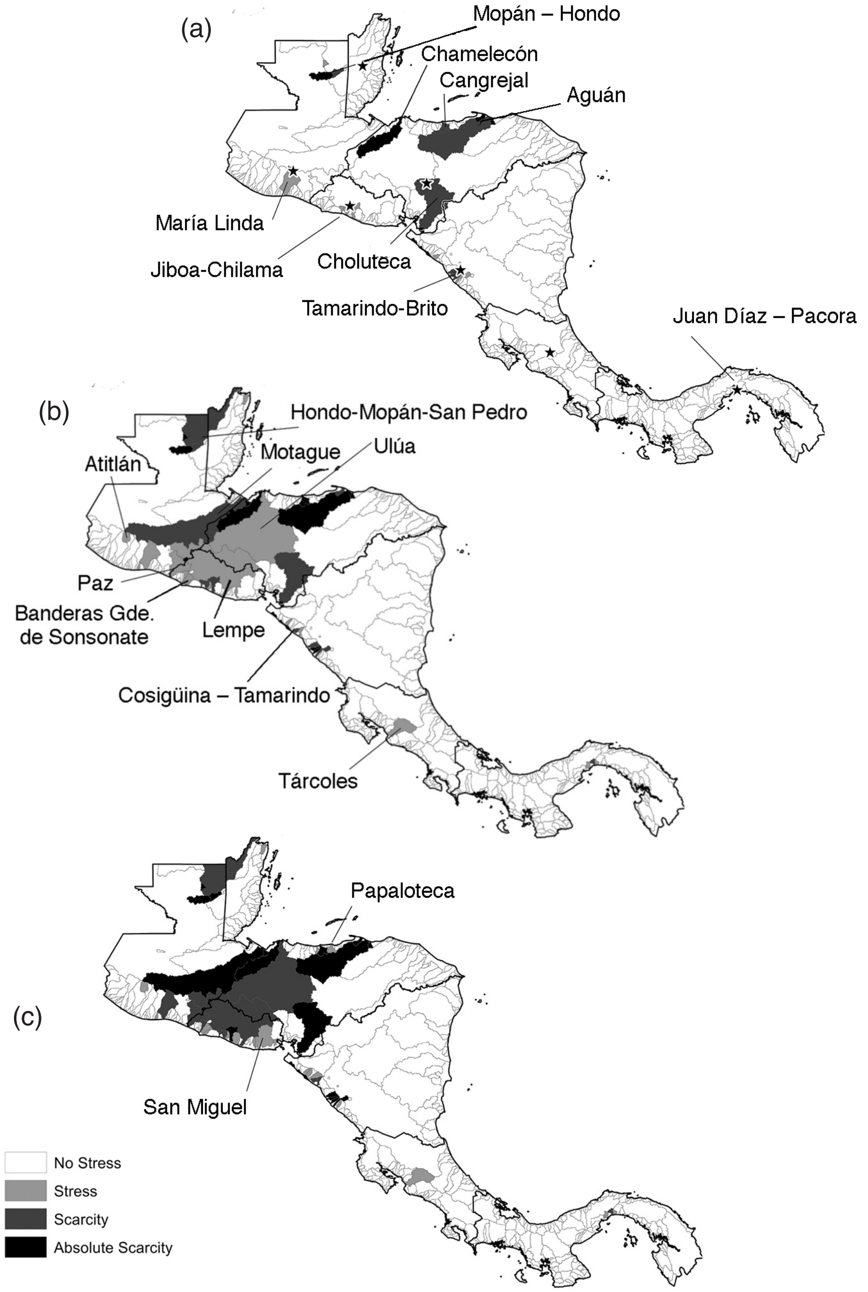

Figure 3.4 Water availability under (a) current and projected (b) 2050 and (c) 2070 climate conditions assuming the same population density as in year 2000. Water availability is measured in m^3/per capita where *absolute scarcity*, *scarcity*, *stress* and *no stress* thresholds are <500, 500–1000, 1000–1700 and >1700, respectively. Stars denote the location of capital cities.

a large area with limited resource availability between Honduras, El Salvador and Guatemala. The Motagua basin also modeled to be under *scarce* condition by 2050. The Tárcoles basin in Costa Rica moves to the *stressed* category (from *no stress*) while basins with capital cities see their water availability worsened (Figure 3.4b).

For the 2070 period, the same pattern prevails but gets amplified (poor-get-poorer behavior) with a further decrease in water availability, except for the San Miguel and Papaloteca river basins that become *stressed* only in 2070 (Figure 3.4c). Under future climate conditions (2050 and 2070), we found an increase in the number of people living with limited water resources, with all areas falling into the stressed categories. A fraction of 36 percent of the population currently living today without *stress* will fall into the limited resource availability category (10.9 million), and in fact mostly into the *stressed* category (with an increase of 6.9 million people in this category). Under 2070 climate conditions, the number of people with limited resources remains almost constant compared to 2050 (17.2 million) but the number living in *absolute scarcity* conditions is projected to increase by 4.8 million (from 2050 to 2070; Table 3.2).

Discussion

Our water balance modeling framework estimates changes of equilibrium conditions with historical and future climates, accounting for feedbacks between hydrological and vegetation dynamics that can result into complex and non-linear responses. But population density and land use are assumed to be constant in the future. Other hydrological modeling approaches evaluate effects of climate variability (i.e. seasonal and inter-annual) on water balance (Hidalgo *et al.* 2013) but usually use prescribed vegetation parameters and thus cannot account for the feedbacks of vegetation changes on runoff.

Table 3.1 Percentage area of Central American countries with *likely* runoff change (at least 20% decrease or increase) under 2050 and 2070 climate conditions (RCP 4.5) simulated by 19 GCMs of the CMIP5 ensemble.

Country	*2050*		*2070*	
	Increase (>20%)	*Decrease (>20%)*	*Increase (>20%)*	*Decrease (>20%)*
Panama	0	43	0	55
Costa Rica	0	58	0	70
Nicaragua	0	50	0	82
Honduras	6	33	4	55
El Salvador	0	87	0	93
Guatemala	1	54	0	72
Belize	0	65	0	81

Table 3.2 Water availability for human use in Central America under current and future (2050 and 2070) climate conditions (people in millions/percentage). Water availability is defined in m^3/per capita where *absolute scarcity*, *scarcity*, *stress* and *no stress* thresholds are <500, 500–1000, 1000–1700 and >1700 m^3/per capita, respectively.

Threshold	*Current*	*2050*	*2070*
No stress	30.6 / 85	19.7 / 55	18.8 / 52
Stress	2.3 / 6	9.2 / 26	3.0 / 8
Scarcity	2.2 / 6	5.4 / 15	7.8 / 21
Absolute scarcity	1.0 / 3	1.6 / 5	6.4 / 18

Although Imbach *et al.* (2012) performed a previous probabilistic water balance assessment for the region from the SRES climate scenarios of AR4 GCMs (CMIP3), we present here newer GCM simulations and shorter time-horizon scenarios (2050/2070) from AR5, and estimate water availability per capita for each GCM climate. The CMIP5 + MAPSS scenarios showed here show a similar uncertainty range of runoff change than the CMIP3 + MAPSS ones from Imbach *et al.* (2012), indicating a general decrease in river discharge across both previous and current generation of climate models and global warming scenarios. We found 70 percent of the total area with *likely* decreases in 2070, similar to the results for year 2085 using CMIP3 models. Although, radiative forcing under RCP 4.5 in 2070 (3.84 $W.m^{-2}$) is relatively similar to SRES B1 in 2080 (4.09 $W.m^{-2}$), the smaller ensemble used in this study could have an effect on uncertainty estimates. Although, the ensemble used in Imbach *et al.* (2012) was larger because it included different scenarios with the same GCMs (assuming equal weights for each one of them) their pattern is similar to those used in this study, with increased temperature and decreased precipitation for the northern part of the region and increased temperature and mixed signals (between) models for precipitation anomalies. As expected, shorter time horizons have smaller impacts, with half of the region with *likely* runoff reductions (>20%) under 2050 climate conditions (compared to 70% in 2070).

The approach presented here to estimate water availability has limitations that should be kept in mind for the interpretation of our results. First, our analysis is based on mean climate conditions and does not account for seasonal or inter-annual variability that could be important, particularly over dry areas where stress becomes important in dry years and/or with increased runoff variability (i.e. the Pacific watershed of Central America). This means, for example, that catchments found to be under current stress conditions can have sufficient runoff over specific years or within wet seasons. Other studies, at coarser scales, have accounted for inter-annual variability to estimate a significant change in runoff (where change in runoff is assumed significant only if larger than one standard deviation of inter-annual variability of a 30-year reference period; Arnell 2004). Second, this analysis uses the intermediate RCP pathway RCP4.5 and therefore does not explore potentially higher/lower climate forcing scenarios. Third, we estimate changes in water availability assuming no changes in population or water resource demands (for example, for irrigation under drier future conditions). However, increase in water demand (accounting for population increase) has been estimated at 296–364 percent by 2050 depending on the climate scenario (CEPAL 2011). Fourth, the model estimates water balance with potential vegetation and therefore assumes no changes in land use, which could have an effect at other temporal or spatial scales. Finally, and more importantly, we assumed no water transfer between catchments that could lead to a potential redistribution of resource availability, an issue that can be of relevance particularly in basins with large population centers that may develop infrastructure to access resources from other catchments or dam existing catchments to save water (e.g. for the dry season). This could be the case, for example, of all *stressed* catchments under current climate conditions on the Pacific watersheds containing capital cities that could have resources to transport water from nearby catchments.

The Chamelecón basin (Figure 3.4a–c, in Honduras) is the most water limited one under current conditions with availability close to the upper threshold of *absolute scarcity* (479 m^3 per capita), yet keeping in mind a runoff model underestimation of 13 percent. Aguán, Cangrejal and Choluteca also show water *scarcity* under current conditions and the former two moving to *absolute scarcity* under future conditions in this study. CEDEX and SERNA (2002) estimated a hydrological balance of Honduras, based on water resources and sectorial demand estimates, and also found Chamelecón and Cangrejal basins among those with the smaller water surplus (while assuming no problems with access to the resource). They also found the Chamelecón River basin as the only case in Honduras with water deficit at the sub-basin scale (lower parts of the basin). The Hondo basin, in Guatemala, has a treaty dealing with international border issues and equitable use of the resources dating from 1961, indicating potential issues with resource availability (UNEP *et al.* 2007). CEPAL (2011) found El Salvador with *stress* conditions under current climate using a long term average model for water availability and differentiating water use by different sectors (i.e. human consumptions, agriculture and industrial). Changes in future sectors demand were also assessed by the CEPAL study, and are assumed constant as in our case, although their study assessed changes that did not account for within-country disparities in resource availability (only the total country-level resource availability) as well as resources available from trans-boundary basins.

We found a general trend of increased water scarcity in the northern part of Central America, mostly over Guatemala, Honduras and El Salvador, under future scenarios (under RCP 4.5). Although the region uses around 8 percent of available water resources currently, country rates of use are variable. For example Costa Rica and Nicaragua use 20 percent and 1 percent of their total available resources respectively today (GWP *et al.* 2011), meaning that reduction trends will have variable impacts. Furthermore, several basins are shared with neighboring countries (international basins cover 37% of the region, or 191,449 km^2), and these watersheds cover between 75 and 5 percent of country territories (for

Guatemala and Panama respectively showing the largest and smallest percentages; GWP *et al.* 2011). Internationally shared basins have been the source of conflicts in the past (i.e. Lempa river basin linked to siltation problems; Wolf 2007), where decreasing resource availability could become an important factor.

Box 3.1 From emission scenarios to representative concentration pathways

The assessment presented on the fourth IPCC report (AR4; IPCC 2007) was based on simulations from global climate models from the Coupled Model Intercomparison Project 3 (CMIP3) forced by green-house gases (GHG) emissions scenarios from the Special Report on Emission Scenarios (SRES; IPCC 2000). SRES emission scenarios were derived from integrated assessment models (models that explore the physical, biological, economic and social components for impact and policy response assessments) of specific future storylines of demographic and economic development, energy use, technology and land use (IPCC 2000). IPCC fifth assessment report (AR5; IPCC 2013) uses global climate simulations from the Coupled Model Intercomparison Project 5 (CMIP5) forced by representative concentration pathways (RCP). The RCPs are scenarios depicting possible future trajectories of future emissions and concentration of greenhouse gases, air pollutants and land use change covering the range of future radiative forcing (a measure of the global net radiation imbalance at the top of the atmosphere, and measured in $W.m^{-2}$, that is directly related to global mean temperature) found in the literature but that are not based on specific socio-economic storylines (Cubasch *et al.* 2013). RCPs can be explored by the community developing integrated assessment models in order to develop socio-economic and policy storylines while, in parallel, climate modelers develop future climate scenarios (Vuuren *et al.* 2011). The comparison of RCP and SRES based scenarios is rendered complex due to the different emissions scenarios and climate models used for each assessment report. Rogelj *et al.* (2012) however provide a comparison between both (AR4 and 5) climate scenarios based on a common analysis framework of equilibrium climate sensitivities. They found that the range of changes in future mean global temperature is larger for RCPs (likely changes of 1.3–5.7°C for 2090–2099) than SRES (2.0–5.8°C) and differences between specific scenarios. For example, RCP 4.5 global median temperatures (likely changes of 2.0–2.9°C for 2090–2099) have a faster increase until 2050 and slower afterwards when compared to SRES B1 scenario (2.0–3.1°C). RCP 8.5 global median temperatures (likely changes of 3.8–5.7°C for 2090–2099) have a slower increase for the period 2035-2080 and faster in any other period when compared to A1FI (3.9–5.8°C; Rogelj *et al.* 2012). RCP 2.6 has a lower radiative forcing than any SRES scenario (Cubasch *et al.* 2013).

UNEP *et al.* (2007) assessed water availability in 2025 for international basins in Central America, where only the Choluteca basin appears *stressed* and the Ulúa, Lempa, Grande de Sonsonate, Paz, and Motagua (with limited resources in our results for 2050) appear just over the 1700 m^3 per capita *stress* threshold (using CGCM1GSa1 and HadCM2GSa1) under 1 percent per year increase in CO_2 equivalent and sulfate aerosol dampening; Vörösmarty 2000). It is worth noting that this study used a coarser-scale hydrological model (0.5°~50 km; Fekete *et al.* 1999) that might miss some of the runoff variability. Although our study shows stress for the Atitlan and Mopán–Hondo basins, these hold large reservoirs that could allow for resource storage not accounted for in our study. Some basins move out the *no stress* category only under 2070 climate (San Miguel and Papaloteca).

Wolf (2007) estimates that although no Central American country has limited resources (based on mean national estimates), except for El Salvador, the isthmus has drinking water shortages due to accessibility issues. This study also highlights the fact that several capital cities (for El Salvador, Nicaragua, Honduras, and Belize) lay on international basins, where we found reduced future availability due to climate change. Furthermore, San Salvador (Lempa river basin) being currently the capital with most concerns by poor management and limited water resources availability.

Three quarters of the population living on the Pacific side rely mostly on aquifer resources CEPAL (2011) and several capital cities rely to significant extents on aquifer water resources. For example, Negro, Chixoy, La Vaca (a tributary of the Motagua river) in Guatemala; Choluteca in Honduras (5% of urban demand from underground sources); Lempa in El Salvador (37%, who are also used to generate 41% of the country energy supply; Wolf 2007). These areas could have delays in water availability problems depending on water use and storage rates since large amounts of the resources could take longer times to be depleted (as compared to surface resources).

The Lempa River basin (among several other basins), in El Salvador and Honduras, has also suffered agricultural loses during the 2000–2001 droughts, also highlighting the role of climate variability in determining the impacts of water availability.

Arnell (2004) estimated in their global coarse-scale study that 16 percent of Mesoamerican population lived under water stress (defined as less than 1000 m^3 per capita) in 1995, although their study area includes Central America and southern Mexico (the latter is excluded in our study). They also found a large number of people exposed to increased water stress depending on emission scenario and climate model (4–108 million) for Mesoamerica in 2025. Our results are on the lower part of his range, even when accounting for all people under stress (17.4 million under 2070 climate). Comparison of the two results findings is uncertain because Arnell (2004) used a range from specific GCM simulations and emission scenarios, while our approach is based on mean values of runoff (and for a smaller area or at higher resolution). This approach allows for reduced uncertainty in our estimates given the relatively clear signal of change in runoff for our study region. Some models (in Arnell's 2004 study) also show population that will experience a decrease in water stress (between 0 and 82 million people), contrary to our results, although the differences could be areas within Mesoamerica that are outside of our study area.

Finally, it is important to note that our hydrological modeling approach is based on equilibrium conditions with climate and therefore does not account for transient changes meaning that we have no indication on when the evaluated impacts could happen since ecosystems and water dynamics could happen at a different pace than climate change, for example, changes in leaf area index could occur faster than changes in tree fraction cover (Jones *et al.* 2009).

Box 3.2 Policy implications

Given the threats of climate change to water resources and hydrological ecosystem services in Central America, adaptation is needed for all socioeconomic sectors depending on water and watershed services. For example, hydroelectricity is a major source of energy in this region, it is vulnerable to climate change and depends largely on ecosystem services for soil erosion reduction and water flow regulation (Locatelli *et al.* 2010). Flooding and drought are regularly affecting communities and economic activities (Simms and Reid 2006; Wunder and Wertz-Kanounnikoff 2009). Adaptation policies are emerging in all Central American countries but their design is made difficult by uncertainties about climate change trends and a cascade of unknowns about biophysical impacts and socioeconomic consequences. This impact assessment study provides scientific inputs from a biophysical perspective for adaptation options and the next step is to understand the socioeconomic implications and the policy context at regional, national and local levels. Because uncertainties inherent to impact assessments may be difficult to handle by policymakers (Burton *et al.* 2002), long-term and regional impact assessments must be complemented with vulnerability assessments aiming at understanding how and why people and water-dependent economic sectors are vulnerable to climate variations at the local level now and in the future.

Historically, water management policy decisions do not account for climatic change because climate was assumed to be unchanging. Decisions with short-term implications can reasonably ignore climate change and its uncertainties but this is not the case of water management plans, which require infrastructure, land use or socio-economic development in the long term. The approach used in our study helps acknowledging uncertainties, which is an important step in adaptation policy development (Dessai and Wilby 2011). Recognizing uncertainties about future climate change impacts calls for diversified and flexible approaches to adaptation. Depending on the local context, these approaches must combine different measures selected from an adaptation toolbox (i.e. a list of possible measures; Locatelli *et al.* 2008). Adaptation measures in the water sector can involve the demand side (e.g. improving water use efficiency for reducing consumption), the transformation side (e.g. improving treatment and transportation infrastructure) and the supply side (e.g. managing watersheds). The selection of adaptation measures depends on their cost or feasibility but also on the outcomes that the society considers of interest, recognizing trade-offs between them. For example, landscape management in Central America can contribute to protect watershed services, biodiversity and other services (such as carbon or scenic beauty) at the same time, but trade-offs can occur (Locatelli *et al.* 2013). Flexible approaches also require monitoring outcomes and learning from experience in order to achieve an adaptive management.

Because of the complex relationships between climate, ecosystems and water and the role of ecosystems in regulating water quality and quantity, adaptation plans in the water sector cannot be limited to brick and mortar solutions. Central America has a long experience of watershed management and payment for environmental services (PES), particularly in relation with water (Kaimowitz 2005; Kosoy *et al.* 2007). Recent studies and reviews have highlighted that ecosystem management can contribute to the adaptation of the society to climate change (the so-called ecosystem-based adaptation; Pramova *et al.* 2012) and that instruments such as PES can be tailored to become adaptation instruments (Wertz-Kanounnikoff *et al.* 2011). But to conserve ecosystem services that are important to help society to adapt to climate change, adaptation measures must also be designed for those ecosystems, for example through reducing human pressures, conserving biodiversity hotspots and improving landscape connectivity between protected areas (Guariguata *et al.* 2008). For these reasons, the Mesoamerican Biological Corridor has an important role to play in ecosystem adaptation and, thus, societal adaptation (Imbach *et al.* 2013).

The following is an example of interesting initiatives that are emerging in Central America on climate change adaptation. In September 2010, the Adaptation Fund of the United Nations Framework Convention on Climate Change accepted its first two projects. One of these, in Honduras, aims at improving water management and water security for the poor in capital region of Tegucigalpa (Locatelli *et al.* 2011). In addition to measures on the water demand and infrastructure sides, this project highlights the role of forests, for example how cloud forests capture mist from the atmosphere and how deforestation affects water supply. The project developers recognize that ecosystem management (including the creation of protected areas) is crucial for Tegucigalpa water supply and that there are currently no mechanisms to conserve hydrological ecosystem services (Adaptation Fund 2010). In addition to considering ecosystems for societal adaptation, the project also plans to implement adaptation for ecosystems: biological corridors will be conserved and restored to increase connectivity and facilitate ecological adaptation. This example shows how adaptation for people, water, and ecosystems can be integrated in a cross-sectorial approach.

Conclusions

We evaluated the impacts of climate change on water balance and per capita water availability in Central America watersheds using recent GCM results from IPCC AR5. We used a soil–vegetation–atmosphere transfer model, previously calibrated for our study area, to estimate mean runoff at 1 km^2 resolution under historical (1950–2000) and future (2040–2060 and 2060–2080) climate conditions for the intermediate global warming scenario RCP 4.5. We estimated per capita water availability based on population count per watershed and an index of water stress to assess changes in future resource availability. We found a general decreasing trend in water availability per capita, with resource availability limitations mostly in the northern part of Central America as well as in basins with high population density (i.e. capital cities). Our study updated previous water balance scenarios developed for the region- and watershed-scale indicators of potential stress in resource availability due to climate change.

Acknowledgements

This research has received financial support from AC3 project from the International Development Research Centre (IDRC) Canada; the CRP-FTA (Consortium Research Program on Forests, Trees, and Agroforestry); and the CASCADE project, which is part of the International Climate Initiative (ICI). The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) supports CASCADE on the basis of a decision adopted by the German Bundestag.

References

Adaptation Fund, 2010. *Proposal for Honduras: Addressing Climate Change Risks on Water Resources in Honduras: Increased Systemic Resilience and Reduced Vulnerability of the Urban Poor*. Adaptation Fund Board, Project and Programme Review Committee, Second Meeting. Bonn, Germany: Adaptation Fund Board.

Aguilar, E., Peterson, T.C., Obando, P.R., Frutos, R., Retana, J. a., Solera, M., Soley, J., García, I.G., Araujo, R.M., Santos, a. R., Valle, V.E., Brunet, M., Aguilar, L., Álvarez, L., Bautista, M., Castañón, C., Herrera, L., Ruano, E., Sinay, J.J., Sánchez, E., Oviedo, G.I.H., Obed, F., Salgado, J.E., Vázquez, J.L., Baca, M., Gutiérrez, M., Centella, C., Espinosa, J., Martínez, D., Olmedo, B., Espinoza, C.E.O., Núñez, R., Haylock, M., Benavides, H., and Mayorga, R., 2005. Changes in precipitation and temperature extremes in Central America and northern South America, 1961–2003. *Journal of Geophysical Research* 110(D23): 1–15.

Arnell, N.W., 2004. Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change* 14(1): 31–52.

Brown, A. and Matlock, M., 2011. *A Review of Water Scarcity Indices and Methodologies*. White Paper 106. Tempe, AZ: The Sustainability Consortium.

Burton, I., Huq, S., Lim, B., Pilifosova, O., and Schipper, E.L., 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. *Climate Policy* 2(2): 145–159.

CEDEX and SERNA, 2002. *Balance hídrico de Honduras*. Tegucigalpa, Honduras: SERNA.

CEPAL, 2011. *La economía del cambio climático en Centroamérica*. Mexico DF: CEPAL

Chapin III, S., Walker, B.H., Hobbs, R.J., Hooper, D.U., Lawton, J.H., and Sala, O.E., 1997. Biotic Control over the Functioning of Ecosystems. *Science* 277(July): 500–504.

CIESIN, IFPRI, WB, and CIAT, 2011. Global rural–urban mapping project, version 1 (GRUMPv1): population count grid. Palisades, NY: NASA Socioeconomic Data and Applications Center (SEDAC). Retrieved November 1, 2013 from http://sedac.ciesin.columbia.edu/data/set/grump-v1-population-count.

CONAPAS, 2006. *Estrategia Nacional de agua potable y saneamiento*. Managua, Nicaragua: CONAPAS.

Costanza, D., de Groot, R., Farber, R., Grasso, S., Hannon, M., Limburg, B., Naeem, K., O'Neill, S., Paruelo, R., Raskin, J., Sutton, R., and van den Belt, P.M., 1997. The value of world´s ecosystem services and natural capital. *Nature* 387(6630): 253–260.

Cubasch, U., Wuebbles, D., Chen, D., Facchini, M.C., Frame, D., Mahowald, N., and Winther, J.-G. 2013. Introduction. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, 119–158. Cambridge: Cambridge University Press.

Dargaville, R.J., Heimann, M., McGuire, A.D., Prentice, I.C., Kicklighter, D.W., Joos, F., Clein, J.S., Esser, G., Foley, J., Kaplan, J., Meier, R.A., Melillo, J.M., Moore III, B., Ramankutty, N., Reichenau, T., Schloss, A., Sitch, S., Tian, H., Williams, L.J., and Wittenberg, U., 2002. Evaluation of terrestrial carbon cycle models with atmospheric CO_2 measurements: results from transient simulations considering increasing CO_2, climate, and land-use effects. *Global Biogeochemical Cycles* 16(4): 1092.

DeClerck, F.A.J., Chazdon, R., Holl, K.D., Milder, J.C., Finegan, B., Martinez-Salinas, A., Imbach, P., Canet, L., and Ramos, Z., 2010. Biodiversity conservation in human-modified landscapes of Mesoamerica: past, present and future. *Biological Conservation* 143(10): 2301–2313.

De Groot, R.S., Wilson, M.A., and Boumans, R.M.J., 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics* 41(3): 393–408.

Dessai, S. and Wilby, R.L., 2011. How can developing country decision makers incorporate uncertainty about climate risks into existing planning and policymaking processes? In *World Resources Report*. Washington, DC: World Resources Institute.

Diaz, S., Hodgson, J.G., Thompson, K., Cabido, M., Cornelissen, J.H.C., Jalili, a., Montserrat-Martí, G., Grime, J.P., Zarrinkamar, F., Asri, Y., Band, S.R., Basconcelo, S., Castro-Díez, P., Funes, G., Hamzehee, B., Khoshnevi, M., Pérez-Harguindeguy, N., Pérez-Rontomé, M.C., Shirvany, F. a., Vendramini, F., Yazdani, S., Abbas-Azimi, R., Bogaard, a., Boustani, S., Charles, M., Dehghan, M., Torres-Espuny, L., Falczuk, V., Guerrero-Campo, J., Hynd, a., Jones, G., Kowsary, E., Kazemi-Saeed, F., Maestro-Martínez, M., Romo-Díez, a., Shaw, S., Siavash, B., Villar-Salvador, P., and Zak, M.R., 2004. The plant traits that drive ecosystems: evidence from three continents. *Journal of Vegetation Science* 15(3): 295–304.

Falkenmark, M., 1989. The massive water scarcity threatening Africa: why isn't it being addressed? *Ambio* 2: 112–118.

Fekete, B.M., Vörösmarty, C.J., and Grabs, W., 1999. *Global Composite Runoff Fields on Observed River Discharge and Simulated Water Balances*. Koblenz, Germany: Global Runoff Data Center.

Giorgi, F., 2006. Climate change hot-spots. *Geophysical Research Letters* 33(April): 1–4.

Gleick, P.H., 1996. Basic water requirements for human activities: meeting basic needs. *Water International* 21(2): 83–92.

Gómez-Delgado, F., Roupsard, O., le Maire, G., Taugourdeau, S., Pérez, A., van Oijen, M., Vaast, P., Rapidel, B., Harmand, J.M., Voltz, M., Bonnefond, J.M., Imbach, P., and Moussa, R., 2011. Modelling the hydrological behaviour of a coffee agroforestry basin in Costa Rica. *Hydrol. Earth System Sciences* 15(1): 369–392.

Guariguata, M., Cornelius, J., Locatelli, B., Forner, C., and Sánchez-Azofeifa, G.A., 2008. Mitigation needs adaptation: tropical forestry and climate change. *Mitigation and Adaptation Strategies for Global Change* 13(8): 793–808.

GWP, UE, ZONAF, and BCIE, 2011. *Situación de los recursos hídricos en Centroamérica. Hacia una gestión integrada.* Tegucigalpa, Honduras: GWP.

Hastenrath, S. and Polzin, D., 2013. Climatic variations in Central America and the Caribbean. *International Journal of Climatology* 33(6): 1348–1356.

Hawkins, E. and Sutton, R., 2012. Time of emergence of climate signals. *Geophysical Research Letters* 39(1): [n.p.].

Hidalgo, H.G., Amador, J.A., Alfaro, E.J., and Quesada, B., 2013. Hydrological climate change projections for Central America. *Journal of Hydrology* 495: 94–112.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., and Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* 25(15): 1965–1978.

Holdridge, L.R., 1947. Determination of world plant formations from simple climatic data. *Science* 105: 367–368.

Imbach, P., Molina, L., Locatelli, B., Roupsard, O., Ciais, P., Corrales, L., and Mahé, G., 2010. Climatology-based regional modelling of potential vegetation and average annual long-term runoff for Mesoamerica. *Hydrology and Earth System Sciences* 14(10): 1801–1817.

Imbach, P., Molina, L., Locatelli, B., Roupsard, O., Mahé, G., Neilson, R., Corrales, L., Scholze, M., and Ciais, P., 2012. Modeling potential equilibrium states of vegetation and terrestrial water cycle of Mesoamerica under climate change scenarios. *Journal of Hydrometeorology* 13(2): 665–680.

Imbach, P.A., Locatelli, B., Molina, L.G., Ciais, P., and Leadley, P.W., 2013. Climate change and plant dispersal along corridors in fragmented landscapes of Mesoamerica. *Ecology and Evolution* 3(9): 2917–2932.

IPCC, 2000. *Emission Scenarios*. Cambridge: Cambridge University Press.

IPCC, 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

IPCC, 2013. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Jones, C., Lowe, J., Liddicoat, S., and Betts, R., 2009. Committed terrestrial ecosystem changes due to climate change. *Nature Geoscience* 2(7): 484–487.

Jones, R.G., Noguer, M., Hassel, D.C., Hudson, D., Wilson, S.S., Jenkins, G.J., and Mitchell, J.F.B. 2004 *Generating High Resolution Climate Change Scenarios Using PRECIS*. Exeter: Met Office, Hadley Center.

Kaimowitz, D., 2005. Useful myths and intractable truths: the politics of the link between forests and water in Central America. In M. Bonell and L. Bruijnzeel (eds). *Forests, Water and People in the Humid Tropics: Past, Present and Future Hydrological Research for Integrated Land and Water Management*. Cambridge: Cambridge University Press.

Karmalkar, A., Bradley, R., and Diaz, H., 2011. Climate change in Central America and Mexico: regional climate model validation and climate change projections. *Climate Dynamics* 37(3): 605–629.

Kindermann, J., Würth, G., Kohlmaier, G.H., and Badeck, F.-W., 1996. Interannual variation of carbon exchange fluxes in terrestrial ecosystems. *Global Biogeochemical Cycles* 10(4): 737–755.

Kosoy, N., Martinez-Tuna, M., Muradian, R., and Martinez-Alier, J., 2007. Payments for environmental services in watersheds: insights from a comparative study of three cases in Central America. *Ecological Economics* 61(2–3): 446–455.

Krinner, G., Viovy, N., de Noblet-Ducoudré, N., Ogée, J., Polcher, J., Friedlingstein, P., Ciais, P., Sitch, S., and Prentice, I.C., 2005. A dynamic global vegetation model for studies of the coupled atmosphere-biosphere system. *Global Biogeochemical Cycles* 19(1): GB1015.

Lehner, B., Verdin, K., and Jarvis, A., 2008. New global hydrography derived from spaceborne elevation data. *Eos, Transactions American Geophysical Union* 89(10): 93–94.

Locatelli, B. *et al.* 2008. *Face à un avenir incertain: Comment les forêts et les populations peuvent s'adapter au changement climatique*. Bogor: CIFOR.

Locatelli, B., Imbach, P., Vignola, R., Metzger, M., and Hidalgo, E., 2010. Ecosystem services and hydroelectricity in Central America: modelling service flows with fuzzy logic and expert knowledge. *Regional Environmental Change* 11(2): 393–404.

Locatelli, B., Evans, V., Wardell, A., Andrade, A., and Vignola, R., 2011. Forests and climate change in Latin America: linking adaptation and mitigation. *Forests* 2(1): 431–catelli, B., Imbach, P., and Wunder, S. 2013. Synergies and trade-offs between ecosystem services in Costa Rica. *Environmental Conservation* 41: 27–36.

Lutz, J., Englin, J., and Shonkwiler, J., 2000. On the aggregate value of recreational activities. *Environmental and Resource Economics* 15: 217–226.

Magaña, V., Amador, J.A., and Medina, S., 1999. The midsummer drought over Mexico and Central America. *Journal of Climate* 12(6): 1577–1588.

Malhi, Y. and Wright, J., 2004. Spatial patterns and recent trends in the climate of tropical rainforest regions. *Philosophical Transactions of the Royal Society of London B* 359(1443): 311–329.

Mastrandrea, M.D., Field, C.B., Stocker, T.F., Edenhofer, O., Ebi, K.L., Frame, D.J., Held, H., Kriegler, E., Mach, K.J., Matschoss, P.R., Plattner, G.-K., Yohe, G.W., and Zwiers, F.W., 2010. *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties*. Geneva: IPCC. Retrieved from www.ipcc.ch/pdf/supporting-material/uncertainty-guidance-note.pdf.

MEA, 2005. *Ecosystems and Human Well-being: Synthesis*. Washington, DC: Island Press.

Mora, C., Frazier, A.G., Longman, R.J., Dacks, R.S., Walton, M.M., Tong, E.J., Sanchez, J.J., Kaiser, L.R., Stender, Y.O., Anderson, J.M., Ambrosino, C.M., Fernandez-Silva, I., Giuseffi, L.M., and Giambelluca, T.W., 2013. The projected timing of climate departure from recent variability. *Nature* 502(7470): 183–187.

Nakaegawa, T., Kitoh, A., Ishizaki, Y., Kusunoki, S., and Murakami, H., 2013a. Caribbean low-level jets and accompanying moisture fluxes in a global warming climate projected with CMIP3 multi-model ensemble and fine-mesh atmospheric general circulation models. *International Journal of Climatology* 34(4): 964–977.

Nakaegawa, T., Kitoh, A., Murakami, H., and Kusunoki, S., 2013b. Annual maximum 5-day rainfall total and maximum number of consecutive dry days over Central America and the Caribbean in the late twenty-first century projected by an atmospheric general circulation model with three different horizontal resolutions. *Theoretical and Applied Climatology* 116: 155–168.

Neelin, J.D., Münnich, M., Su, H., Meyerson, J.E., and Holloway, C.E., 2006. Tropical drying trends in global warming models and observations. *Proceedings of the National Academy of Sciences of the United States of America* 103(16): 6110–6115.

Neilson, R.P., 1995. A model for predicting continental-scale vegetation distribution and water balance. *Ecological Applications* 5(2): 362–385.

Ohlsson, L., 2000. Water conflicts and social resource scarcity. *Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere* 25(3): 213–220.

Pattanayak, S.K., 2004. Valuing watershed services: concepts and empirics from southeast Asia. *Agriculture, Ecosystems and Environment* 104(1): 171–184.

Pramova, E., Locatelli, B., Djoudi, H., and Somorin, O.A., 2012. Forests and trees for social adaptation to climate variability and change. *Wiley Interdisciplinary Reviews: Climate Change* 3(6): 581–596.

Rauscher, S., Giorgi, F., Diffenbaugh, N., and Seth, A., 2008. Extension and intensification of the Meso-American mid-summer drought in the twenty-first century. *Climate Dynamics* 31(5): 551–571.

Rogelj, J., Meinshausen, M., and Knutti, R., 2012. Global warming under old and new scenarios using IPCC climate sensitivity range estimates. *Nature Climate Change* 2(4): 248–253.

Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, a, Leemans, R., Lodge, D.M., Mooney, H. a, Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., and Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. *Science* 287(5459): 1770–1774.

Salameh, E., 2000. Redefining the Water Poverty Index. *Water International* 25(3): 469–473.

Scholze, M., Knorr, W., Arnell, N.W., and Prentice, I.C., 2006. A climate-change risk analysis for world ecosystems. *Proceedings of the National Academy of Sciences* 103(35): 13116–13120.

Simms, A. and Reid, H., 2006. *Up in Smoke? Latin America and the Caribbean: The Threat from Climate Change to the Environment and Human Development*. London: IIED.

Sitch, S., Huntingford, C., Gedney, N., Levy, P.E., Lomas, M., Piao, S.L., Betts, R., Ciais, P., Cox, P., Friedlingstein, P., Jones, C.D., Prentice, I.C., and Woodward, F.I., 2008. Evaluation of the terrestrial carbon cycle, future plant geography and climate-carbon cycle feedbacks using five Dynamic Global Vegetation Models (DGVMs). *Global Change Biology* 14(9): 2015–2039.

UNDP, 2006. *Una alianza para el desarrollo mundial*. New York: UNDP.

UNEP, UNA, and OSU, 2007. *Hydropolitical Vulnerability and Resilience along International Waters: Latin America and the Caribbean*. Nairobi: UNEP.

UNFPA, 2006. *The State of the World Population*. New York: UNFPA.

Vörösmarty, C.J., 2000. Global water resources: vulnerability from climate change and population growth. *Science* 289(5477): 284–288.

Vörösmarty, C.J., Douglas, E.M., Green, P.A., and Revenga, C., 2005. Geospatial indicators of emerging water stress: an application to Africa. *AMBIO* 34(3): 230–236.

Vuuren, D. *et al.* 2011. The representative concentration pathways: an overview. *Climatic Change* 109(1–2): 5–31.

Wertz-Kanounnikoff, S., Locatelli, B., Wunder, S., and Brockhaus, M., 2011. Ecosystem-based adaptation to climate change: what scope for payments for environmental services? *Climate and Development* 3(2): 143–158.

Williams, P., Hannah, L., Andelman, S., Midgley, G., Araújo, M., Hughes, G., Manne, L., Martinez-Meyer, E., and Pearson, R., 2005. Planning for climate change: identifying minimum-dispersal corridors for the Cape Proteaceae. *Conservation Biology* 19(4): 1063–1074.

Wolf, A.T., 2007. Shared waters: conflict and cooperation. *Annual Review of Environment and Resources* 32(1): 241–269.

Woodward, R.T. and Wui, Y.-S., 2001. The economic value of wetland services: a meta-analysis. *Ecological Economics* 37(2): 257–270.
Wunder, S. and Wertz-Kanounnikoff, S., 2009. Payments for ecosystem services: a new way of conserving biodiversity in forests. *Journal of Sustainable Forestry* 28(3–5): 576–596.
Yates, D.N., Kittel, T.G.F. and Cannon, R.F. Comparing the correlative Holdridge model to mechanistic biogeographical models for assessing vegetation distribution response to climatic change. *Climatic Change* 44: 59–87.

Note

1 ACCESS1-0, BCC-CSM1-1, CCSM4, CESM1-CAM5-1-FV2, CNRM-CM5, GFDL-CM3, GFDL-ESM2G, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, MIROC-ESM-CHEM, MIROC-ESM, MIROC5, MPI-ESM-LR, MRI-CGCM3, and NorESM1-M.