Toward evaluating the effect of climate change on investments in the water resources sector: insights from the forecast and analysis of hydrological indicators in developing countries*

Kenneth Strzepek, Michael Jacobsen, Brent Boehlert and James Neumann

MIT JOINT PROGRAM

SCIENCE

POLICY

GLOBAL CHANGE

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY of GLOBAL CHANGE

The MIT Joint Program on the Science and Policy of Global Change combines cutting-edge scientific research with independent policy analysis to provide a solid foundation for the public and private decisions needed to mitigate and adapt to unavoidable global environmental changes. Being data-driven, the Program uses extensive Earth system and economic data and models to produce quantitative analysis and predictions of the risks of climate change and the challenges of limiting human influence on the environment—essential knowledge for the international dialogue toward a global response to climate change.

To this end, the Program brings together an interdisciplinary group from two established MIT research centers: the Center for Global Change Science (CGCS) and the Center for Energy and Environmental Policy Research (CEEPR). These two centers—along with collaborators from the Marine Biology Laboratory (MBL) at Woods Hole and short- and long-term visitors—provide the united vision needed to solve global challenges.

At the heart of much of the Program's work lies MIT's Integrated Global System Model. Through this integrated model, the Program seeks to: discover new interactions among natural and human climate system components; objectively assess uncertainty in economic and climate projections; critically and quantitatively analyze environmental management and policy proposals; understand complex connections among the many forces that will shape our future; and improve methods to model, monitor and verify greenhouse gas emissions and climatic impacts.

This reprint is one of a series intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

Ronald G. Prinn and John M. Reilly,
Program Co-Directors

For more information, contact the Program office:

MIT Joint Program on the Science and Policy of Global Change
Postal Address:
Massachusetts Institute of Technology
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 (USA)
Location:
Building E19, Room 411
400 Main Street, Cambridge
Access:
Tel: (617) 253-7492
Fax: (617) 253-9845
Email: *globalchange@mit.edu*
Website: *http://globalchange.mit.edu/*

Toward evaluating the effect of climate change on investments in the water resources sector: insights from the forecast and analysis of hydrological indicators in developing countries

Kenneth Strzepek[1]**, Michael Jacobsen**[2]**, Brent Boehlert**[3] **and James Neumann**[3]

[1] Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology, 77 Massachusetts Avenue, E19-411, Cambridge, MA 02139-4307, USA
[2] World Bank, MC 6-235, 1818 H Street, NW Washington, DC 20433, USA
[3] Industrial Economics, Incorporated, 2067 Massachusetts Avenue, Cambridge, MA 02140, USA

E-mail: strzepek@mit.edu

Abstract
The World Bank has recently developed a method to evaluate the effects of climate change on six hydrological indicators across 8951 basins of the world. The indicators are designed for decision-makers and stakeholders to consider climate risk when planning water resources and related infrastructure investments. Analysis of these hydrological indicators shows that, on average, mean annual runoff will decline in southern Europe; most of Africa; and in southern North America and most of Central and South America. Mean reference crop water deficit, on the other hand, combines temperature and precipitation and is anticipated to increase in nearly all locations globally due to rising global temperatures, with the most dramatic increases projected to occur in southern Europe, southeastern Asia, and parts of South America. These results suggest overall guidance on which regions to focus water infrastructure solutions that could address future runoff flow uncertainty. Most important, we find that uncertainty in projections of mean annual runoff and high runoff events is higher in poorer countries, and increases over time. Uncertainty increases over time for all income categories, but basins in the lower and lower-middle income categories are forecast to experience dramatically higher increases in uncertainty relative to those in the upper-middle and upper income categories. The enhanced understanding of the uncertainty of climate projections for the water sector that this work provides strongly support the adoption of rigorous approaches to infrastructure design under uncertainty, as well as design that incorporates a high degree of flexibility, in response to both risk of damage and opportunity to exploit water supply 'windfalls' that might result, but would require smart infrastructure investments to manage to the greatest benefit.

Keywords: climate change, water resources, infrastructure, economic development, investment

1. Introduction

Major infrastructure investments in virtually any sector require rigorous economic/financial analysis to ensure that expected returns justify investment, and that key risks that might jeopardize those returns are fully evaluated. Failure to consider changes in future climate impacts risks reliance on a faulty time series of future returns, but with most economic analysis incorporating discount rates on the order of 7–10%, decision making is heavily influenced by the net monetary flows of the first two decades—too short to reflect most effects of a changing climate. In this time perspective other variables are much more important. However, a bigger issue, in particular in developing countries, is whether water resources infrastructure investments that look economically attractive today are consistent with the best long-term development path. National governments and international financial institutions should consider, for example, whether a large multipurpose dam, with attendant irrigated agriculture, electricity dependent industry and related settlement patterns is sustainable in the face of long-term water challenges. Practical examples include options to invest in irrigation infrastructure in the Okavango basin in Botswana (World Bank 2010a); options to invest in high value irrigated agricultural production in parts of the Balkans, Central Asia, and the Southern Caucasus (Sutton *et al* 2013); and proposed hydropower investments in northern and western sub-basins of the Zambezi River basin in southern Africa (World Bank 2010b). In developed country contexts alternatives to large-scale infrastructure investments may be reasonable substitutes for infrastructure (e.g., water efficiency, input substitution, and other non-infrastructure related changes might be employed to maintain service levels). Nonetheless, while such alternatives may also play a role in developing country contexts, the general under-investment in large-scale infrastructure here (see Foster and Briceño-Garmendia 2010) suggests that long-lived infrastructure investments should continue to be proposed and thus require more rigorous analysis.

The best analyses of large-scale infrastructure include consideration of future climates and sensitivity analyses, but they are typically not tied to the specific, internally consistent scenarios of future precipitation and temperature changes that have been developed for climate change assessments (IPCC 2007), do not incorporate the full range of changes that could be associated with future climates and in particular do not adequately take into consideration the uncertainty with respect to future climates which is indicated by the full suite of climate models and emission scenarios of IPCC (2007) (e.g., Kuik *et al* 2008, Kirshen *et al* 2008, Ward *et al* 2010). It is now clear that the wide range of potential future climate and hydrologic outcomes suggest the use of planning tools such as robust decision-making (Lempert and Groves 2010), which focus on resilience to uncertain futures rather than optimization in relation to predicted futures and on methods of decision making for large-scale infrastructure that put a very high value on flexibility (De Neufville and Scholtes 2011).

In response to this growing need to evaluate the climate resilience of proposed development paths and related infrastructure investments, the World Bank has recently developed a method to evaluate the effects of climate change on six hydrological indicators across 8951 basins of the world. The indicators are designed for decision-makers and stakeholders to consider climate risk when planning water resources and related infrastructure—here we refer to risk as the product of severity (the magnitude of change) and frequency (the likelihood of change). These indicators reflect impacts of climate change (severity) on irrigation and drainage, large water supply and urban wastewater treatment, small water supply and rural wastewater treatment, flood protection, and river basin management and multipurpose infrastructure. To fully understand climate change as a risk factor, however, we are limited by an inability to attribute reliably the frequency (or probability) of alternative projections of climate change. The next best solution is to provide a representation of the breadth of future change across many plausible predictions of future climate. To accomplish this goal, the analysis examines relative changes from an historical baseline to three future periods for 56 GCM-SRES combinations available from the IPCC Fourth Assessment (IPCC 2007), enabling users to employ a risk-based approach to the effect of climate on investment plans. As described here, the results provide insights into key water resources challenges likely to arise in developing regions, including the prospect of much larger variability in key hydrological indicators in the poor countries least able to manage those risks.

2. Methods

Developing projections of hydrological indicators for 8951 world river basins under a wide range of possible future climate conditions presents challenges in characterizing baseline conditions (including the unit of analysis), projecting key climate variables, and developing hydrological indicators at the basin level. We review our methods for each of these three steps below.

2.1. Characterizing baseline conditions

The focus of this study is water resources planning and development at the regional and local level, and as such, the river basin was identified as the appropriate scale for this analysis. A key challenge then is determining an appropriate global definition for river basins. We rely on the USGS HydroSHEDS global basin definitions, based on a 1 km digital elevation model. We chose a combination of Level 3 and Level 4 basins from HydroSHEDS, in an attempt to roughly match basin size to the size of a typical GCM gridbox, in order to ensure the results were not over-specified relative to the scale of GCM results. Nonetheless, the Level 3 and 4 basins defined in this study vary significantly in size, ranging from approximately 2500 km^2, which is similar to a grid cell of $0.5° \times 0.5°$, to more than 62 500 km^2, which is similar to a grid cell of $2.5° \times 2.5°$.

For climate data, we rely on a 30-year historical baseline (1961–1990), with the goal of projecting to future 30-year periods centered on three future eras: the 2030s, 2050s, and 2080s. Baseline precipitation and temperature data for the 1961–1990 baseline was taken from the University of East Anglia's Climate Research Unit (CRU) TS 2.1 data set, which provides monthly data at a $0.5° \times 0.5°$ resolution.

2.2. Projecting key climate variables from a suite of GCM/SRES combinations

Projecting changes in climate variables from GCM simulations has often involved downscaling approaches, but both statistical and dynamical downscaling have well-studied uncertainties (Kerr 2011), and the time and costs of these computationally intensive approaches rarely allow the use of more than a few GCMs. Our goal in this work is to characterize the broadest possible range of 'not implausible' climate futures, as defined by the currently available set of GCM-SRES combinations. The only practical approach for a global analysis is to use projected changes in temperature and precipitation for 56 GCM-SRES combinations at their native resolutions. These native resolution changes were mapped onto a 0.5° × 0.5° grid, and then combined with the corresponding 0.5° × 0.5° grid of CRU baseline modeled data. Basin-scale aggregation was then achieved using GIS software to overlay basin boundaries with the 0.5° × 0.5° grids, and then aggregating cells based upon their weighted area in each basin. This approach was designed to capture the range of potential climate change impacts at a higher resolution without downscaling the GCMs themselves, thereby achieving a balance between precision and accuracy.

Note that the 56 climate projections represent the full range of available models for the B1, A1B, and A2 Special Report on Emissions Scenario (SRES) scenarios evaluated in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). There are 17, 22, and 17 GCM runs, respectively, available for the three emissions scenarios, leaving a total of 56 GCM-SRES combinations. These three SRES scenarios were chosen because they are generally in the middle range of the marker SRES scenarios identified by the IPCC, and are the most commonly used emissions scenarios for impact and adaptation assessments.

To compare across GCMs, we converted GCM modeled baselines and projections into decadal average monthly changes relative to the model baseline by subtracting the modeled baseline from the projected values to produce delta temperature and precipitation derived from the archived CMIP3 IPCC AR4 outputs. For each GCM-SRES combination, these relative changes for the decades of the 2030s, 2050s, and 2080s, were then coupled with the 30 year CRU historical dataset to generate three 30 years absolute monthly projections representative of potential future conditions in decades of the 2030s, 2050s, and 2080s.

2.3. Translate trends from climate models into hydrological indicators

Basin-scale runoff is a key component of the six hydrological indicators. To model changes in runoff, this study employed CLIRUN-II: a hydro-climatic modeling framework with components that model, PET, Snow Water Balance, and soil moisture. Potential evapo-transpiration (PET) is a necessary input into runoff modeling as well as irrigation water requirements. CLIRUN-II uses the Modified Hargreaves method (Allen *et al* 1998, Droogers and Allen 2002).

The runoff modeling component is a two-layer, one-dimensional conceptual rainfall-runoff model that simulates natural runoff with six calibration parameters (Strzepek and McCluskey 2010). This class of model requires natural runoff data to calibrate the model over an historic period.

While global databases of gauged flow are available (e.g., WMO 2012) there is no corresponding database of natural flows to use in assessing the performance of this procedure at global scale. McMahon *et al* (2007) are developing a global natural flow database based on statistical characteristics of natural flow and recreating natural flows from gauged flow, but this effort is limited in scope and not appropriate for our application. Hydrologists have taken an alternative approach using global gridded databases of climate time series and using hydrologic models to simulate natural flows. The Global Runoff Data Centre (GRDC) has developed a composite runoff database that combines simulated water balance model runoff estimates with monitored river discharge (Fekete *et al* 2002). This data set consists of average monthly runoff values for each cell at a 0.5° × 0.5° global land grid.

We calibrated the model by minimizing the squared deviation between the 12 monthly GRDC runoff values and the 12 monthly averaged CLIRUN-II model outputs from the 10-year simulation period, which was chosen to best represent the decade used to generate the 12 months of GRDC runoff data. The limitations of using a modeled 'natural' runoff for calibration and having only monthly average values add uncertainty to the results. Other issues with the GRDC data that add to uncertainty in the analysis include: (1) there are large areas (especially in dry regions) that do not have gauge data, (2) the time period of available gauge data varies by station, therefore the resulting monthly discharge regimes are not fully consistent, (3) the historical climate data used in the water balance model (WBM) of the GRDC data set is not the same that was used in the CLIRUN-II model analysis, and (4) the data set is only provided for 12 average monthly values, not for a full time series. Additional uncertainty also exists in the choice of CLIRUN and its model uncertainty. Based on multi-model assessments, Haddeland *et al* (2011) and Schewe *et al* (2013) report that differences between hydrological model results are also a major source of uncertainty.

CLIRUN-II produces a 30-year time series of monthly hydro-climatic variables that are used in calculation of six hydrologic indicators[4]: (1) mean annual runoff (MAR); (2) river basin yield; (3) annual high flow (q10), or 10%

[4] *MAR*: the average annual runoff across 30 years. *Basin yield*: the maximum sustainable reservoir releases within a basin using derived storage yield curve and the reservoir storage available in each basin. *Annual high flow (q10)*: the annual runoff that is exceeded by 10% of years in a given period, also referred to as the 10% exceedence flow. In a 10-year period, the q10 flow would be the second highest flow of the 10 available, which is exceeded only by the highest flow in that decade. Change in q10 is used as an indicator of flood risk. *Annual low flow (q90)*: the converse of annual high flow, this is the 90% exceedence flow, or the annual runoff that is exceeded by 90% of years in a designated period. For a 10-year period, this would correspond to the second lowest recorded flow. Change in annual low flow is used as an indicator of drought risk. *Groundwater (baseflow)*: the sustained flow in a river basin resulting from groundwater runoff. This indicator is used as a proxy for groundwater availability. *Reference crop water deficit*: the crop water demand that exceeds available precipitation. Because it was not possible for this study to measure biophysical crop water demand, PET was used to represent the water demands of a typical perennial grassland over the typical growing season of crops in the basin.
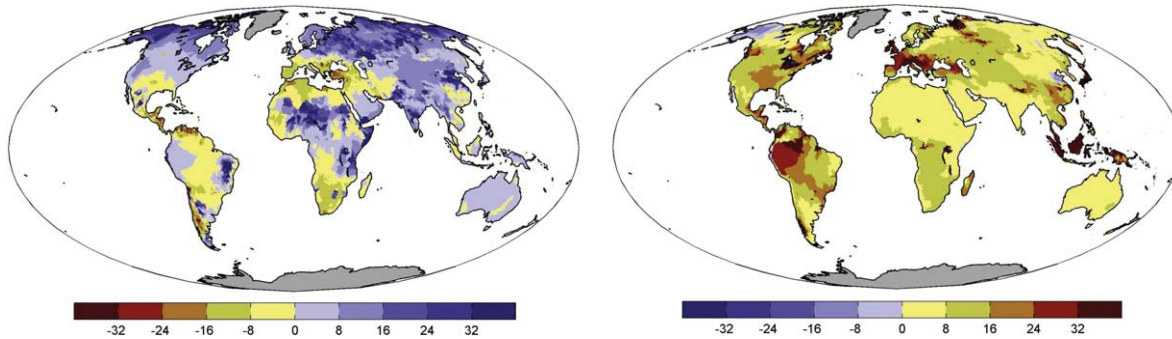
Figure 1. Per cent changes in A2 SRES scenario ensemble mean MAR (left) and reference crop water deficit (right), baseline to 2050s.

exceedence flow; (4) annual low flow (q90), or the 90% exceedence flow; (5) baseflow or the sustained flow in a river basin resulting from groundwater runoff; and (6) reference crop water deficit, which is the crop water demand less available precipitation.

As crop modeling and analysis of agricultural water use at the global basin scale were well beyond the scope of this work, we employ a simplified version of the water deficit index approach (Woli *et al* 2008) to estimate reference crop water deficit. For a given basin-specific growing season, this formulation reduces to the sum of monthly PET minus precipitation for those months in which PET exceeds precipitation. For a more detailed investigations of the impact of climate change on irrigation water demand for a range of GCMs, see Konzmann *et al* (2013).

3. Results

The result of our analysis is a dataset that provides six hydrological indicators for over 8000 basins worldwide, for up to 56 alternative climate futures. The methodology and data set has been utilized by the World Bank in a number of cases for example for a policy note on adaptation options in Botswana (World Bank 2010a), for a policy note on adaptation options for the Sava River basin and for a multi-sector investment opportunity analysis in the Zambezi River basin (World Bank 2010b). A dataset of this size could easily overwhelm users, so the data also includes a user-friendly interface that allows for analysis at the country and regional level, with mapping products and statistical representations of output, such as box and whisker diagrams. The full data set and interface can be accessed at the World Bank Climate Knowledge Portal, by pointing on a map[5]. In this section, then, we first provide a summary overview of our global results, and then outline three observations from our analysis of the results.

3.1. Overview of GCM ensemble mean results

Figure 1 provides an overview of the mean changes in MAR and reference crop water deficit from the baseline to the

2050s across the GCMs run for the A2 SRES scenario—the A2 scenario was chosen for presentation because it was also used in the World Bank *Economics of Climate Change* study (World Bank 2009). Regionally, model results suggest that, on average, MAR will decline in southern Europe; most of Africa; and in southern North America and most of Central and South America. Asia, most of North America, and the Pacific Islands are projected to experience increases in water availability. These general patterns hold for the q10 and q90 indicators as well. Mean reference crop water deficit, on the other hand, combines temperature and precipitation and is anticipated to increase in nearly all locations globally due to rising global temperatures. The most dramatic increases in crop water deficit are projected to occur in southern Europe, southeastern Asia, and parts of South America.

As part of our evaluation of these mean results, we compared our MAR projection to those from another recent analysis (Milly *et al* 2005). Figure 2 compares 2050s MAR projections of the current study to Milly *et al* (2005), each using the same set of the GCMs under the A1B SRES scenario. Although the results differ in several locations such as parts of South America and Australia, the general pattern is very similar globally.

3.1.1. Observation 1: hydrological indicators show a clear regional pattern that intensifies and grows less certain over time. For each of the World Bank regions, figure 3 provides boxplots of per cent changes in MAR from baseline to the 2030s, 2050s, and 2080s across the 17 A2 GCMs. The World Bank region results are population-weighted averages of basin-level values, grouped into regions based on basin centroids. The clear regional trends in MAR become more pronounced and less certain over time, illustrating the widely different challenges in water resources planning in different parts of the world. For example, planning for the projected increases in MAR and q10 in the Europe and Central Asia region poses vastly different challenges for infrastructure development than planning for the anticipated reductions in MAR and q90 in the Middle East and North Africa (MENA). Our data suggest that these differences are much greater at the catchment level. It is important to note, however, that in some regions, the direction of change in MAR become more certain over time. For example, within the MENA region, changes in

---

[5] See for example, the following: http://sdwebx.worldbank. org/climateportal/index.cfm?page=country_impacts_water& ThisRegion=Africa&ThisCcode=KEN
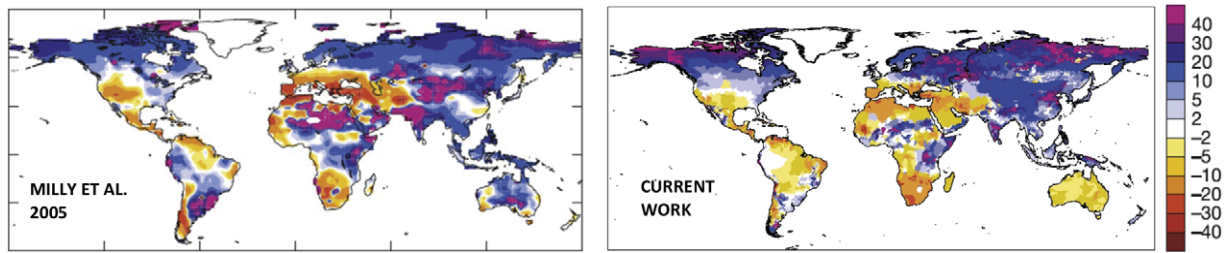
Figure 2. Comparison of projected per cent changes in mean MAR, baseline to 2050s. Milly *et al* (2005) on the left, current study on the right. Maps show A1B SRES scenario and GCMs used by Milly *et al* (2005).
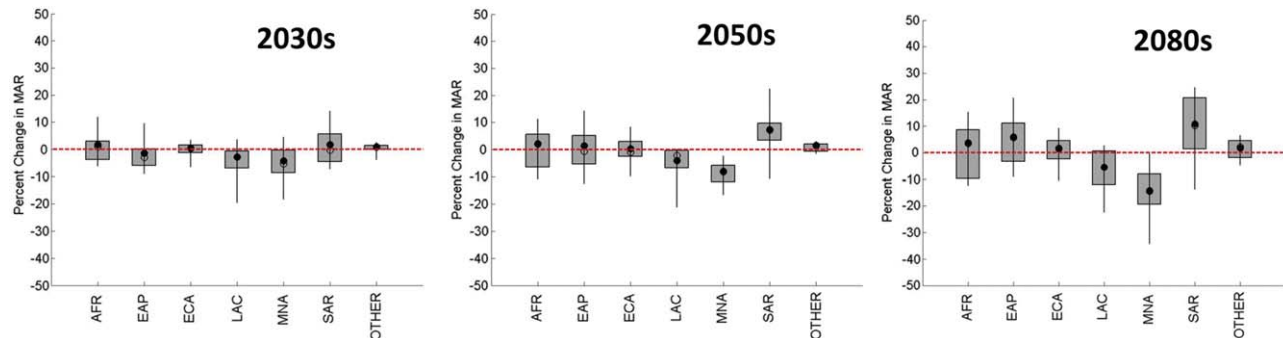

Figure 3. Box and whisker diagrams across A2 GCMs showing per cent changes in MAR between baseline and three periods for the World Bank regions. Regional changes are averages of per cent changes in basin MAR weighted by basin populations. Key: AFR is Africa; EAP is East Asia and the Pacific; ECA is Europe and Central Asia; LAC is Latin America and the Caribbean; MNA is the Middle East and North Africa; and SAR is South Asia.

MAR are both positive and negative in the 2030s, whereas by the 2080s, almost all models project a decrease.

These results, as presented, suggest overall guidance on regions in which to focus water infrastructure solutions that could address future runoff flow uncertainty. The full dataset is much richer, however; the country and basin-level results provide insights at a finer geographic scale, but remain consistent with the geographic scale of results from GCMs. Nonetheless, the indicators do not support project-level analyses. Concerns over whether a particular hydropower investment may face substantial reductions in future flow, for example, require a yet more detailed site-specific analysis that incorporates engineering considerations that could be adopted to adapt to changes in flow. In addition, because our results indicate that the full range of available GCMs span a wide range of hydrologic outcomes, they suggest that project-level analyses may require a new method of decision-making for water infrastructure that puts a very high value on flexibility (De Neufville and Scholtes 2011).

3.1.2. Observation 2: uncertainty in projections of MAR and high runoff events is higher in poorer countries, and increases over time. Our results also suggest that lower-income countries will face greater uncertainty in future hydrological conditions, particularly mean annual runoff and 10% exceedence flows (q10). Figure 4 displays the inter-quartile range for each country of per cent changes in MAR from the baseline to the 2080s across the 17 A2 GCMs

(at left), and boxplots of per cent changes in MAR from baseline to the 2080s across the A2 GCMs for countries within each income category (at right). Income region boxplots are population-weighted averages of basin-level values, grouped spatially based on basin centroids. World Bank per capita income categories include lower (<$1005); lower middle ($1006–$3975), upper middle ($3976–$12 275), and high (>$12 276). Although uncertainty increases over time for all income categories, basins in the lower and lower-middle income categories are forecast to experience dramatically higher increases in uncertainty relative to those in the upper-middle and upper income categories. Strzepek and Schlosser (2010) find similar results for 2050 and the A2 GCMs when analyzing climate change impacts on the Climate Moisture Index.

Figure 5 displays the relationship between income and uncertainty in projected country-level MAR and q10. The figure plots per capita country income against the IQR of projected percentage changes across the 17 A2 GCMs for the basins in that country (aggregated based on population; the size of each marker corresponds to the population of each country). All trends are statistically significant ($p < 0.001$), and steepen over time. Note that both the larger and smaller population countries appear to follow these trends. This result is not surprising, as precipitation is much more variable in low income countries currently, but our work shows that trend will be exacerbated by climate change.
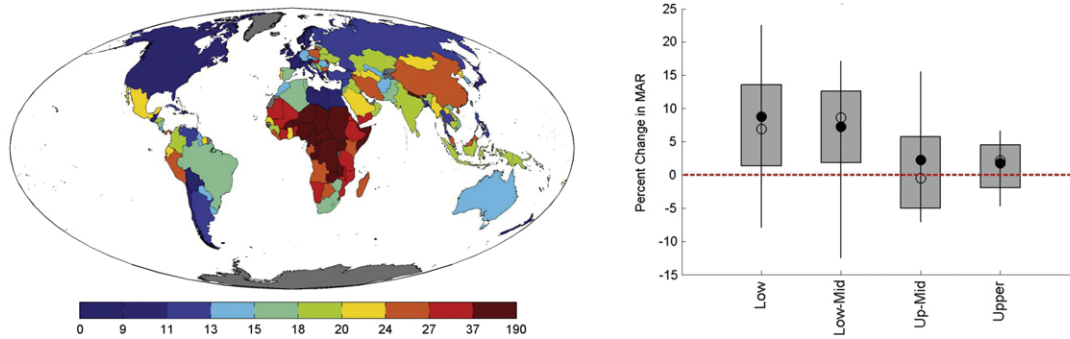
Figure 4. Inter-quartile range of per cent changes of MAR between baseline and the 2080s for each country (left); box and whisker diagram across A2 GCMs showing per cent changes in MAR between baseline and the 2080s for income categories (right). In boxplots, regional changes are averages of per cent changes in basin MAR weighted by basin populations. Key: income categories include lower (<$1005); lower middle ($1006–$3975), upper middle ($3976–$12 275), and high (>$12 276).
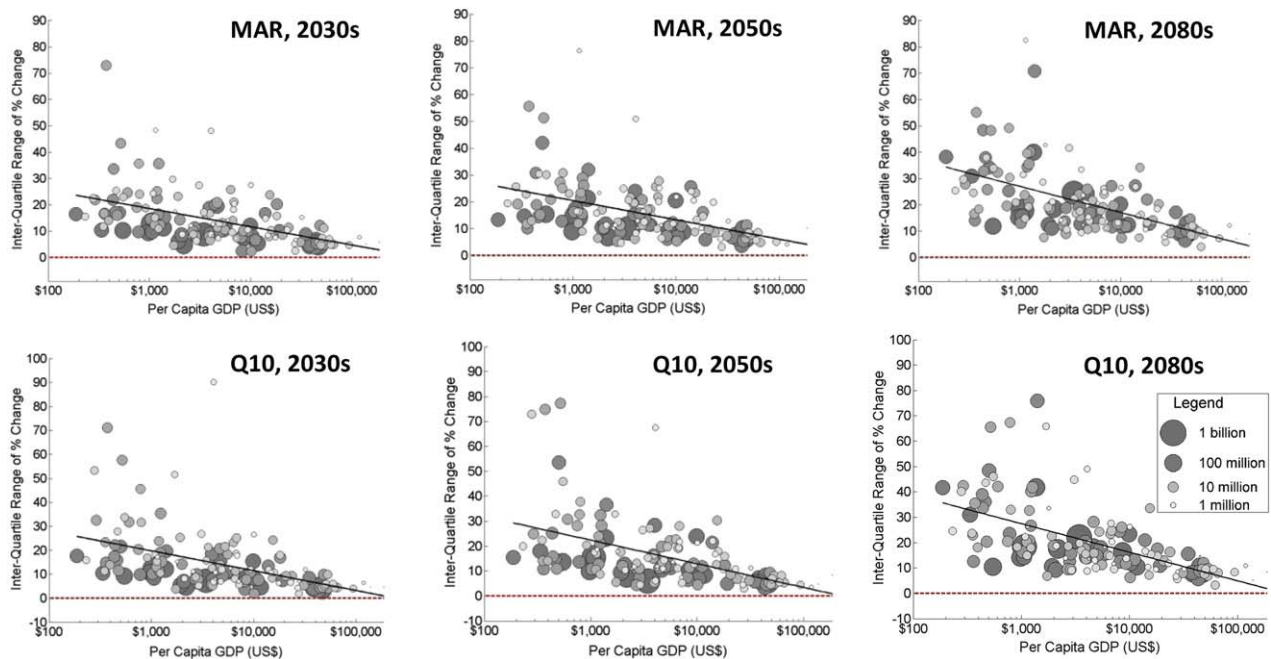

Figure 5. Country GDP (2008, US$) versus inter-quartile ranges of per cent changes in MAR (top) and q10 (bottom) across A2 scenarios, changes are from baseline to three periods; marker sizes scaled by country population. Note: $p < 0.001$ for all trends.

Although the observation 1 results indicates more water runoff in general, the Observation 2 results suggests more uncertainty about the amount, and in particular for poorer countries, who are least prepared to manage uncertainty for reasons related to information, institutions, and infrastructure. First, poor countries have less knowledge about current and future climate. Second, poor countries seldom have the regulatory and institutional capacity (including the capacity for cross sectoral collaboration) to deal with uncertainty. (WMO 2013, Sivakumar *et al* 2011). Third, poorer countries often (though with many notable exceptions in regard to water storage infrastructure) have less water infrastructure, an investment which can serve as an effective response to uncertainty. In policy terms, then, this result underscores the need for an analytical approach to investment evaluation that focuses on uncertainty (e.g. robust decision-making, see Lempert and Groves (2010)) and on practical solutions

(e.g., construction standards, concrete investments) that are flexible (see De Neufville and Scholtes (2011)).

3.1.3. Observation 3: uncertainty in projections of reference crop water deficit is higher in wealthier countries, and increases over time. Interestingly, our analysis suggests that while the uncertainty in MAR and high runoff events increases with income, the opposite trend exists in projections of uncertainty in reference crop water deficit over time, as illustrated in figure 6. This trend appears to be more pronounced than for uncertainty in MAR. While this may appear to be a contradiction, as both measures consider temperature and precipitation forecasts, MAR is more dependent on precipitation outcomes, while reference crop water deficit is more dependent on temperature for the PET component, and also exhibits a threshold effect (when precipitation exceeds PET, deficit is 0). To the extent that
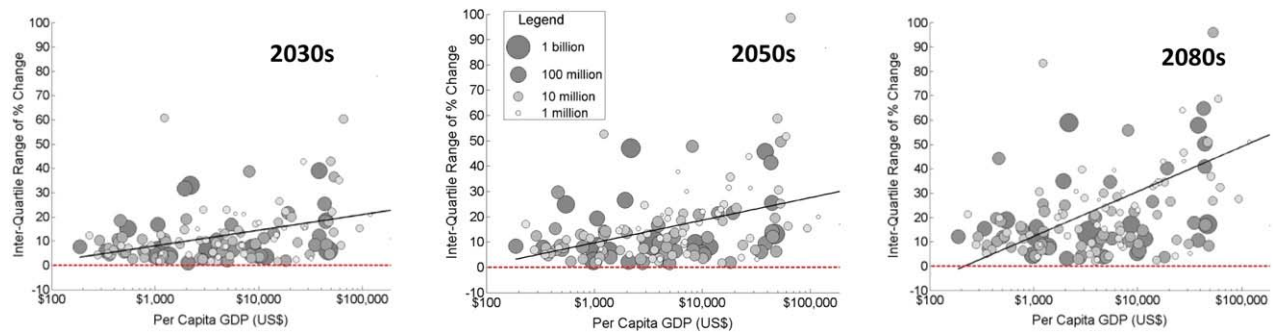
Figure 6. Country GDP (2008, US$) versus inter-quartile ranges of per cent changes in reference crop water deficit across A2 scenarios, changes are from baseline to three periods; marker sizes scaled by country population. Note: $p < 0.001$ for all trends.
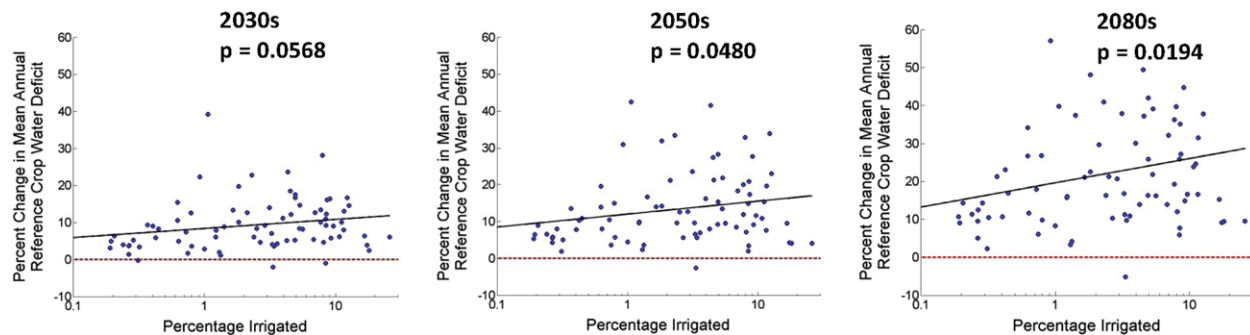

Figure 7. Relationship between reference crop water deficit in A2 forecast scenarios and current country-level percentage of agricultural land that is equipped for irrigation.

higher income countries are in higher latitudes, then, what appears to be at work is temperature outcomes exhibit higher variability in higher latitudes, while precipitation outcomes exhibit higher variability in lower latitudes. Additional work is underway to evaluate the robustness of this outcome.

We also conducted analyses of mean reference crop water deficit (rather than uncertainty) for the A2 scenario results versus income, and found no relationship between our projections with either income or with per cent of land area irrigated by country, suggesting that it is only the uncertainty in projections which vary with income. The result is potentially good news for poor agriculturally oriented countries, and presents a challenge for the agriculture sector in wealthier countries, particularly in areas where adding traditional water storage infrastructure has proven difficult owing to environmental concerns.

We also examined the relationship between the projected reference crop water deficit with climate change and the percentage of agricultural land that is currently irrigated across countries—in this case we forecast that countries with the highest current irrigation penetration also tend to face the highest increases in reference crop water deficit. This relationship is presented in figure 7 for the three future eras. The relationship is not as strong as for other results presented here, but does suggest that areas currently equipped for irrigation may face particular challenges related to increased crop water demand. Some of those issues could be resolved by altering crop choice, improving basin level and/or farm level water use efficiency, or increasing allocations to the

agriculture sector (where possible). All of those measures, however, will require good information and advance planning to address.

4. Limitations

There are several key limitations to this analysis. First are the limitations of any hydrological study relying on climate change projections, namely (1) the assumptions, model physics, and parameterization of the GCMs; and (2) the unpredictability of future development pathways and the resulting scenarios for emissions of greenhouse gases, land use changes, and other factors influencing climate change; and (3) fundamental uncertainties in the impact of climate change on the hydrologic cycle and water resources and the modeling hereof.

In addition, there are several uncertainties which stem directly from using rainfall-runoff models in global climate change studies. These lumped models tend to be relatively simple, and often require a minimum amount of input in order to reduce both the uncertainty associated with inputs and the possibility of compounding errors. Their performance also relies heavily upon the quality of the calibration process, which is driven by the quality of the naturalized runoff inputs. Where the GRDC inputs are actually gauged flows, CLIRUN-II is being calibrated to human influenced flow rather than naturalized flow. Yet another issue is that because both the GRDC and CRU datasets tend to include too few extreme events (runoff and weather, respectively), there is a

good chance that extreme events are under-represented in the CLIRUN-II results.

In terms of input data, both the CRU and GRDC datasets have additional uncertainties. Climatological station data is not always available for every time and place, an issue that tends to be more common in developing countries where station coverage is often poor. When and where weather records are not available, the CRU team uses an interpolation method to fill in missing data. Interpolation accuracy is of particular concern in areas with significant variation in elevation, and the accuracy of the original station data, in itself, is a source of notable uncertainty.

5. Discussion

The results presented here are designed to provide a sense of the value of hydro-indicators developed through this work; the real value rests in the value of these indicators to inform project planning, using a consistent and broad set of results. Infrastructure project design will nonetheless continue to require much more detailed hydrologic analyses. For example, climate change is expected to alter the seasonal pattern of precipitation, with the result that water can be in short supply at exactly the time it is needed most, during the high power demand or agricultural growing season. Higher temperatures also lead to more rapid evaporation from reservoirs, already a major consumptive use of water in many basins, and potentially more rapid evaporation from wetland areas such as those that characterize some areas, such as the Kafue flats region of the Zambezi River basin in southern Africa. These finer scale project-level assessments require a greater spatial and temporal scale than we can achieve with an indicators approach.

At a minimum, the enhanced understanding of the uncertainty of climate projections for the water sector that this work provides strongly support the adoption of rigorous approaches to infrastructure design under uncertainty, as well as design that incorporates a high degree of flexibility, in response to both risk of damage and opportunity to exploit water supply 'windfalls' that might result, but would likely require infrastructure to manage to the greatest benefit. In addition, it may make sense to not only consider changes to infrastructure investment levels, project design, and project operating rules, but also to consider non-infrastructure alternatives that can be effective 'in-the-moment' adaptations to changing climate. Despite the well-established infrastructure investment gap in many developing countries (SOFRECO Consortium 2011, Vivid Economics 2012, Foster and Briceño-Garmendia 2010), non-infrastructure alternatives may in specific situations postpone the need for some new climate-sensitive infrastructure. Certainly, climate change is not the only driver behind the need for more rigorous evaluations—issues of governance, institutional capacity, and the need for education and outreach to support wise use of infrastructure investments continue to be important as well.

The work also suggests a number of improvements that could be made in future efforts. First, there is a need for better hydrometeorological data—in particular in poor countries. The benefits of better data will be realized not only in the planning phases of these projects, but also in the operational phases. A better understanding of current variability may be at least as important as improving the physics in the GCMs, particularly when it is made clear that current water infrastructure is poorly adapted to current climate, let alone future climate risks. Improvements are particularly needed in both precipitation monitoring and understanding of naturalized runoff flows. Second, as noted above, a clear short-term need while data are enhanced and GCMs improved is focus in the near term on better planning models and practices for managing 'deep uncertainty'. Third, efforts are needed to mainstream what we have learned into the policies, planning and practice of vulnerable countries and the international finance community.

Finally, our results in figures 4 and 5 in particular provide a new insight about the relationship between water resources, climate, and country-level income, which deserves further attention. There is already a substantial and growing literature linking the temperature component of climate to country-level income (Acemoglu *et al* 2002, Dell *et al* 2009), and suggesting that the temperature component of climate may provide an indicator of future impacts of climate change (Horowitz 2009). Our work is prospective, concluding that lower-income countries that are least able to manage uncertainty in water availability are likely to face the greatest challenges in this area as a result of climate change. The results also suggests a subtle but potentially powerful factor in development research as well, that not only water availability but the level of certainty in water availability may be a key component of development success (Brown *et al* 2008), which is deserving of further exploration.

References

Acemoglu D, Johnson S and Robinson J A 2002 Reversal of fortune: geography and institutions in the making of the modern world income distribution *Q. J. Econ.* **117** 1231–94

Allen R G, Pereira L S, Raes D and Smith M 1998 Crop evapotranspiration—guidelines for computing crop water requirements *FAO Irrigation and Drainage Paper* 56 (Rome: United Nations Food and Agriculture Organization)

Brown C, Domeisen D, Meeks R, Hunu K and Yu W 2008 *Exploring the Effect of Hydroclimate Variability on Economic Growth in Sub-Saharan Africa: A Water Security Index* (*Report 2 of the Water and Growth Study*) (Washington DC: World Bank) (www.africainfrastructure.org)

De Neufville R and Scholtes S 2011 *Flexibility in Engineering Design* (Cambridge, MA: MIT Press)

Dell M, Jones B F and Olken B A 2009 Temperature and income: reconciling new cross-sectional and panel estimates *Am. Econ. Rev.* **99** 198–204

Droogers P and Allen R 2002 Estimating reference evapotranspiration under inaccurate data conditions *Irrig. Drain. Syst.* **16** 33–45

Fekete B, Vorosmarty C and Grabs W 2002 High-resolution fields of global runoff combining observed river discharge and simulated water balances *Glob. Biogeochem. Cycles* **16** 15-1–10

Foster V and Briceño-Garmendia C (ed) 2010 *Africa's Infrastructure: A Time for Transformation* (Washington, DC: World Bank)

Haddeland I *et al* 2011 Multimodel estimate of the global terrestrial water balance: setup and first results *J. Hydrometeorol.* **12** 869–84

Horowitz J K 2009 The income–temperature relationship in a cross-section of countries and its implications for predicting the effects of global warming *Environ. Resour. Econ.* **44** 475–93

IPCC (Intergovernmental Panel on Climate Change) 2007 Regional climate projections *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 847–940

Kerr R 2011 Vital details of global warming are eluding forecasters *Science* **334** 173–4

Kirshen P, Watson C, Douglas E, Gontz A, Lee J and Tian Y 2008 Coastal flooding in the Northeastern United States due to climate change *Mitig. Adapt. Strateg. Glob. Change* **13** 437–51

Konzmann M, Gerten D and Heinke J 2013 Climate impacts on global irrigation requirements under 19 GCMs, simulated with a vegetation and hydrology model *Hydrol. Sci. J.* **58** 1–18

Kuik O, Buchner B, Catenacci M, Goria A, Karakaya E and Tol R 2008 Methodological aspects of recent climate change damage cost studies *Integr. Assess.* **8** 19–40

Lempert R J and Groves D G 2010 Identifying and evaluating robust adaptive policy responses to climate change for water management agencies in the American west *Technol. Forecast. Soc. Change* **77** 960–74

McMahon T A, Vogel R M, Peel M C and Pegram G G S 2007 Global streamflows—part 1: characteristics of annual streamflows *J. Hydrol.* **347** 243–59

Milly P, Dunne K and Vecchia A 2005 Global pattern of trends in streamflow and water availability in a changing climate *Nature* **438** 347–50

Schewe J *et al* 2013 Multi-model assessment of water scarcity under climate change *Proc. Natl Acad. Sci.* at press

Sivakumar M V K, Motha P, Wilhite D A and Qu J J (ed) 2011 Towards a compendium on national drought policy—proceedings of an expert team meeting *Proc. an Expert Mtg. on the Preparation of a Compendium on National Drought Policy (July 2011)* (Geneva: World Meteorological Organization) p 135 AGM-12; WAOB-2011

SOFRECO Consortium 2011 *PIDA: Interconnecting, Integrating, and Transforming a Continent* (Programme for Infrastructure Development in Africa, a joint initiative of the African Union Commission, the New Partnership for Africa's Development Planning and Coordination Agency, and the African Development Bank)

Strzepek K and McCluskey A 2010 *Water and Climate: Modeling the Impact of Climate Change on Hydrology and Water Availability* (Washington, DC: The World Bank) (http://documents.worldbank.org/curated/en/2010/09/12815320/modeling-impact-climate-change-global-hydrology-water-availability)

Strzepek K and Schlosser C 2010 *Climate Change Scenarios and Climate Data. Development and Climate Change* (*Discussion Paper* no. 9) (Washington, DC: The World Bank) (http://documents.worldbank.org/curated/en/2010/10/12924239/climate-change-scenarios-climate-data)

Sutton W, Srivastava J and Neumann J 2013 *Looking Beyond the Horizon: How Climate Change Impacts and Adaptation Responses will Reshape Agriculture in Eastern Europe and Central Asia* (*Directions in Development Series*) (Washington, DC: The World Bank) doi:10.1596/978-0-8213-9768-8

Vivid Economics 2012 *The Cost of Adaptation to Climate Change in Africa* (*Report Prepared for the African Development Bank Group*)

Ward P, Strzepek K, Pauw W, Brander L, Hughes G and Aerts J 2010 Partial costs of global climate change adaptation for the supply of raw industrial and municipal water: a methodology and application *Environ. Res. Lett.* **5** 044011

WMO (World Meteorological Organization) 2012 *Global Runoff Data Centre* (www.bafg.de/nn_266918/GRDC/EN/Home/)

WMO 2013 *Overview of Current and Emerging Major Partnerships/Regional Hydromet Development Projects* (Geneva: World Meteorological Organization) IPM/(2013)/Doc. 4; ITEM 2.1

Woli P, Ingram K and Jones J 2008 Crop water stress as estimated by water deficit index and some popular drought indices *Conf. Proc.: Climate Information for Managing Risks*

World Bank–EACC 2009 The costs to developing countries of adapting to climate change: new methods and estimates *The Global Report of the Economics of Adaptation to Climate Change Study* (Washington, DC: The World Bank) (available online at www.worldbank.org/eacc)

World Bank 2010a *Botswana Climate Variability and Change, Understanding the Risks* (*Policy Note to the Government of Botswana, November 2010*)

World Bank, Water Resources Management, Africa Region 2010b *The Zambezi River Basin: A Multi-Sector Investment Opportunities Analysis* vol 1 (Washington, DC: The World Bank) pp 1–37 (http://siteresources.worldbank.org/INTAFRICA/Resources/Zambezi_MSIOA_-_Vol_1_-_Summary_Report.pdf, last accessed Jan 13)

Joint Program Reprints are available free of charge (limited quantities). To order: please use contact information on inside of front cover.

2013-10 Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback, Gao, X., C. Adam Schlosser, Andrei Sokolov, Katey Walter Anthony, Qianlai Zhuang and David Kicklighter, *Environmental Research Letters*, 8(3): 035014 (2013)

2013-11 Future trends in environmental mercury concentrations: implications for prevention strategies, Sunderland, E.M. and N.E. Selin, *Environmental Health*, 12(2): 1–5 (2013)

2013-12 Re-evaluation of the lifetimes of the major CFCs and CH_3CCl_3 using atmospheric trends, Rigby, M., R.G. Prinn, S. O'Doherty, S.A. Montzka, A. McCulloch, C.M. Harth, J. Mühle, P.K. Salameh, R.F. Weiss, D. Young, P.G. Simmonds, B.D. Hall, G.S. Dutton, D. Nance, D.J. Mondeel, J.W. Elkins, P.B. Krummel, L.P. Steele and P.J. Fraser, *Atmospheric Chemistry and Physics*, 13: 2691–2702 (2013)

2013-13 Nuclear exit, the US energy mix, and carbon dioxide emissions, Jacoby, H.D. and S. Paltsev, *Bulletin of the Atomic Scientists*, 69(2): 34–43 (2013)

2013-14 Land–Ocean Warming over a Wide Range of Climates: Convective Quasi-Equilibrium Theory and Idealized Simulations, Byrne, M.P. and P.A. O'Gorman, *J. Climate*, 26(12): 4000–4016 (2013)

2013-15 Winners and losers: Ecological and biogeochemical changes in a warming ocean, Dutkiewicz, S., J.R. Scott and M.J. Follows, *Global Biogeochemical Cycles*, 27(2): 463–477 (2013)

2013-16 Response of evapotranspiration and water availability to changing climate and land cover on the Mongolian Plateau during the 21st century, Liu, Y., Q. Zhuang, M. Chen, Z. Pan, N. Tchebakova, A. Sokolov, D. Kicklighter, J. Melillo, A. Sirin, G. Zhou, Y. He, J. Chen, L. Bowling, B. Miralles and E. Parfenova, *Global and Planetary Change*, 108: 85–99 (2013)

2013-17 A Numerical Investigation of the Potential for Negative Emissions Leakage, Winchester, N. and S. Rausch, *American Economic Review*, 103(3): 320–325 (2013)

2013-18 Off-line algorithm for calculation of vertical tracer transport in the troposphere due to deep convection, Belikov D.A., S. Maksyutov, M. Krol, A. Fraser, M. Rigby, H. Bian, A. Agusti-Panareda, D. Bergmann, P. Bousquet, P. Cameron-Smith, M.P. Chipperfield, A. Fortems-Cheiny, E. Gloor, K. Haynes, P. Hess, S. Houweling, S.R. Kawa, R.M. Law, Z. Low, L. Meng, P.I. Palmer, P.K. Patra, R.G. Prinn, R. Saito and C. Wilson, *Atmospheric Chemistry and Physics*, 13: 1093–1114 (2013)

2013-19 Economic impacts of climate change on water resources in the coterminous United States, Henderson, J., C. Rodgers, R. Jones, J. Smith, K. Strzepek and J. Martinich, *Mitigation and Adaptation Strategies for Global Change*, doi: 10.1007/s11027-013-9483-x (2013)

2013-20 Policy Diffusion of Emission Standards: Is There a Race to the Top? Saikawa, E., *World Politics*, 65(01): 1–33 (2013)

2013-21 A stochastic minimum principle and an adaptive pathwise algorithm for stochastic optimal control, Parpas, P. and M. Webster, *Automatica*, 49(6): 1663–1671 (2013)

2013-22 Is Small Better? A Comparison of the Effect of Large and Small Dams on Cropland Productivity in South Africa, Blanc, É. and E. Strobl, *The World Bank Economic Review*, doi: 10.1093/wber/lht026 (2013)

2013-23 Probabilistic projections of 21st century climate change over Norther Eurasia, Monier, E., A. Sokolov, A. Schlosser, J. Scott and X. Gao, *Environmental Research Letters*, 8(4): 045008 (2013)

2013-24 Quantifying regional economic impacts of CO_2 intenstity targets in China, Zhang, D., S. Rausch, V.J. Karplus and X. Zhang, *Energy Economics*, 40(2013): 687–701 (2013)

2013-25 Toward evaluating the effect of climate change on investments in the water resource sector: insights from the forecast and analysis of hydrological indicators in developing countries, Strzepek, K., M. Jacobsen, B. Boehlert and J. Neumann, *Environmental Research Letters*, 8(4): 044014 (2013)