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Water, Poverty, and the Economy

Physical Impacts of Climate Change on Water Resources

Fernando Miralles-Wilhelm, Leon Clarke, Mohamad Hejazi, Sonny Kim, Kelly Gustafson, Raul Muñoz-Castillo, and Neal Graham

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Abstract

This paper documents an initial study focused on understanding the physical impacts of climate change on water resources throughout the world. The research performed in this study is based on the application of an Integrated Assessment Model to quantify these impacts for a wide range of scenarios of socioeconomic development that offer a mix of possible futures for the availability, use, and management of water resources. Through this research and analysis, this study provides an integrated qualitative and quantitative understanding of the implications of several selected issues, including climate change and mitigation, and socioeconomic and technological developments, on water scarcity and water-energy-food interactions in a global context. The understanding gained through this analysis is expected to contribute to the ongoing dialogue on the sustainability of multiple human activities and their trajectories toward global development pathways.

Introduction

Despite the well-recognized role of water in transmitting climate impacts to some of the growth drivers of the economy, the water sector has been largely ignored in climate change deliberations. The impacts are projected to vary by region, and are likely to include changes in average hydroclimate patterns (precipitation, surface runoff, and stream flow), as well as increases in the probability of extreme events. Climate shocks are likely to impose higher costs than gradual changes in climate averages. Prudent management of water resources will be pivotal in addressing the climate challenge—both for adapting to the effects of climate change and for meeting global goals to mitigate greenhouse gases (GHG).

The precise consequences of climate change on the hydrological cycle are uncertain, which makes adaptation especially challenging. Uncertainty regarding impacts is partly a consequence of the limitations of climate models. Despite improvements in climate science, the Global Circulation Models (GCMs) developed to project climate futures generate a wide range of projections that often disagree on both the direction and magnitude of precipitation changes. Furthermore, GCMs have not been designed to predict changes in the hydrological cycle and lack the precision required for planning and managing water resources. These errors are compounded when projections are "downscaled" from regional to the finer spatial scales necessary for planning and the design of infrastructure. In addition, changes in the hydrological cycle imply that future water systems may not resemble the past (nonstationarity), so historic trends—as used in engineering designs—no longer serve as a reliable guide for assessing and managing future risks.

Identifying and analyzing the consequences of climate change in water resources requires integrated modeling that allows proper incorporation of the potential impacts of climate in the hydrological cycle into all major sectors that use water, such as the urban, environment, agriculture, and energy sectors. It also

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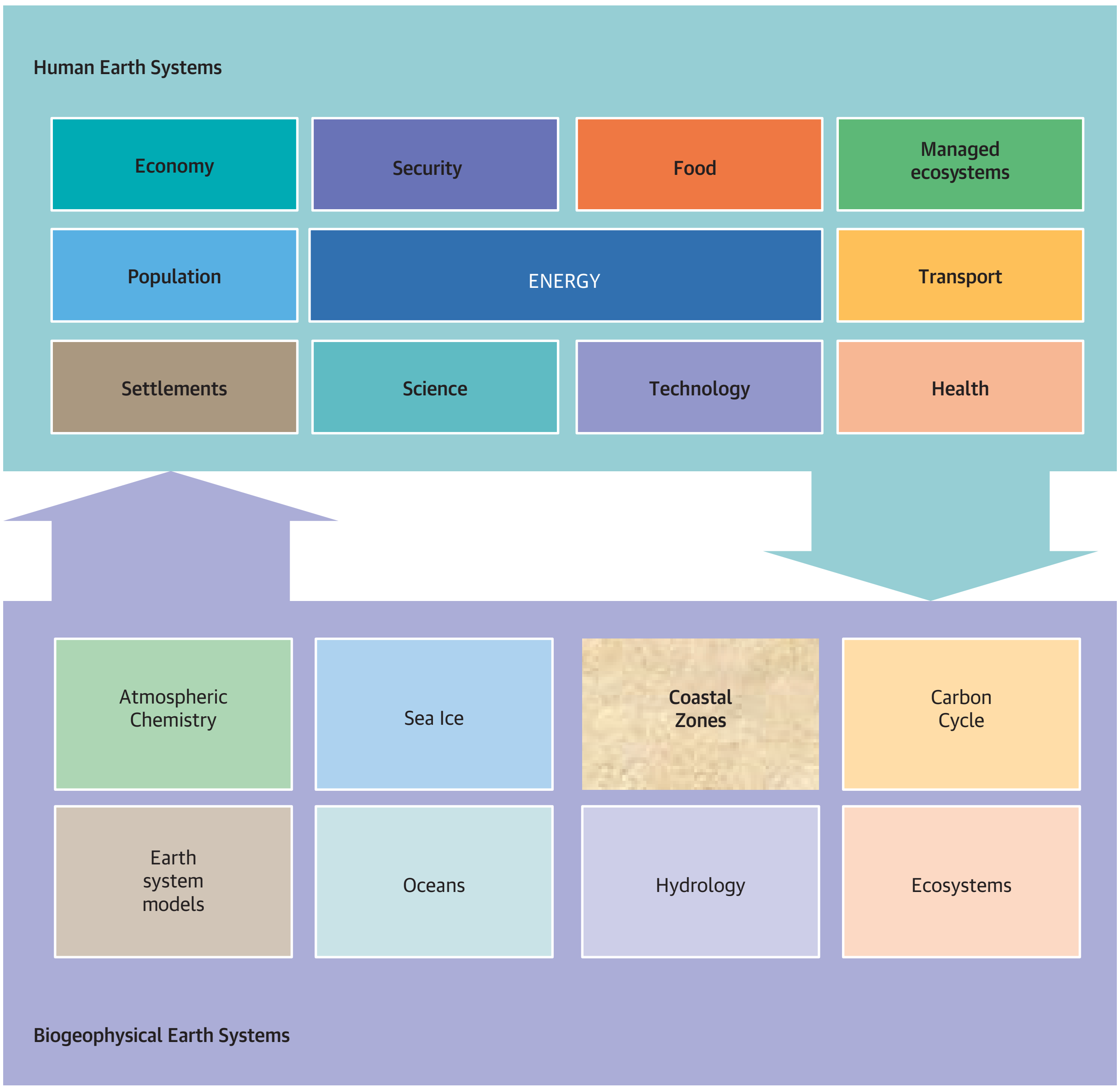
This paper aims to investigate the impacts of climate change on water resources throughout the world, and specific effects on water-dependent sectors of the economy, such as urban, energy, and agriculture sectors.

requires the use of economic tools to determine the economic costs and benefits of different adaptation strategies.

The use of Integrated Assessment Models (IAMs) to identify the physical impacts of climate change on water resources has advanced greatly in the past decade. IAMs use a set of different assumptions and interrelated factors simultaneously and include both physical and social science models that consider demographic, political, and economic variables that affect greenhouse gas emission scenarios. IAMs allow researchers to explore interactions between sectors and to understand the potential ramifications of climate actions. Figure 1 illustrates a typical IAM.

FIGURE 1. A Typical Integrated Assessment Model (IAM)



Research Methods

The analysis in this paper is conducted utilizing an IAM called the Global Change Assessment Model (GCAM) as the main analytical tool.[1] The analysis involves setting up and running multiple GCAM simulation scenarios to shed light on three important questions:

1. What are the physical impacts of climate change on water scarcity around the world, and particularly on surface runoff?
2. What are the impacts of future development scenarios under consideration on water scarcity?
3. What are the impacts of implementing climate change mitigation on water scarcity?

To investigate the physical impacts of climate change on water scarcity, the results from multiple GCMs are used as inputs into GCAM, to assess the level of uncertainty propagating from climate models and their implications on water scarcity conditions at the scale of individual countries. Three GCMs that span the range of uncertainty (wet, dry, and normal) are selected to drive the GCAM simulations, with and without accounting for the impacts of climate change on water availability. The results allow for a comparison between the uncertainties surrounding climate models and the corresponding distribution of water scarcity around the world.

Next, several Shared Socioeconomic Pathway scenarios (SSPs) are simulated, using hydrologic inputs from the GCMs, to show how socioeconomic and technological development might affect water demands, and consequently water scarcity in different basins. SSPs describe potential future pathways for the evolution of key aspects of society that would affect our abilities to mitigate, and adapt to, climate change. Five SSPs were selected for this study that reflect a broad range of possibilities. The analysis focuses on quantifying regional water demands for different uses of water resources, and projecting river basins under water scarcity. The results of these simulations can also be used to compare the relative effects of socioeconomic and technological changes to the effects of climate change.

Finally, the study examines the implications of limited water resources on energy and agricultural decisions. Simulations are carried out with and without constraining water resources as a limited resource in water-using sectors (such as domestic water supply, energy, and agriculture). The results shed light on any changes in water demands by sector due to changes in water availability in the coming decades.

Using the Global Change Assessment Model (GCAM) to Quantify Impacts of Climate Change

The research questions posed in this paper are focused on quantifying the impacts of climate change, future development scenarios, and intervention policies on water resources throughout the world. This research also lays the groundwork for an analytical tool that can be used to support decisions not only in the scenarios documented in this paper, but other policy and intervention options that may be considered moving forward.

The methodological procedure used in this investigation can be summarized by the following major steps:

- A given climate model is selected as input, providing spatial and temporal distributions of climate variables such as temperature and precipitation.
- These climate variables are used in GCAM to run its water supply (hydrology) submodel (Hejazi et al. 2013, 2014a, 2014b).
- The GCAM numerical solution procedure is based on a partial-equilibrium economics approach that is documented in references such as Edmonds and Reilly (1983), Brenkert et al. (2003), Kim et al. (2006), and Clarke et al. (2007).
- GCAM outputs include water withdrawal (demands) for each of the major water-using

economic sectors (such as food production, energy generation, and municipal supply); these outputs are also used to calculate a water scarcity indicator (WSI).

- These outputs are generated for each one of the modeling scenarios simulated in GCAM (including the reference scenario, SSPs, mitigation scenario, as discussed later in this paper).

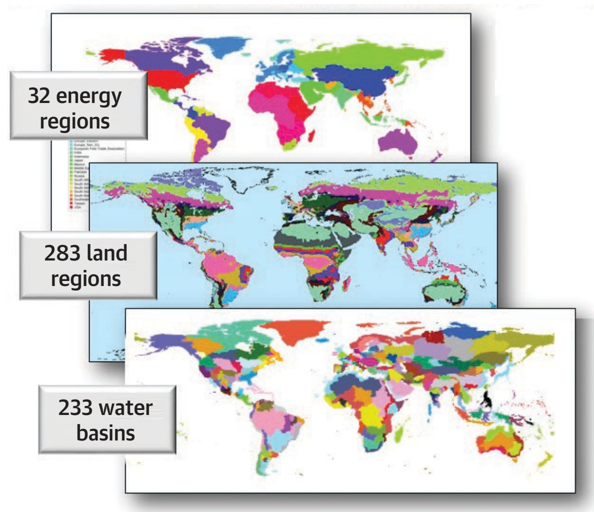
A Brief Description of GCAM

The Global Change Assessment Model (GCAM) is an Integrated Assessment Model (IAM) for exploring consequences and responses to global change.[2] Climate change is a global issue that impacts all regions of the world and all sectors of the global economy. Thus, any responses to the threat of climate change, such as policies or international agreements to limit greenhouse gas emissions, can have wide-ranging consequences throughout the energy system, as well as on water resources, energy generation, food production, land use, and land cover. IAMs endeavor to represent all world regions and all sectors of the economy in an economic framework in order to explore interactions between sectors and understand the potential ramifications of climate change mitigation actions.

A key advantage of GCAM over some other IAMs is that it is a Representative Concentration Pathway (RCP)-class model. This means it can be used to simulate scenarios, policies, and emission targets from various sources, including the Intergovernmental Panel on Climate Change (IPCC).

GCAM is formulated in a dynamic-recursive modeling approach, with technology-rich representations of the economy, energy sector, land use, and water resources linked to climate models that can be used to explore climate change mitigation policies including carbon taxes, carbon trading, regulations, and accelerated deployment of energy technology (map 1). Regional population and labor productivity growth assumptions drive the energy and land-use systems, employing numerous technology options to produce, transform, and provide energy services as well as to produce agriculture and forest products, and to determine land use and land cover. Outputs of GCAM include projections of future energy supply and demand and the resulting greenhouse gas emissions; and radiative forcing and climate effects of 16 greenhouse gases, aerosols, and short-lived species at 0.5×0.5 degree resolution—contingent on assumptions about future population, economy, technology, and climate mitigation policy. On the water side, six major water use sectors are considered: agricultural irrigation, municipal water supply, primary resource extraction (energy/mining), livestock production, electricity generation, and industrial manufacturing.

MAP 1. GCAM Links Economic, Energy, Land-use, Water, and Climate Systems



Representative Concentration Pathways (RCPs)

Representative concentration pathways are used to make assumptions about climate change mitigation levels. RCPs are four greenhouse gas concentration (not emissions) trajectories adopted by the IPCC for its fifth Assessment Report (AR5) in 2014 (Moss et al. 2008). They describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases are emitted in the years to come. The four RCPs—RCP2.6, RCP4.5, RCP6.0, and RCP8.5—are named after a possible range of radiative forcing values in the year 2100 relative to preindustrial values (increases of +2.6, +4.5, +6.0, and +8.5 W/m^2, respectively) (Weyant et al. 2009).

The RCPs are consistent with a wide range of possible changes in future anthropogenic (man-made) GHG emissions. RCP2.6 assumes that global annual GHG emissions (measured in CO_2-equivalents) peak between 2010 and 2020, with emissions declining substantially thereafter. Emissions in RCP4.5 peak around 2040, then decline. In RCP6.0, emissions peak around 2080, then decline. In RCP8.5, emissions continue to rise throughout the twenty-first century.

For the purposes of this study, a "no climate policy" reference scenario has been implemented in GCAM to reflect "reference" or baseline efforts toward climate mitigation. RCP4.5 is used as a "climate policy" scenario to reflect the implementation of climate mitigation policies in GCAM simulations.

Water Scarcity Index

The Water Scarcity Index (WSI) for a given GCAM simulated scenario is determined as follows:

- Water demands (total water withdrawals) are simulated in GCAM; these results are downscaled to the grid scale and mapped up to country scale.
- The hydrology (water supply) module in GCAM is used to generate runoff estimates using climate information from the three GCMs—CCSM, GISS, and FIO-ESM—at the basin level.[3]
- The surface runoff generated is mapped up to the country scale.
- The total inflow into each country is calculated as the sum of available surface runoff and groundwater resources; groundwater data are obtained from the FAO's Aquastat database.[4]
- Runoff and inflow data are aggregated from monthly to average annual estimates.
- The WSI for each country is calculated (annually) as:

$$WSI = \frac{Demands}{Runoff + Inflow}$$

A water scarcity index value of 0.4 or higher ($WSI \geq 0.4$) is used in this study to denote severe scarcity; ($0.2 \leq WSI < 0.4$) denotes moderate scarcity; ($0.1 \leq WSI < 0.2$) denotes low scarcity; and ($WSI<0.1$) denotes no scarcity, or abundant water resource availability in a country as compared with water demands.

Global Climate Models (GCMs)

For this study, three different Global Climate Models (GCMs) are selected to represent different climate model assumption and formulations, in an effort to provide a robust envelope of impacts of climate change on water resources and the corresponding analysis of results.

CCSM. The Community Climate System Model[5] is a GCM developed by the University Corporation for Atmospheric Research (UCAR). The coupled components include an atmospheric model (Community Atmosphere Model), a land-surface model (Community Land Model), an ocean model (Parallel Ocean Program), and a sea ice model (Community Sea Ice Model) (Hoffman 2006).

GISS. The Goddard Institute for Space Studies[6] GCM is primarily aimed at the development of coupled atmosphere-ocean models for simulating Earth's climate system. Primary emphasis is placed on investigation of climate sensitivity globally and regionally, including the climate system's response to diverse forcings such as solar variability, volcanoes, anthropogenic and natural emissions of greenhouse gases and aerosols, and paleoclimate changes. A major focus of GISS GCM simulations is to study the human impact on the climate, as well as the effects of a changing climate on society and the environment.

FIO-ESM. The FIO Earth System Model[7] is a GCM developed by the First Institute of Oceanography in China. It includes an ocean surface wave model in addition to atmosphere, ocean, land, and ice components, and is coupled with a simulation model of the fully global carbon cycle process and its interactions with the climate system. The historical simulation of the global carbon cycle follows the design of the CMIP5 (Climate Model Inter-comparison Project Phase 5) long-term simulation experiments.[8] The simulation results are used to evaluate the performance of the model, including the atmosphere, ocean, land surface, and biogeochemical process of the ocean and terrestrial ecosystems.

Shared Socioeconomic Pathways (SSPs)

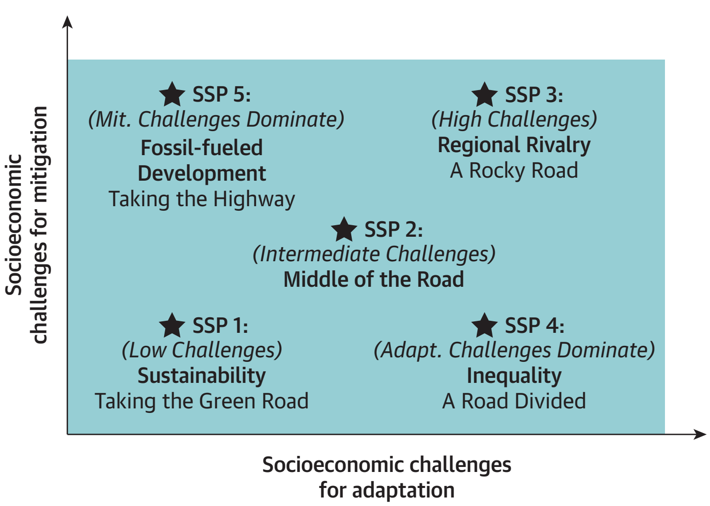
Long-term scenarios play an important role in research on global environmental change. The climate change research community is developing new scenarios integrating future changes in climate and society to investigate climate impacts as well as options for mitigation and adaptation. One component of these new scenarios is a set of alternative futures of societal development known as the shared socioeconomic pathways (SSPs). The conceptual framework for the design and use of the SSPs calls for the development of global pathways describing the future evolution of key aspects of society that would together imply a range of challenges for mitigating and adapting to climate change.

O'Neill et al. (2015) present the "SSP narratives," a set of five qualitative descriptions of future changes in demographics, human development, economy and lifestyle, policies and institutions, technology, and environment and natural resources. Development of the narratives drew on expert opinion to identify key determinants of these challenges that were essential to incorporate in the narratives, and combine these elements in the narratives in a manner consistent with their interrelationships. The narratives are intended as a description of plausible future conditions at the level of large world regions that can serve as a basis for integrated scenarios of emissions and land use, as well as analyses of climate impact, adaptation, and vulnerability.

Within the conceptual framework for integrated scenarios, the SSPs are designed to span a relevant range of uncertainty in societal futures. Unlike most global scenario exercises, the relevant uncertainty space that the SSPs are intended to span is defined primarily by the nature of the outcomes, rather than the inputs or elements that lead to these outcomes. Therefore, the SSP outcomes are specific combinations of socioeconomic challenges to mitigation and socioeconomic challenges to adaptation. That is, the SSPs are intended to describe worlds in which societal trends result in making mitigation of, or adaptation to, climate change harder or easier, without explicitly considering climate change itself. The SSPs used for this study are illustrated in figure 2.

Figure 3 shows key assumptions made by the five SSPs of future global population, GDP, and GDP per capita,

FIGURE 2. Shared Socioeconomic Pathways (SSPs) Representing Different Combinations of Challenges to Mitigation and Adaptation



Source: adapted from O'Neill et al. 2015.

FIGURE 3. **Global Population, GDP, and GDP per capita Made by Each of the Five SSPs**

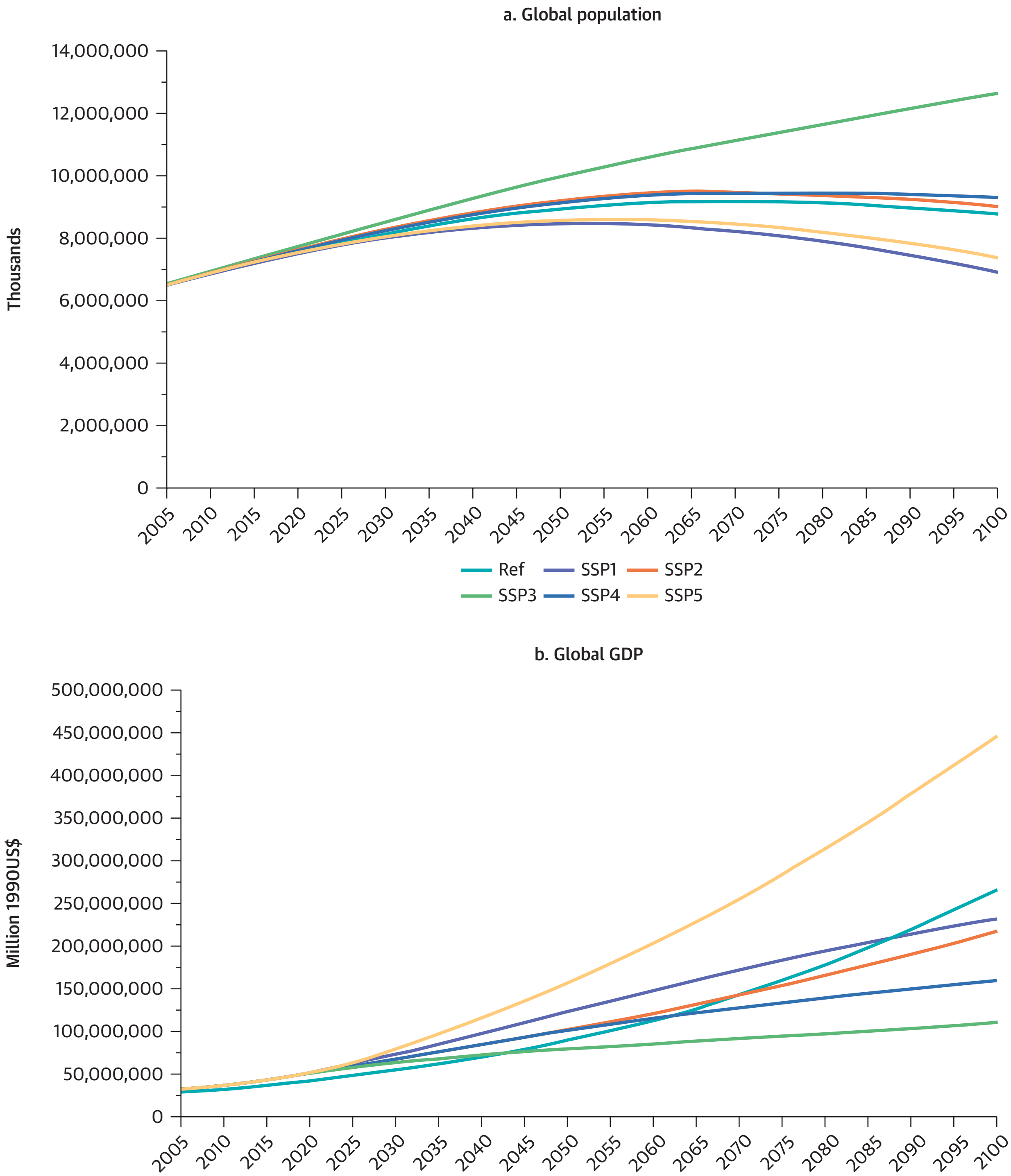


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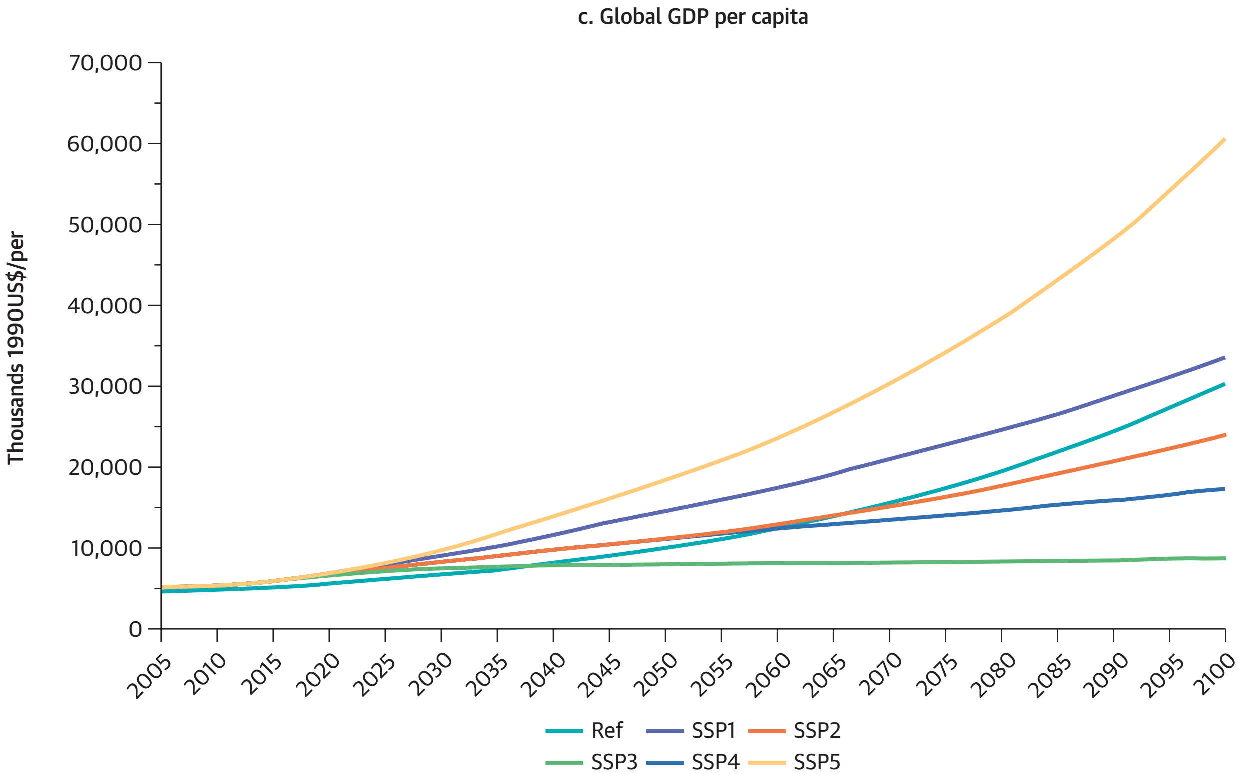
FIGURE 3. continued



Note: Ref = reference scenario; SSP = Shared Socioeconomic Pathway.

which were used as inputs for the GCAM simulations. Table 1 summarizes socioeconomic data assumed by the SSPs.

Globally, total runoff volume is confidently estimated to remain relatively constant throughout the 21st century. However, runoff is likely to decline substantially in some countries and regions, including Russia, Central Asia, Central Africa, and the Middle East.

Results and Discussion

Estimates of total annual runoff volume for the three GCMs used in this study are shown in figure 4. This is the sum of the runoff generated for the 233 water basins around the world in GCAM. The figure shows that the three different climate models agree that there is not a significant trend (upward or downward) of the total runoff volume generated; this suggests that the amount of surface water globally will remain practically fixed throughout the coming decades.

These results underscore a main message that freshwater is a finite resource with multiple uses, and thus requires careful management with due consideration of issues of water quality and efficiency.

While the total global runoff volume, an indicator of overall water availability may not vary significantly over the next decades, there are some variations worth noting among regions and countries.

Map 2 displays estimated runoff depth around the world, as predicted by the three GCMs for the year 2050 (maps showing changes to 2100 were generated,

TABLE 1. Shared Socioeconomic Pathways as Implemented in GCAM

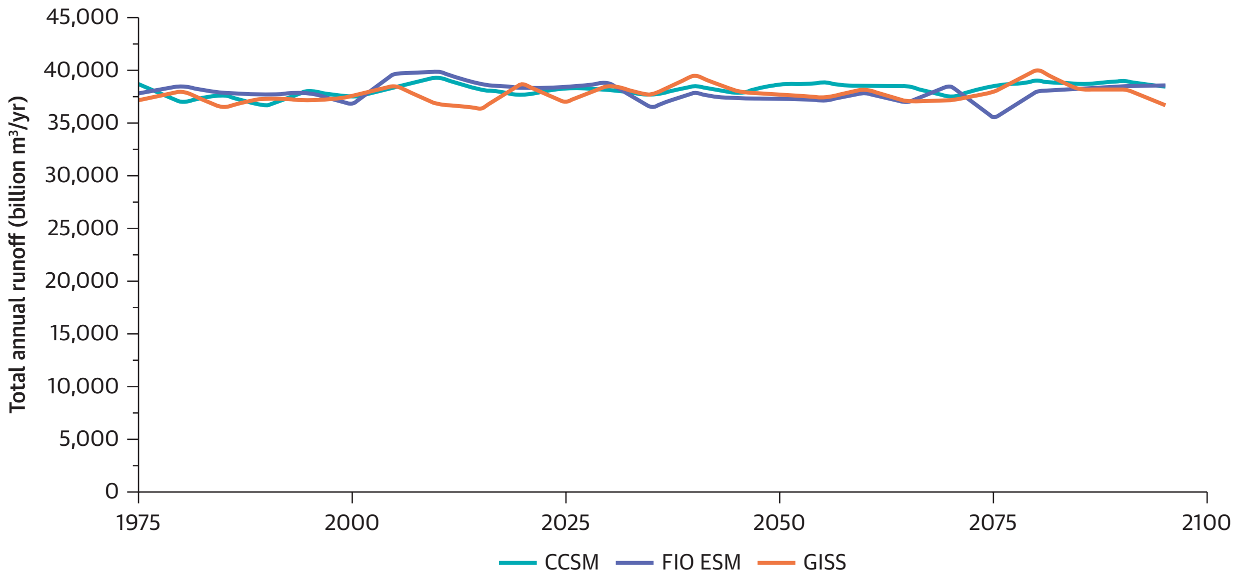
		SSP1	SSP2	SSP3	SSP4			SSP5
					High-income	Medium-income	Low-income	
Socioeconomics	Population in 2100	6.9 billion	9 billion	12.7 billion	0.9 billion	2.0 billion	6.4 billion	7.4 billion
	GDP per capita in 2100	$46,306	$33,307	$12,092	$123,244	$30,937	$7,388	$83,496
Fossil resources (technological change/acceptance)	Coal	Med/Low	Med/Med	High/High	Med/Low	Med/Med	Med/High	High/High
	Conventional gas and oil	Med/Med	Med/Med	Med/Med	High/Low	High/Low	High/Low	High/High
	Unconventional oil	Low/Med	Med/Med	Med/Med	Med/Low	Med/Low	Med/Low	High/High
Electricity (technology cost)	Nuclear	High	Med	High	Low	Low	Low	Med
	Renewables	Low	Med	High	Low	Low	Low	Med
	CCS	High	Med	Med	Low	Low	Low	Low
Fuel preference	Renewables	High	Med	Med	High	High	High	Med
	Traditional biomass	Low	Low	High	Low	Low	High	Low
Energy demand (service demands)	Buildings	Low	Med	Low	High	Med	Low	High
	Transportation	Low	Med	Low	High	Med	Low	High
	Industry	Low	Med	Low	High	Med	Low	High
Agriculture and land use	Food demand	High	Med	Low	High	Med	Low	High
	Meat demand	Low	Med	High	Med	Med	Med	High
	Productivity growth	High	Med	Low	High	Med	Low	High
	Trade	Global	Global	Global	Regional	Regional	Local	Global
	SPA policy				Afforestation	Limited afforestation	No land policy	
Pollutant emissions	Emissions factors	Low	Med	High	High	High	High	Low

Note: Med = medium; SPA = [Shared Policy Assumption].

but are excluded for brevity). Runoff depth, measured as total runoff divided by total land area, provides a better means of comparing runoff trends among countries than measuring runoff in water volume because it allows for large countries to be compared with smaller countries. Some trends can be summarized as follows:

- North America. There are no major variations in runoff; the overall trend is for a small decrease in runoff in Canada and the United States, but some simulations (CCSM and GISS) project small increases for the United States by 2050.
- Central America. There is a consistent trend toward diminishing runoff across all three models. There is significant disagreement between the models on runoff in South America, with two of the three (CCSM and FIO) predicting relatively stable runoff patterns throughout the continent, but GISS predicting extreme short falls in runoff in Brazil, Colombia, Ecuador, Peru, and República Bolivariana de Venezuela.
- Europe and Central Asia. There is a consistent trend toward lesser runoff in all model simulations, with the Russian Federation showing a sharp decrease in runoff in the second half of the century.
- East Asia. The runoff profile is relatively stable and high (particularly in the Pacific). All simulations project runoff decreases in China. Two (CCSM and GISS) out of

FIGURE 4. Estimates of Global Runoff Generation Using the CCSM, FIO, and GISS Climate Models

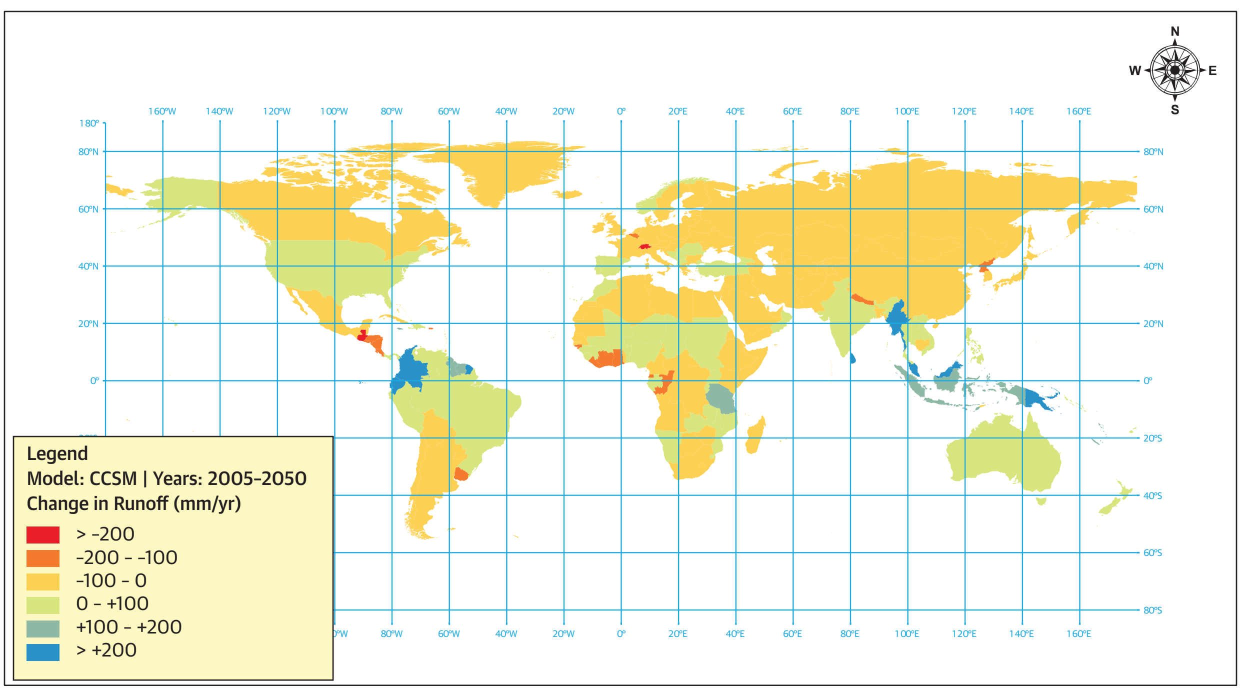


Note: Global runoff generation reflects the sum for all countries. CCSM = Community Climate System Model; FIO-ESM = First Institute of Oceanography Earth System Model; GISS = Goddard Institute for Space Studies Model.

MAP 2. Change in Global Runoff by Country 2005–50

mm/year

a. CCSM (Community Climate System Model)



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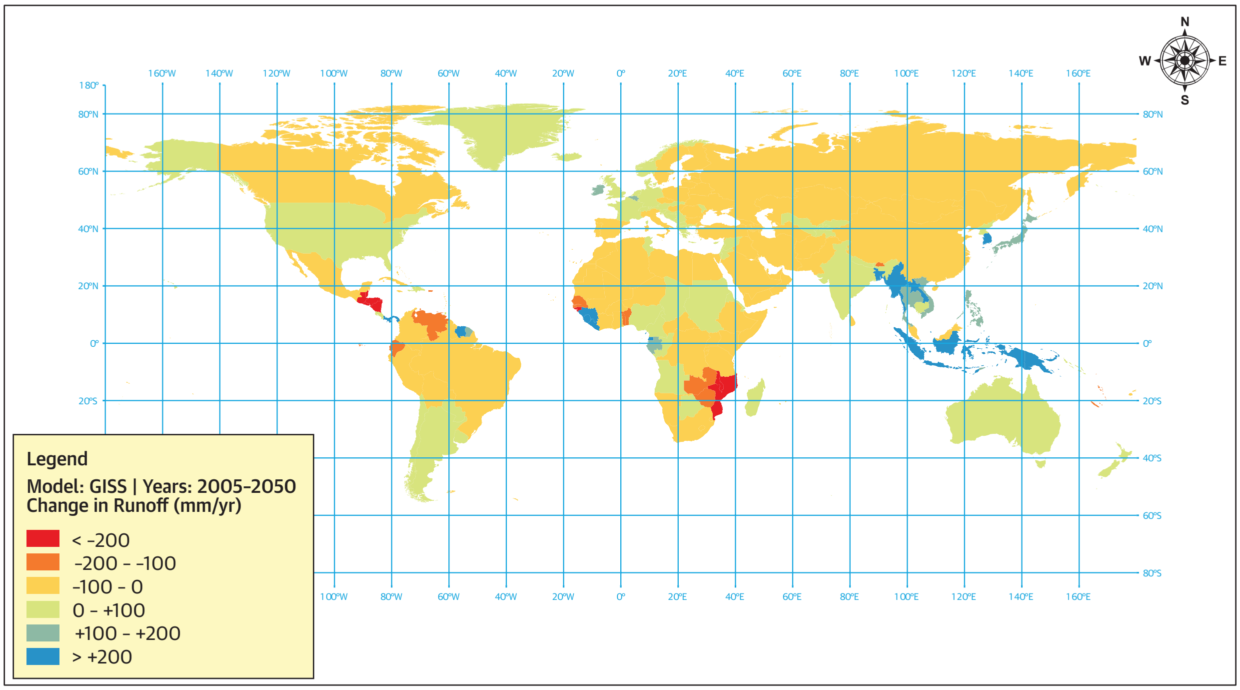
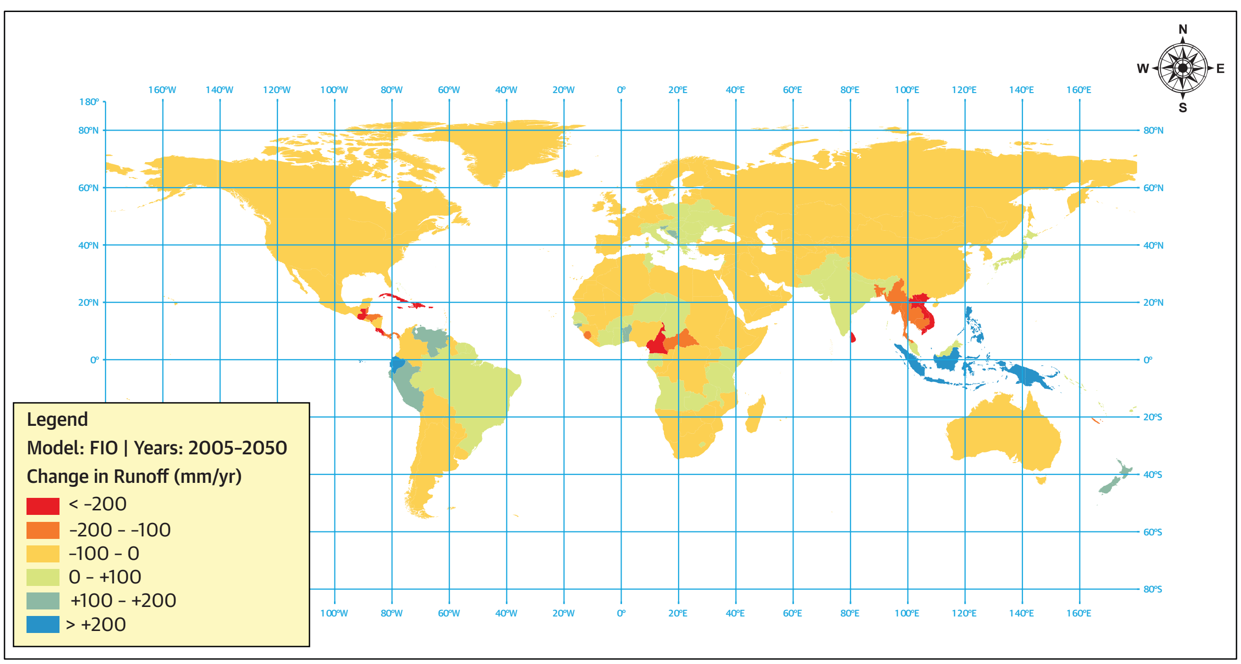
MAP 2. continued

b. GISS (Goddard institute for space studies) model



c. FIO-ESM (First Institute of Oceanography Earth System Model)



the three climate model simulations in GCAM show a decreasing trend in runoff for Bangladesh, Cambodia, Lao PDR, Myanmar, Thailand, and Vietnam.

- India. The results are mixed. Simulation results for South Asia show runoff projections for India increasing during the second half of the century when using the CCSM climate model as input. Using the FIO as input results in a fairly stable runoff generation rate. Using GISS as climate model input results in a slight decrease in runoff for India as early as 2025 that continues in the second half of the century.

- Middle East and North Africa. There is a consistent trend toward decreasing runoff to the lower runoff ranges. The Islamic Republic of Iran appears to be somewhat of an exception; its runoff generation rate is more or less stable (but still in the low range, always below 200 mm/yr).

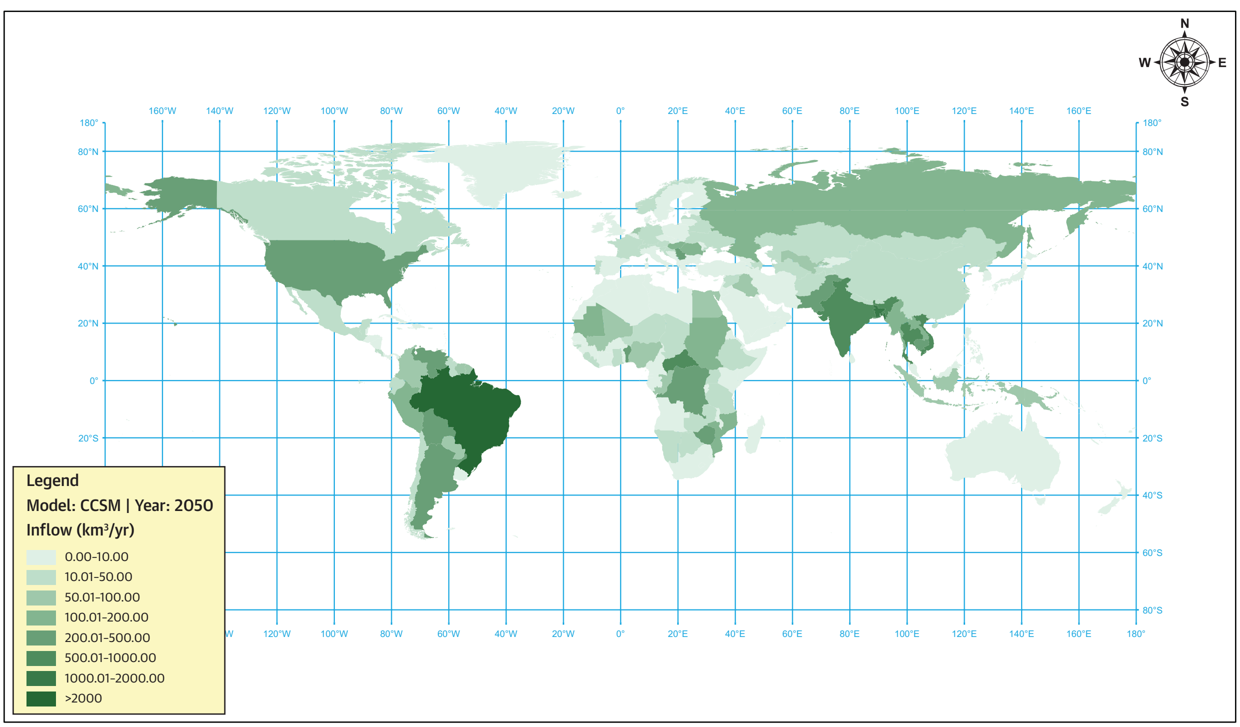
- Africa. There is a greater variation of runoff generation. In the southern part of the continent, countries like South Africa and Botswana show a consistent trend toward lesser runoff. Countries in the lower latitudes (20N to 20S) exhibit small variations in runoff (less than +/- 100 mm/yr) in general. The GISS model input produces larger decreases in runoff toward the second half of the century in the Central African Republic, the Democratic Republic of Congo, Malawi, Mozambique, Tanzania, Zambia, and Zimbabwe.

Projected Volumetric Inflow

The rate of volumetric inflow into each country is presented in map 3 for each of the climate models for the year 2050. Volumetric inflow accounts for streamflow

MAP 3. Inflow Distribution by Country, 2050
(km^3/year)

a. CCSM (Community Climate System Model)



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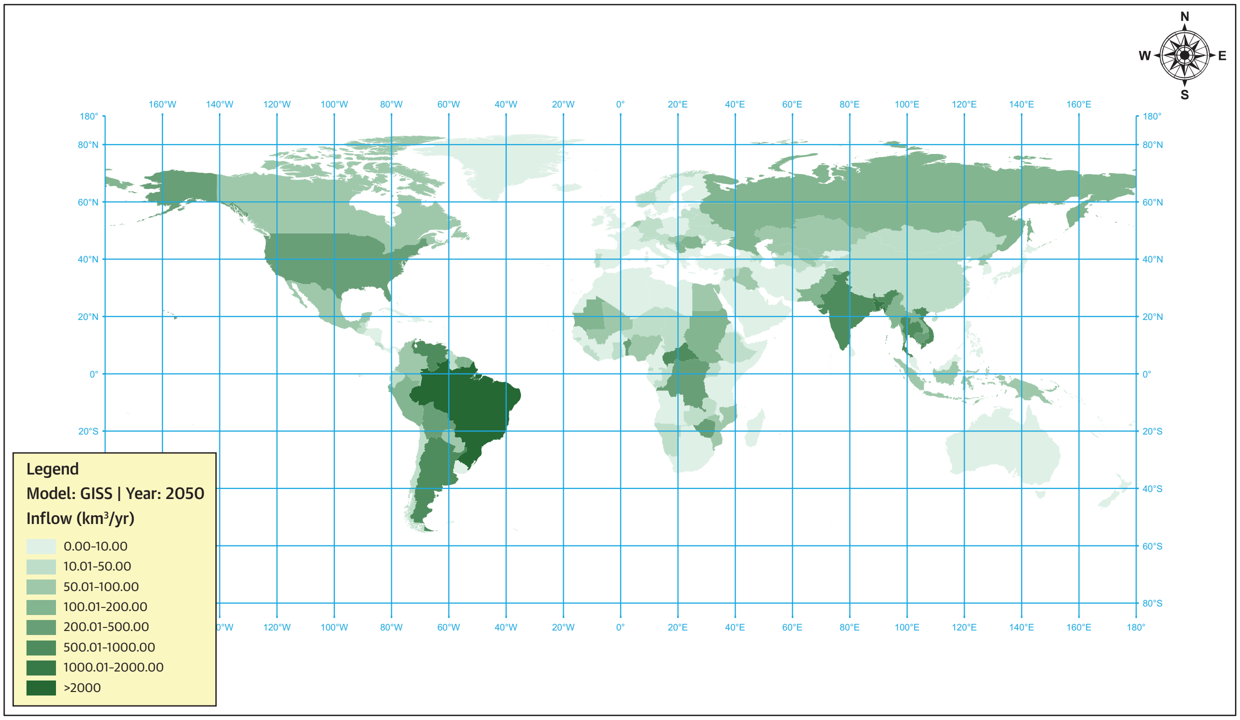
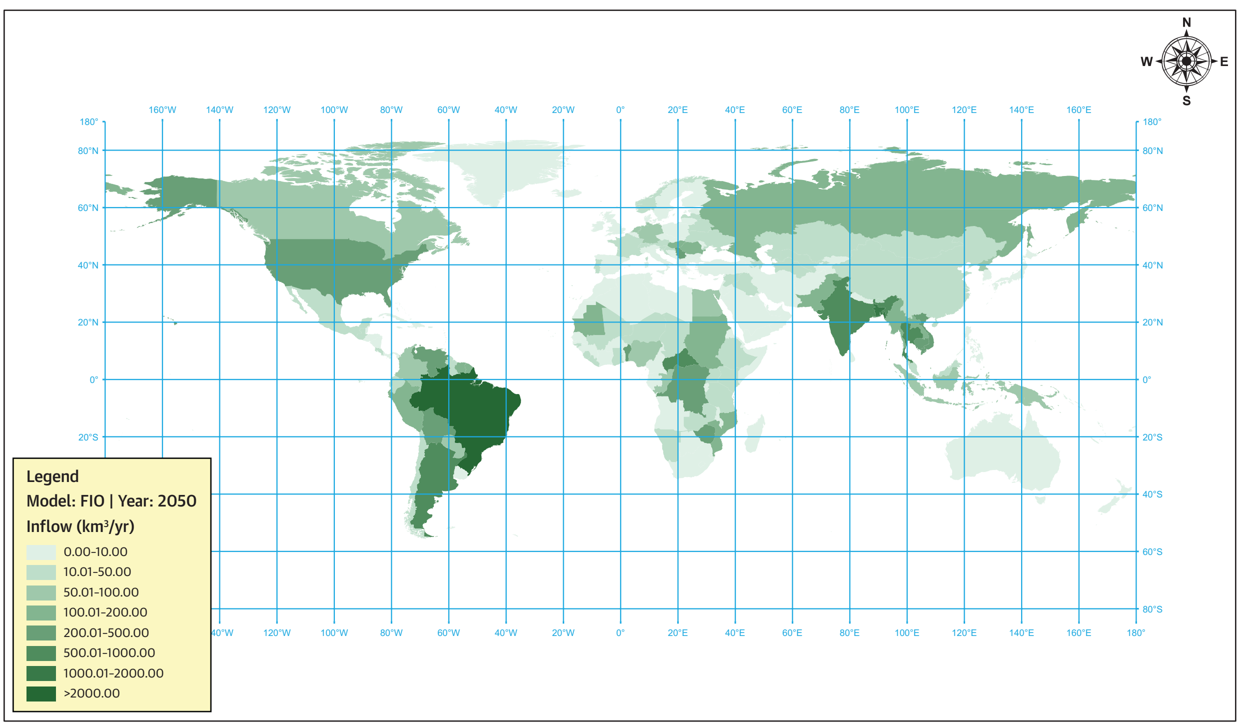
MAP 3. continued

b. GISS (Goddard Institute for Space Studies) Model



c. FIO-ESM (First Institute of Oceanography Earth System Model)



in rivers crossing from one country to another, plus the contribution of groundwater storage within a basin (or country). Because of this, inflow is more of a hydraulic process than a hydrologic one. This means that the inflow flux is driven more by land surface features (such as soil type, land use, geology, and geomorphology) than by climate (which has a primary influence on the rate of runoff generation through its relationship with rainfall and temperature); thus the results for inflow into countries show lesser dependence on the climate model used.

Projected Water Scarcity

Finally, the reference (business-as-usual) scenario for these GCAM simulations is used to portray the current and future status of water stress/scarcity around the world without the introduction of climate mitigation policies. Map 4 shows the simulation results for the Water Scarcity Index (WSI) in the reference scenario, comparing years 2005, 2025, 2050, and 2095.

Global trends in water demand and water scarcity will be strongly affected by socioeconomic factors, with a significant majority of water going to irrigated agriculture.

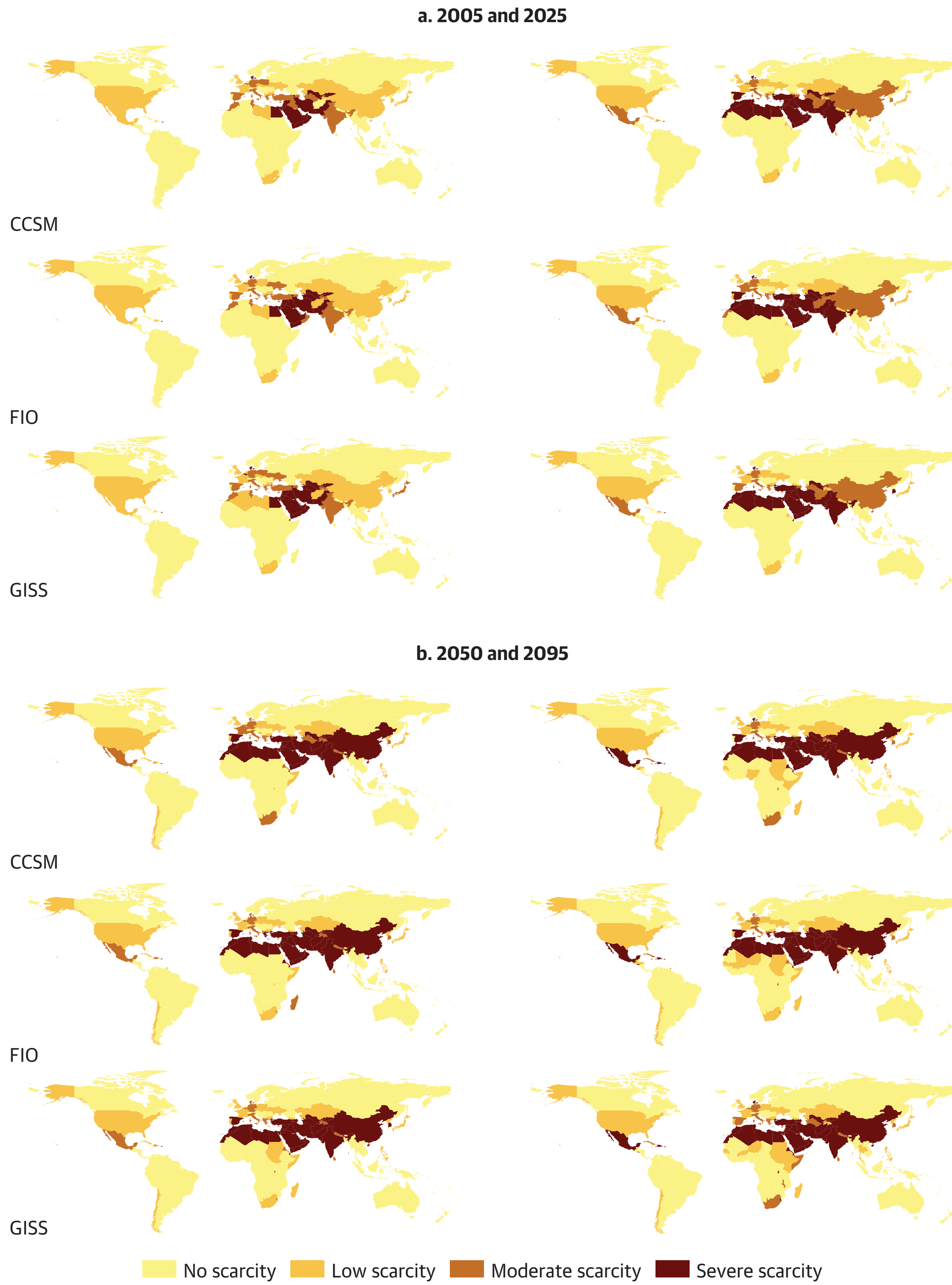
These results illustrate three key trends in the WSI. First, there is a general trend upward in water scarcity in the majority of countries of the world; this is reasonable to expect given increased pressure in water resources (increased demand) as a result of population growth, development, and other factors. Second, the WSI results appear to be fairly consistent across the three climate models used; this suggests that water scarcity is dominated by water demands rather than by the climate-influenced water availability (surface and groundwater). Finally, it appears that severe and moderate water scarcity around the world will increase significantly within the next few decades (between 2025 and 2050), particularly in countries such as China, India, and Mexico, and the Middle East and North Africa (MENA) region.

The Socioeconomic Impacts of Future Development Scenarios on Water Scarcity

In order to determine the socioeconomic impacts of future development scenarios on water scarcity, both the future supply and demand of water are estimated and compared, to determine regions where water scarcity may arise. Hydrologic inputs (supply) into the WSI calculation (runoff and inflows) come from the three GCMs used in the prior section, while water demands are dictated by the SSP scenarios simulated. These water demands are summarized in figure 5, broken down by water demand sector. SSP1 results in a curbing of water demand starting in the year 2050, and the decrease occurs across all demand sectors. SSP2 results show an increase in water demand followed by a plateau toward 2070 and a very slight decrease in water demand across all sectors toward the end of the simulation period in 2095. SSP3 results show, as expected, a continuous increase in water demand across all sectors, with particular strong growth in irrigation water use. SSP4 results shows a water demand that plateaus starting in 2060, a similar trend to that found in SSP2. However, SSP4 stabilizes at lower values than those in SSP2, reflecting the lesser energy generation and use of water in SSP4; increased efforts for mitigation reduce the pressure over water resources.

This effect is further illustrated in figure 6, which displays total global water demand across the five SPs, as well as water demand for three select sectors: agriculture, electricity, and municipal use. Starting with total water use, the image shows that there is a very large plausible range of water demand by 2100, ranging from 4,500 billion km^3/year for SSP1 to 6,500 billion km^3/year for SSP3 and SSP5. This implies that future global demand for water is highly dependent on socioeconomic factors. For irrigation, the range is much tighter between the five SSPs, implying that socioeconomic factors will not play a large role in

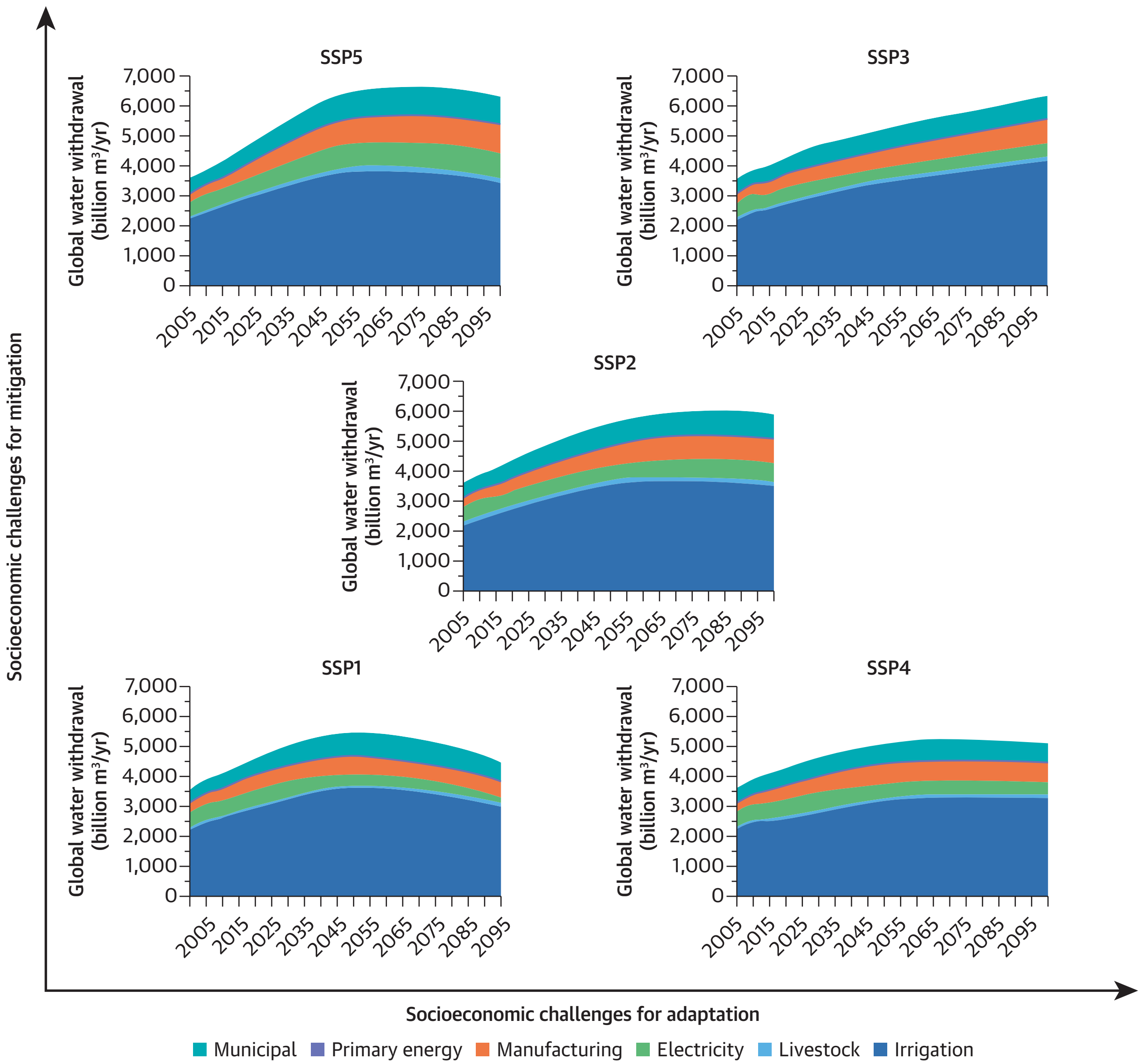
MAP 4. **Water Scarcity Indicator per Country**



Note: CCSM = Community Climate System Model; FIO = First Institute of Oceanography Earth System Model; GISS = Goddard Institute for Space Studies Model.

FIGURE 5. Water Demand (Global Water Withdrawal) for the Five SSPs and Broken Down by Major Water-using Sectors

billion m³/year

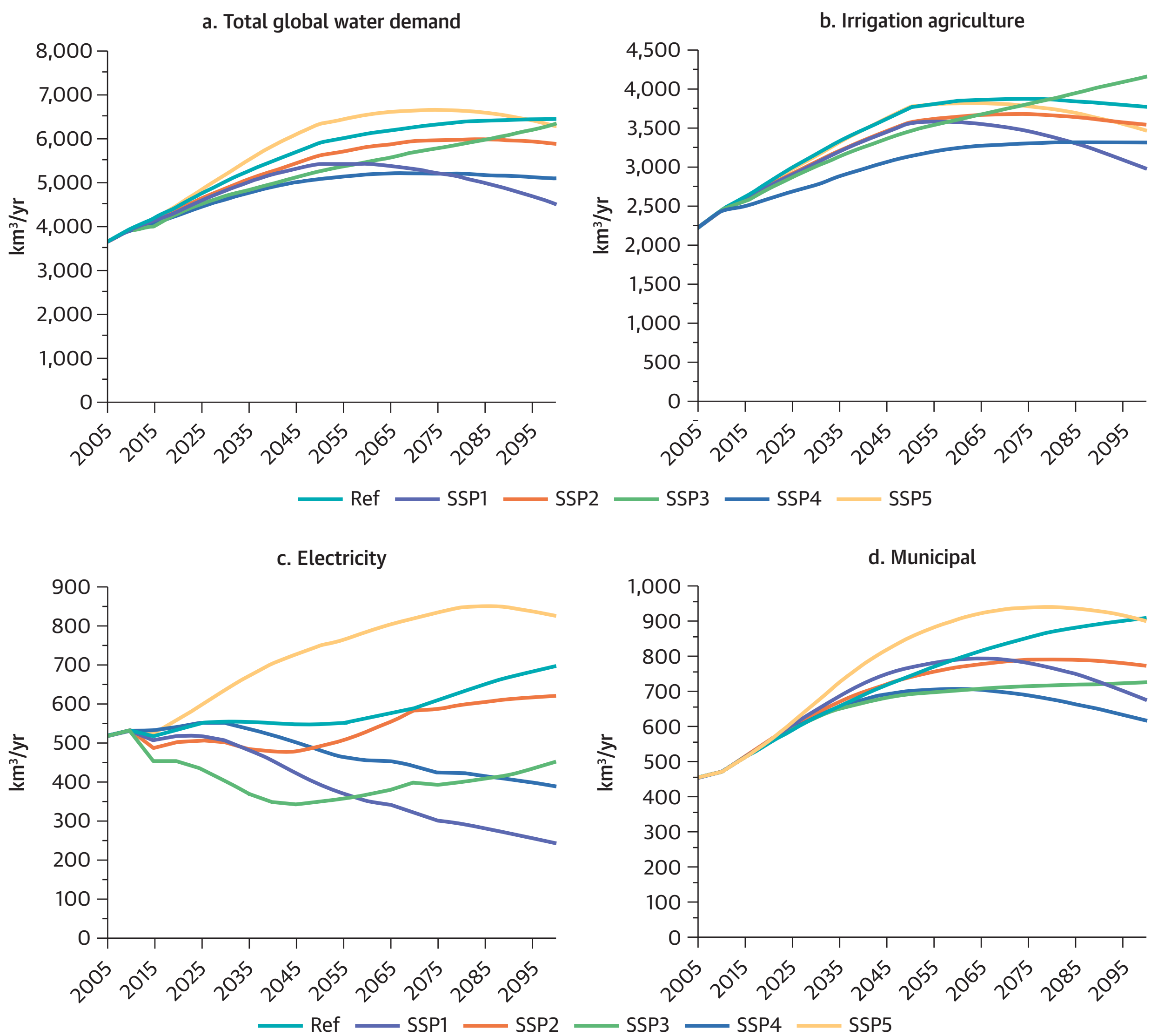


Note: SSP = Shared Socioeconomic Pathway.

determining agricultural water use. Global water use for electricity generation, on the other hand, shows a very large spread between SSP1 and SSP5, with a nearly 300 percent increase in water withdrawal predicted for the latter scenario over the former by the year 2100. This is driven mostly by the assumption of a much larger size of the economy implicit in SSP5.

The relationship between the SSPs and the key water-using sectors—energy and food—is illustrated in figure 10.

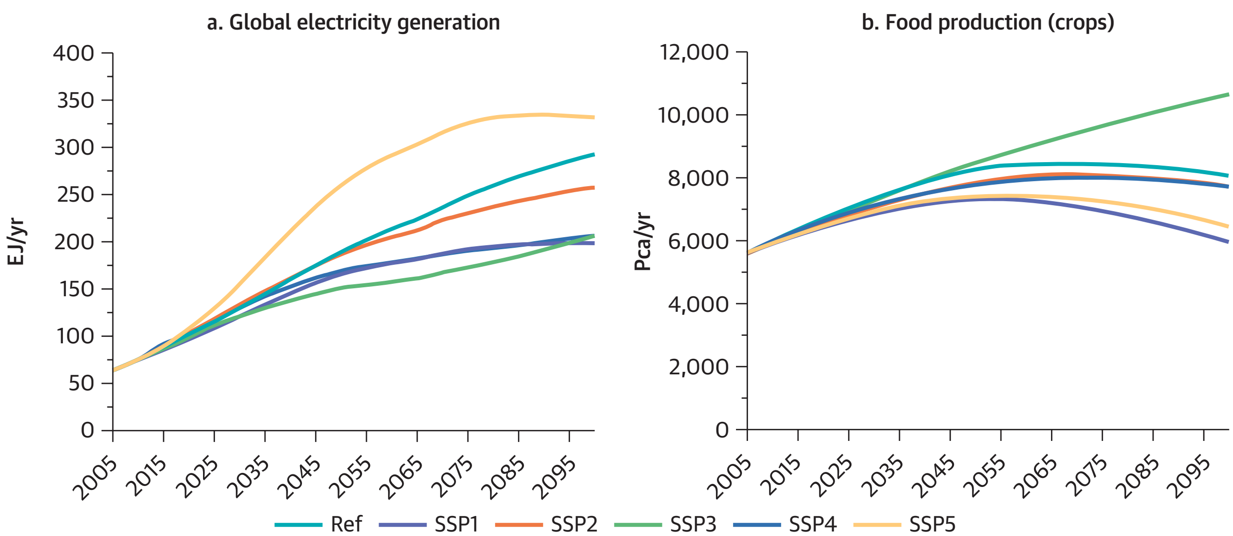
FIGURE 6. Water Demand (Global Water Withdrawal) across Five SSPs, by Sector



Note: Ref = reference scenario; SSP = Shared Socioeconomic Pathway.

Global generation of electricity tends to follow a similar pattern to that of the water demand for electricity shown in figure 6. The levels of energy production is significantly greater in SSP5 than in the other four scenarios, again because of the assumption of a much larger economy. It is interesting to note that SSP1, SSP3, and SSP4 all predict similar levels of energy production throughout the twenty-first century. However, as figure 6 shows, SSP1 predicts significantly less water consumption in the electricity sector than the other SSPs. Water demand for global food production tapers off and then declines in all scenarios (SSP1 and SSP5 circa 2050, SSP2 and SSP4 circa 2070) except for SSP3. This is mostly consistent with the irrigation water use trends shown in Figure 6.

FIGURE 7. Energy and Food Production at the Global Scale for the Different SSPs



Note: Ref = reference scenario; SSP = Shared Socioeconomic Pathway.

Projected Effects of Mitigation Policies

Simulations show that mitigation policies that reduce greenhouse gas concentrations throughout the 21st century will have little impact on water scarcity.

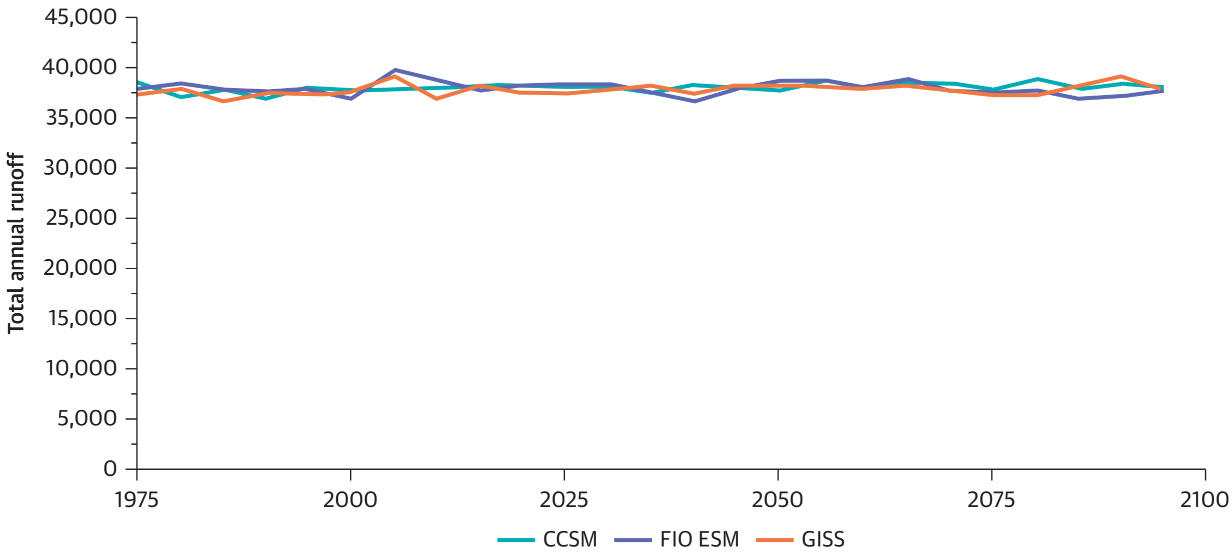
Finally, two simulation scenarios are compared to determine the potential effects that mitigation policies may have on future water scarcity. Under the "no mitigation policy" scenario (SSP1) water demand follows a trajectory that reaches 6.0 W/m^2 in 2100, while water supply is calculated using climate scenario RCP6.0. Under a "mitigation policy" scenario (SSP1 with a mitigation policy), water demand follows a trajectory that reaches 4.5 W/m^2 in 2100, while water supply is calculated using climate scenario RCP4.5.

Figure 8 shows the estimates of total annual runoff volume for the three GCMs used in this study, under a climate mitigation policy scenario. When these results are compared to those presented in figure 4 for the GCAM reference scenario, the global amount of runoff generated is practically the same. The difference in radiative forcing between implementing a climate change mitigation policy (6.0 W/m^2) and not (4.5 W/m^2) is not large enough to result in a significant difference in total water supply. As in the results for the no mitigation policy case, implementing a climate policy with RCP4.5 does not result in a significant trend (upward or downward) of the total runoff volume generated, suggesting that the amount of surface water globally remains practically fixed throughout the coming decades. Map 5 displays the spatial distribution of runoff depth around the world under a climate mitigation policy, showing some variations worth noting among regions and countries.

When there are no constraints on water demands, the results represent a response to changes only in demand and energy from the mitigation policy put in place. Since SSP1 is a sustainable scenario—and without a climate policy the radiative forcing is 6.0 W/m^2, while with the policy it is 4.5 W/m^2—the difference in forcing is not large enough in this scenario and the results do not show a dramatic difference in total water demand (figure 9).

FIGURE 8. Estimates of Global Runoff Generation using the CCSM, FIO, and GISS Climate Models under a Climate Mitigation Policy

billion m³/year

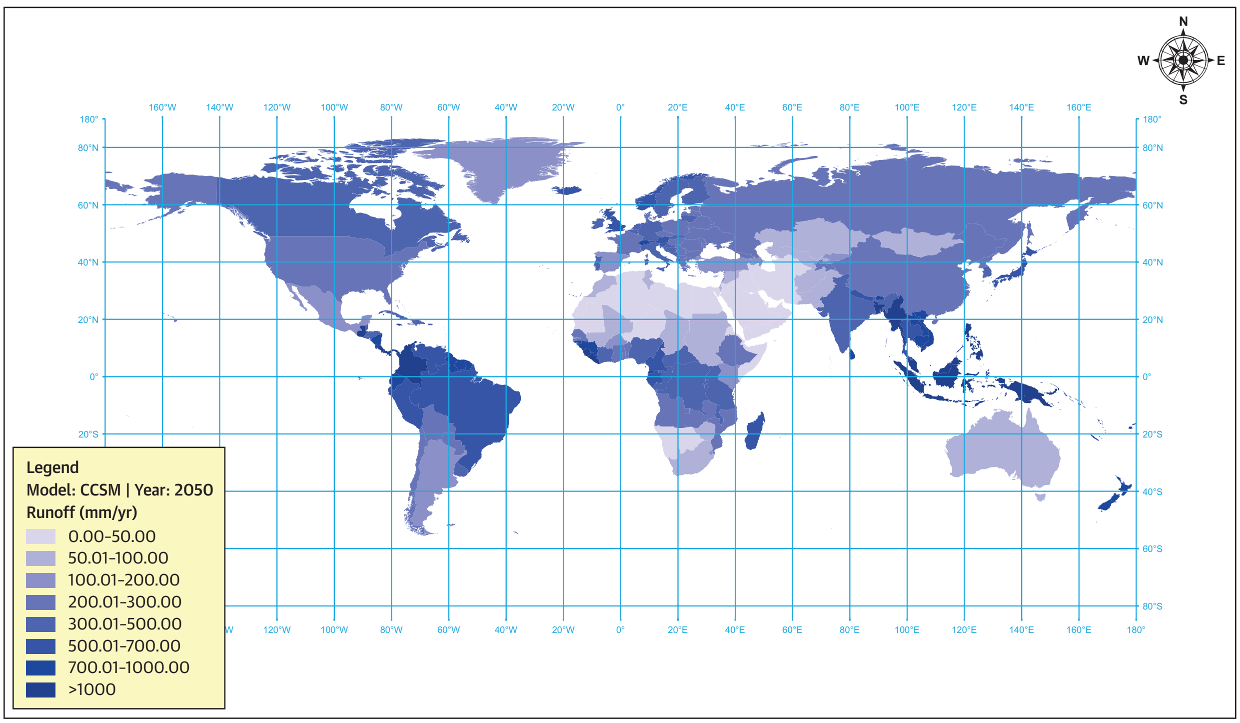


Note: The estimates include the sum for all countries. CCSM = Community Climate System Model; FIO-ESM = First Institute of Oceanography Earth System Model; GISS = Goddard Institute for Space Studies Model.

MAP 5. Distribution of Changes in Global Runoff by Country, under a Climate Mitigation Policy, Projected using Climate Models CCSM, GISS, and FIO, Year 2050,

mm/year

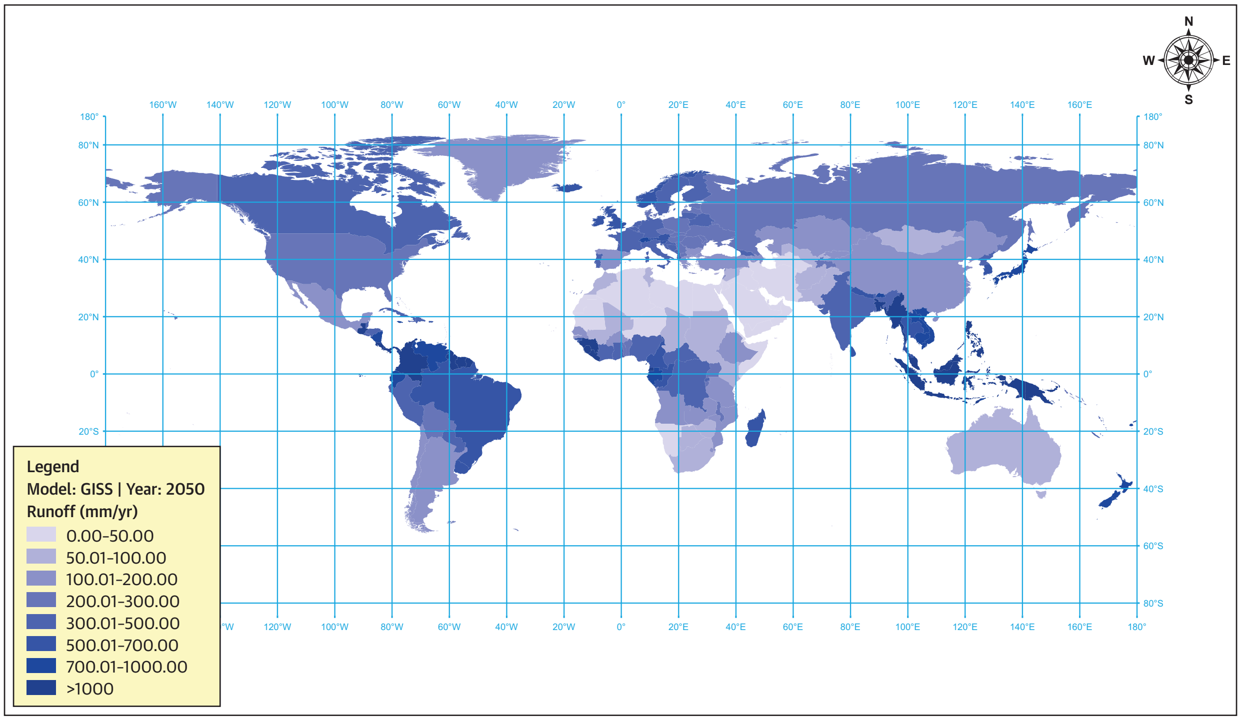
a. CCSM (Community Climate System Model)



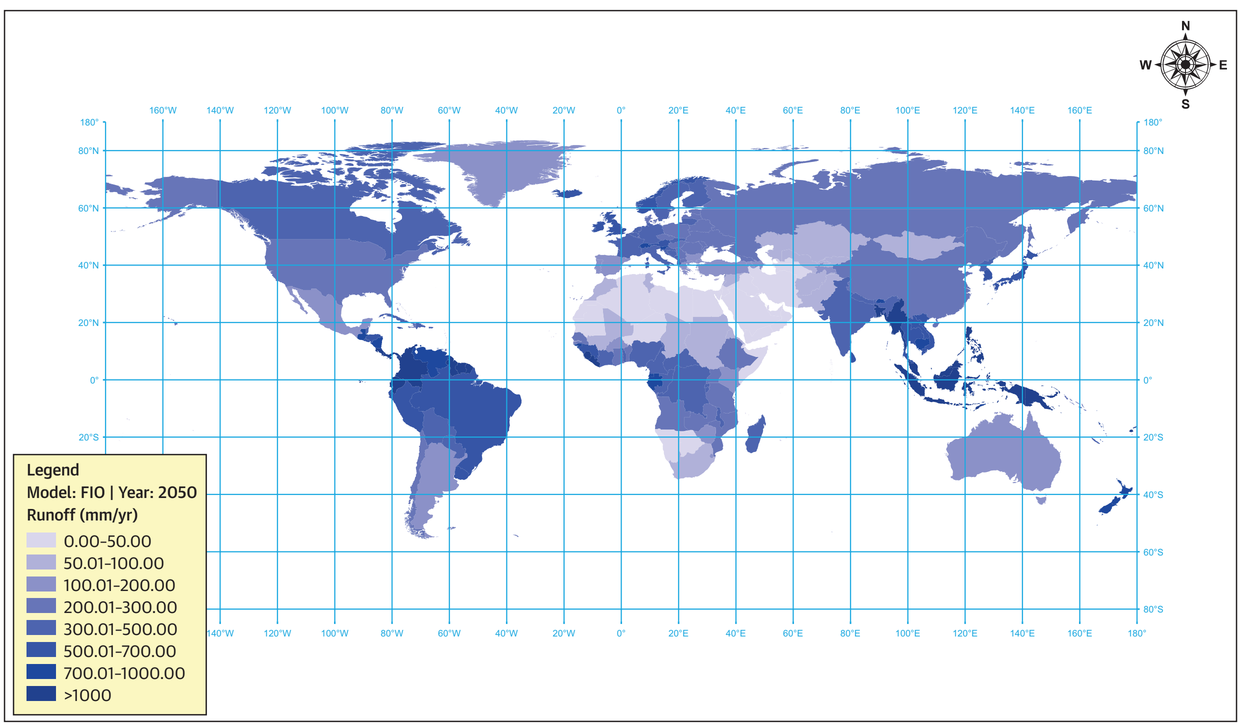
Map continues next page

MAP 5. continued

b. GISS (Goddard Institute for Space Studies) Model

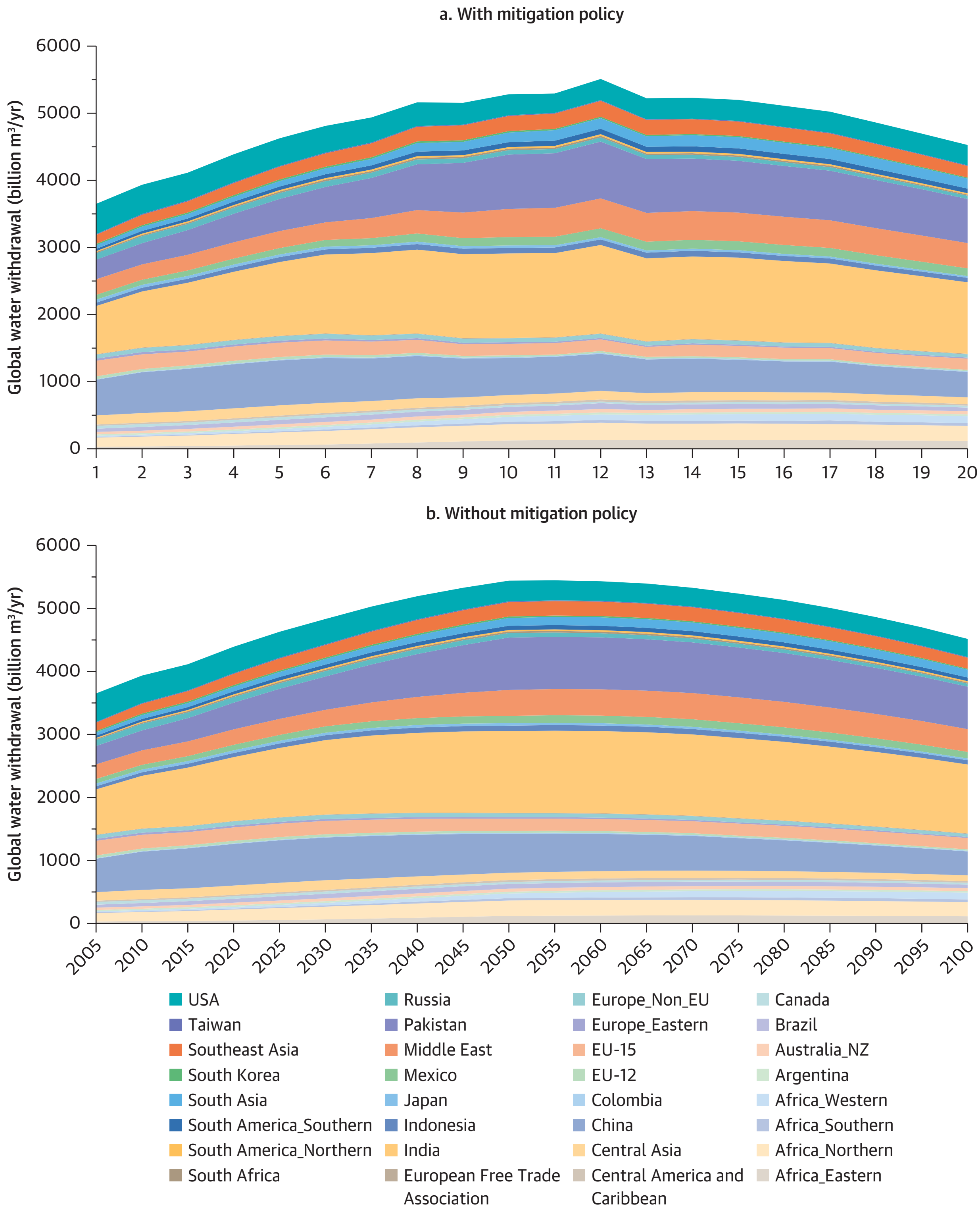


c. FIO-ESM (First institute of oceanography earth system model)



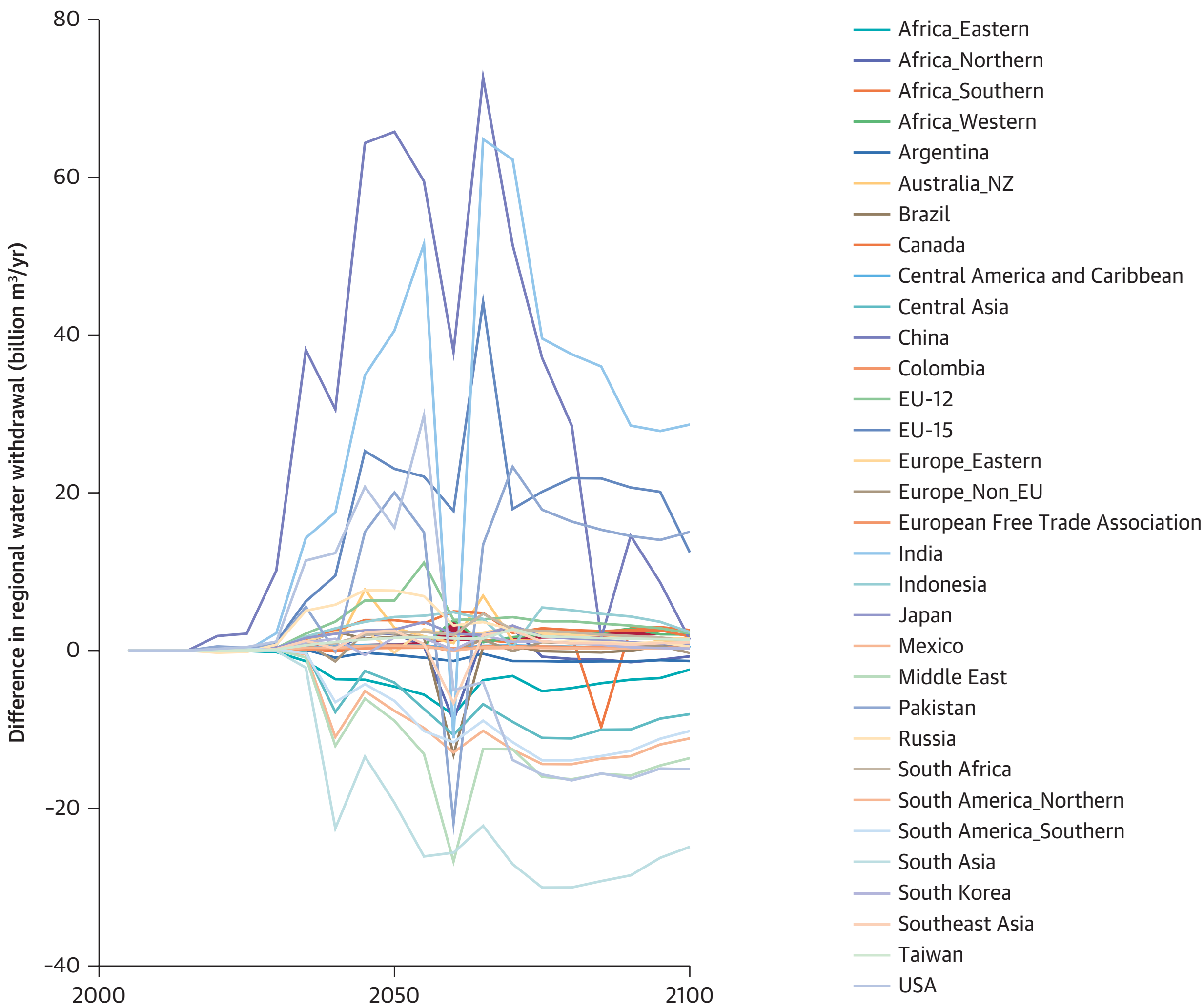
Note: CCSM = Community Climate System Model; FIO-ESM = First Institute of Oceanography Earth System Model; GISS = Goddard Institute for Space Studies Model.

FIGURE 9. Global Water Withdrawal under SSP1 in Mitigation Policy and a No Mitigation Policy Scenarios



Note: SSP = Shared Socioeconomic Pathway.

FIGURE 10. Difference in Global Water Withdrawal under SSP1 between Mitigation Policy and No Mitigation Policy Scenarios for the 32 GCAM Regions



Note: Difference = No mitigation policy (Reference) – Mitigation policy. EU = European Union.

Global water withdrawals actually decrease slightly with the mitigation policy implemented, but some regions of the world decrease while others increase, as is shown in figure 10. China and India see significant increases in water use as a result of the mitigation policy, while the rest of South Asia (excluding India), Western Africa, much of North America (Mexico, United States), and Central America and the Caribbean see the largest decreases in water withdrawal.

Conclusion

This paper documents an initial study focused on understanding the physical impacts of climate change on water resources throughout the world. The research performed in this paper is based on the application of an IAM (GCAM) to quantify these impacts for a wide range of scenarios of socioeconomic development that offer a mix of possible futures for the availability, use, and management of water resources. The understanding gained through this analysis is expected to contribute to the ongoing dialogue on the sustainability of multiple human activities and their trajectories toward global development pathways.

Through this research and analysis, this study provides an integrated qualitative and quantitative understanding of the implications of several selected issues, including climate change and mitigation, socioeconomic and technological developments on water scarcity, and water-energy-food interactions in a global context.

A key message that follows from these results is that, at a global scale, the rate of runoff generation will not vary significantly over this century. These results reinforce the notion that freshwater is a finite resource with multiple uses, requiring careful management with due consideration of issues of water quality and efficiency. While the global runoff volume may not vary significantly over the coming decades some variations are worth noting among regions and countries.

Simulation results show a general upward trend in water scarcity in the majority of the world's countries; this is reasonable to expect given increased pressure on water resources (increased demand) as a result of population growth, development, and other factors. These Water Scarcity Index results appear to be fairly consistent among the three climate models used, suggesting that water scarcity is dominated by water demands rather than by the climate-influenced water availability (surface and groundwater). Severe and moderate water scarcity around the world is likely to advance significantly between 2025 and 2050, in countries and regions where water is already somewhat scarce, such as China, India, Mexico, and the Middle East and North Africa.

Implementing climate change mitigation policies (emissions reduction) results in a slight decrease in global water withdrawals, but some regions of the world decrease while others increase.

Data on future projections of water supply and demand for different climate and socioeconomic development scenarios generated through this study need to be validated at the regional and country levels so they can provide reliable intelligence for purposes of water resources assessment and management.

IAMs such as GCAM provide a quantitative economic framework for an integrated analysis of water supply and demand, multiple demand sectors, climate inputs, and other forcing factors such as land use change, policy interventions, and technological developments. These models provide a viable tool to explore additional issues related to the water-energy-food nexus. Further research can be focused on such issues as the implications of groundwater availability and changes in pumping costs on future water supply and its effect on urban services, energy, and food security; the repercussions of removing existing distortions (subsidies) in water availability and distribution in the future; the economic costs of noncooperation across basins/countries/regions and the potential benefits of cooperation; quantifying trade-offs in water availability and its impact on major economic sectors; defining effective adaptation strategies/investments that are necessary to mitigate the impact of climate change on water scarcity and stress; and identifying and planning key investments at regional and country levels to address economic water scarcity.

Notes

1. http://www.globalchange.umd.edu/models/gcam.
2. GCAM is a publicly available, open source modeling tool, developed and maintained by the Pacific Northwest National Laboratory, part of the US Department of Energy. It is available at http://www.globalchange.umd.edu/models/gcam/download/. Further details about GCAM can be found on its wiki site: https://wiki.umd.edu/gcam.
3. CCSM = Community Climate System Model; FIO-ESM = First Institute of Oceanography Earth System Model; GISS = Goddard Institute for Space Studies Model.

4. http://www.fao.org/nr/water/aquastat/main/index.stm.
5. http://www.cesm.ucar.edu/about/.
6. http://www.giss.nasa.gov/projects/gcm/.
7. http://cclics.rcec.sinica.edu.tw/xms/content/show.php?id=3429.
8. http://cmip-pcmdi.llnl.gov/cmip5/.

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