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Water, Poverty, and the Economy

State of Knowledge on Climate Change, Water, and Economics

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WORLD BANK GROUP

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Cover design: Jean Franz, Franz & Company, Inc.

Abstract

The current state of knowledge on climate change and water points to predominantly negative effects on the economy and society. This paper reviews the literature on these effects by geographical region and notes the differences as well as the uncertainties.

An important feature of the projections is the fact that the climate effects will occur on top of a water scarcity situation that currently prevails in many parts of the world. The impact of climate change on scarcity is generally small compared to the impact of the socioeconomic factors. Adopting steps to increase the efficiency of water use could make a big contribution to addressing water problems, including those caused by climate change.

In-depth estimates of damages from climate change related to water have been made to 2060 and, less accurately, to 2100. The 2060 estimates indicate that the negative impacts from changes in water supply or changes in water-related extreme events and marine flows could amount to about 1.5 percent of GDP in 2060 in the absence of mitigation or adaptation. This average figure, however, may be an underestimate for a number of reasons. Estimates to 2100 of potential damages in economic terms are even more uncertain, but there are strong reasons to believe they will be greater as a percentage of GDP—perhaps around 10 percent globally, and possibly even higher.

Adaptation can make a major contribution to reducing damages from climate change in all mitigation scenarios, and more so when mitigation is absent or limited. Adaptation will require both private and public actions. Adaptation measures need further analysis to include more of the softer options (such as those involving the use of ecosystems) and to incorporate steps to increase efficiency in the use of scarce water, as well as other resources.

In terms of next steps, work is needed on how future economic growth could be affected by the effects of climate change on water and on water-related extreme events. In addition, a better understanding of how increases in the efficiency of water use could affect the water-energy-economic nexus in the context of climate change is needed. Finally, a better estimate of the likely reduction of damages from adaptation is needed, based on a detailed bottom-up assessment rather than a top-down one.

Introduction

Water is the central driver of the impacts of climate change on society. It touches almost all areas and sectors of economic activity, through sea level rise and storm surges; and through changes in precipitation, in evaporation due to higher temperatures, and in snowmelt and glacier melt. This discussion paper aims to show how climate impacts channeled through water will affect the economy and society in the coming decades, how these impacts depend in part on the evolution of greenhouse gas (GHG) emissions, and what measures can be taken to address the impacts. As the title indicates, the perspective taken is an economic one: impacts are assessed as far as possible in economic terms, as are the measures to reduce them through mitigation and adaptation.

This discussion paper was authored by Anil Markandya, Ikerbasque Professor, Basque Centre for Climate Change, and Honorary Professor, University of Bath.

Studies of the effects of climate change focus on the sectors shown in table 1, which highlights the links to changes in water. Changes in the availability of water or its rate of flow affect agriculture, coastal zones, ecosystems, extreme events, health, energy, water stress, human security, and tipping points (large-scale disruptive events).

Throughout the next century, climate effects on water will be characterized by increasing variability in rainfall, increased uncertainty of river flows, and major changes in groundwater recharge.

The table clearly illustrates how water plays a key role in the way climate change affects societies. Furthermore, these effects will be superimposed on a background of current water scarcity in many parts of the world.

Uncertain Water Supplies

Climate model simulations suggest that, overall, global average precipitation will increase as global temperatures rise. As a result, total water availability is expected to increase with climate change, but large regional differences are expected. At high latitudes and in some wet tropical areas, river flow and water availability are projected to increase; however, they are expected to decrease in some dry regions at mid-latitudes and in the dry tropics (Calzadilla 2010).

TABLE 1. Categories of Climate Impacts and the Role of Water in Producing those Impacts

Sector	Impacts	Role of Water
Agriculture	Changes in crop yields (including cropland productivity and water stress) Livestock mortality and morbidity from heat and cold exposure Changes in pasture- and rangeland productivity Changes in aquaculture productivity	Changes in precipitation, surface runoff, snowfall, groundwater. Variability of rainfall. Increased demand due to higher temperatures.
Coastal zones	Loss of land and physical capital from sea level rise Nonmarket impacts in coastal zones	Sea level changes, storm surges.
Ecosystems	Loss of ecosystems and biodiversity Changes in forest plantation yields Changes in potential fisheries catch	As for agriculture, through changing river flow regimes and water quality.
Extreme events	Mortality, land, and capital damages from hurricanes Mortality, land, and capital damages from floods	All such events involve increased variability of water.
Health	Mortality and morbidity from heat and cold exposure (including heatwaves) Mortality and morbidity from infectious diseases and cardiovascular and respiratory diseases	Increase in water-borne diseases from extreme events.
Energy	Changes in energy demand for cooling and heating	Changes in demand for water. Changes in snowfall.
Tourism	Changes in tourism flows and services	
Water stress	Changes in energy supply Changes in irrigation water availability Changes in drinking water to end users (including households)	Directly related to water availability.
Human security	Civil conflict Migration	Water can be a source of conflict.
Tipping points	Large-scale disruptive events	Melting of polar ice sheets.

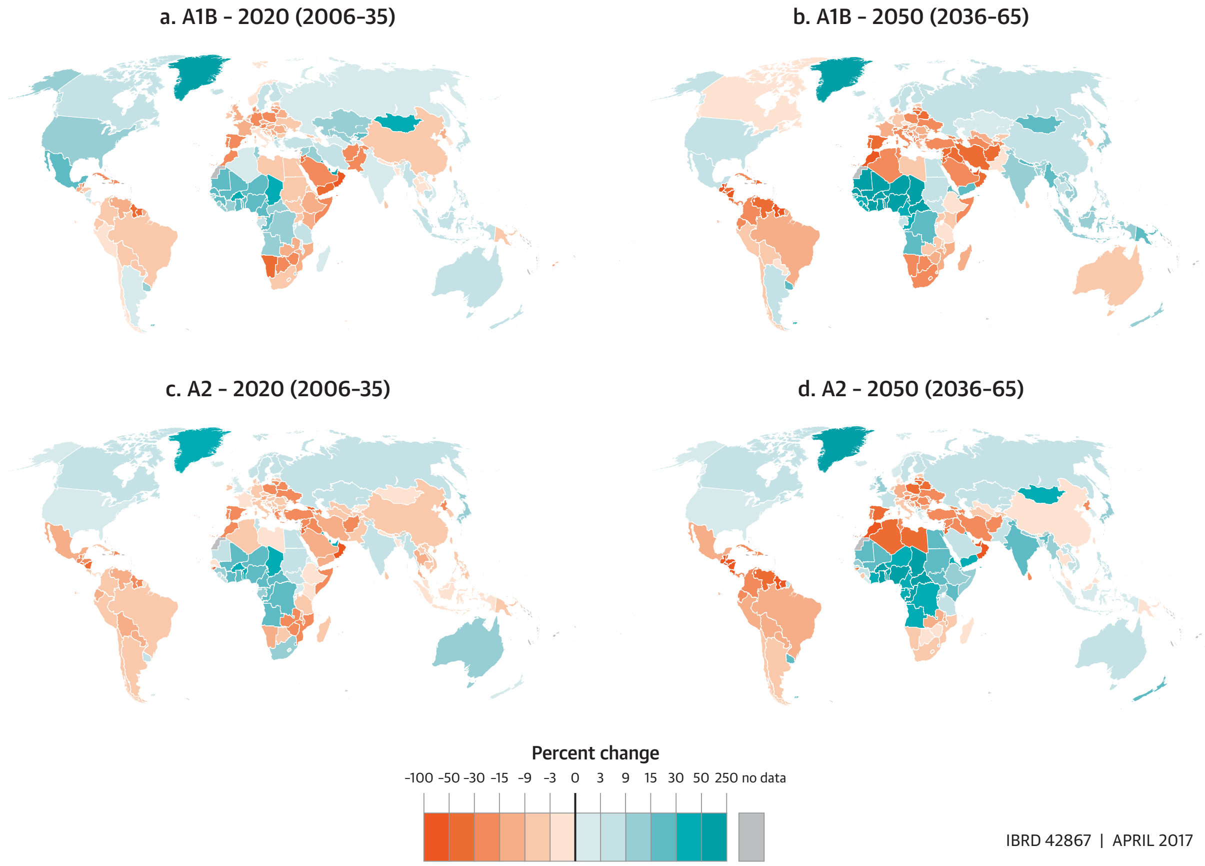
Source: Adapted from OECD 2015a.

In many regions, the positive effects of higher annual runoff and total water supply are likely to be offset by the negative effects of changes in precipitation patterns, intensity, and extremes, as well as shifts in seasonal runoff. By itself, an increase in precipitation would increase soil moisture. However, even with higher precipitation, surface runoff may decrease in some river basins because of greater evaporation in a warmer atmosphere (IPCC 2001). Temperature is particularly important in regions dominated by snow, determining the timing of snowmelt and thus the seasonality of available water. Therefore, the overall global impacts of climate change on freshwater systems are expected to be negative (Bates et al. 2008; Calzadilla et al. 2013).

River flow is a useful indicator of freshwater availability for agricultural production. Irrigated agriculture, which currently accounts for 90 percent of global water consumption, relies on the availability of water from surface and groundwater sources, which depend on the seasonality and inter-annual variability of river flow. Consequently, when river flow limits a region's water supply and hence constrains its ability to irrigate crops, the impacts can be severe.

Calzadilla (2010) provides a map of predicted changes in river flow relative to the 1961–90 period for two time periods (the 2020s and 2050s) and for the two emission scenarios (A1B and B2).[1] The map (reproduced as map 1) shows large regional differences, which do not change

MAP 1. **Percentage Change in Annual Average River Flow for 2020 and 2050 under Two Emissions Scenarios Relative to the 1961–90 Average**



Source: Calzadilla 2010.

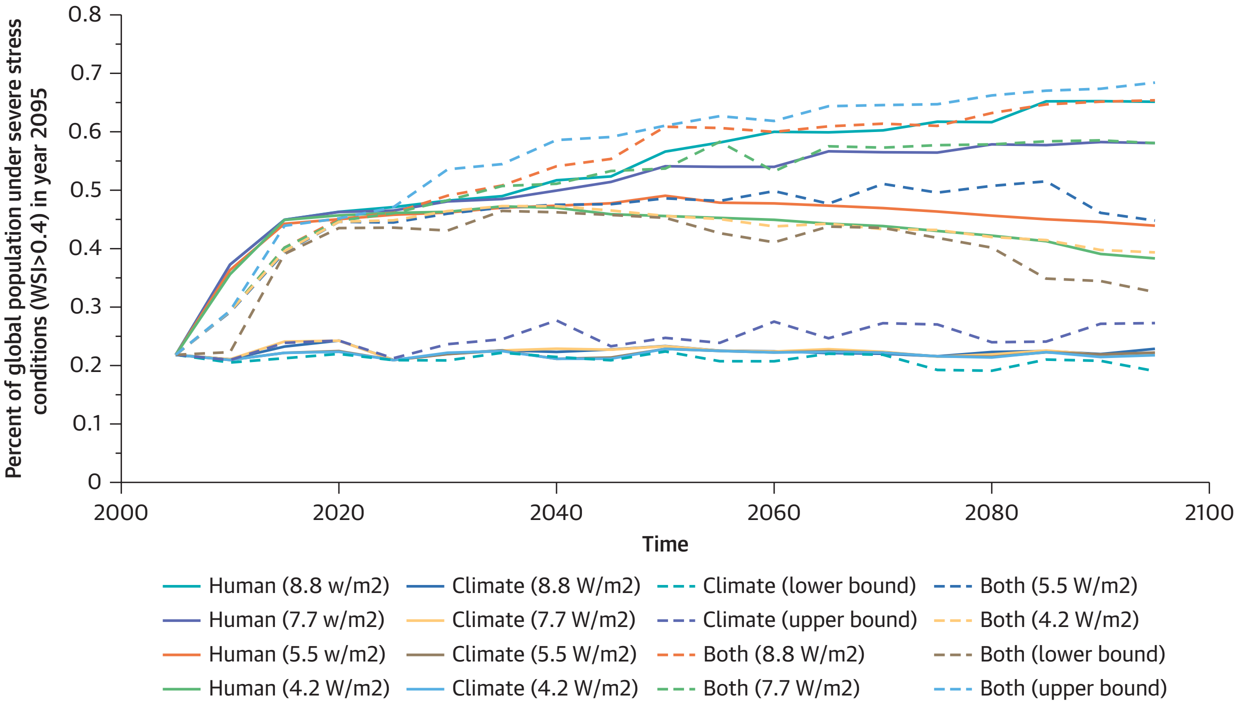
notably across the emissions scenarios. For both emission scenarios and time periods, the number of countries subject to decreasing river flow is projected to be higher than those with increasing river flow. Significant decreases in river flow are predicted for northern regions in South America, southern Europe, the Middle East, North Africa, and southern Africa. By contrast, substantial increases in river flow are predicted for boreal regions of North America and Eurasia, western Africa and southern Asia. Some exceptions are parts of eastern Africa and the Middle East, where changes in river flow vary depending on the scenario and time period.

Information on the effects of climate change on groundwater is more limited than for surface water, but work since 2007 has been increasing the knowledge base (Jiménez Cisneros et al. 2014). In general, areas where total runoff is expected to increase (decrease) are also ones where groundwater resources will increase (decrease) (see figure 1 for the regions). Changes in precipitation intensity may also decrease groundwater recharge as infiltration capacity is exceeded (typical in humid areas), but it may also increase it as a result of fast percolation (typical in semi-arid areas).

Less snowfall is expected to lead to less groundwater recharge even if precipitation remains constant. Coastal groundwater is affected not only by runoff but also by sea level rise. Unconfined aquifers are likely to suffer salt water intrusion over a long period.

There is also some evidence that changes in groundwater recharge can also affect stream flows. A study from Uganda indicates that high temperature increases are expected to decrease groundwater outflow to the Upper Nile Basin so much that the spring discharge will disappear and the flow regime will change from bimodal to unimodal (Jiménez Cisneros et al. 2014).

FIGURE 1. **Percent of Population Facing Severe Water Stress**



Source: Hejazi et al. 2014b. Courtesy of the Pacific Northwest National Laboratory, operated by Battelle for the U.S. Department of Energy.

Note: The figure is derived using Ensemble Mean GCM. W/m^2 = watts per square meter.

Higher Levels of Runoff and Lower Water Quality

Heavy rainfall events are expected to increase in frequency, and are likely to lead to an increase in erosion. Yang et al. (2003) estimate a 14 percent increase in erosion rates in the 2090s relative to the 1980s, with an increase of 40-50 percent in Australia and Africa. The largest amount is expected in semi-arid areas, where extreme events may account for up to 40 percent of the erosion. In temperate regions, the impacts of such events are less clear. They could result in a sharp increase in erosion or a decline in areas where rainfall is predicted to fall in the erosion-sensitive months. In general, land management practices are critical to the rate of erosion. With conservation tillage, these rates can be reduced significantly.

Climate change is also likely to increase sediment loads in rivers through soil erosion processes coupled with land use changes. This in turn can reduce flow rates. The phenomenon is more pronounced in rivers affected by melting glaciers and permafrost degradation, such as the Ganges.

Literature on the impacts of climate change on the quality of water is limited and uncertainty concerning the effects is high. Studies indicate that impacts are highly dependent on local conditions and on the current state of pollution of the water body. In general, observed impacts are likely to continue.

Current data indicate that for lakes and rivers, the most frequent impacts are more eutrophication and higher nutrient loads from increased storm runoff. Higher runoff also results in higher salts, pathogens, and heavy metals in the water. For rivers, the reported impacts point to reduced water quality, even when runoff increases. Instead of diluting the pollution, the process sweeps the pollutants from the soil into the watercourses. Some of these flows also reduce oxygen concentrations. In this context, it is important to note that the availability of freshwater can be reduced by the negative impacts of climate change on water quality from toxins, such as those produced by algae (OECD 2012, 2014; IPCC 2014).

Higher levels of runoff are likely to lead to increased erosion and sediment loads in rivers, and a reduction in water quality in many parts of the world.

Linkages between observed effects on water quality and water variability need to be interpreted with care, as many other factors also must be taken into account. Nevertheless, there is a medium level of confidence that if observed deterioration of water quality continues, measures already in place to control pollution may be inadequate in light of the negative impacts of climate change (Jiménez Cisneros et al. 2014).

Reductions in Meltwater and Constraints on Year-Round Water Supplies

As with precipitation, changes in snowfall in the past century are indeterminate; however, consistent with observed warming, shorter snowfall seasons are observed over most of the Northern Hemisphere, with snowmelt seasons starting earlier. Decreases in the extent of permafrost and increases in its average temperature are widely observed in some regions of the Arctic and Eurasia (IPCC 2013, chapter 4). In most parts of the world, glaciers are losing mass. For example, almost all glaciers in the tropical Andes have been shrinking rapidly since the 1980s; similarly, Himalayan glaciers are losing mass at present (Bolch et al. 2011).

Meltwater from accumulated snowfall and glaciers feed many of the world's rivers and help replenish groundwater stocks. Hotter temperatures will reduce snowfall seasons and shrink glaciers, constraining year-round water supplies.

All projections for the twenty-first century (WGI AR5, chapter 13) show continued mass loss from glaciers. As the glaciers shrink, their relative contribution to summer flows decreases, and the annual runoff peak shifts toward spring (Jiménez Cisneros et al. 2014, chapter 4). This shift is expected with *very high confidence* in most regions, although not in the eastern

Himalayas, where the monsoon and the melt season coincide. The relative importance of high summer glacier meltwater can be substantial. Glacier meltwater also increases in importance during droughts and heat waves. If the warming rate is constant, and if, as expected, ice melting per unit area increases and total ice-covered area decreases, the total annual yield passes through a broad maximum, known as "peak meltwater." Peak-meltwater dates have been projected between 2010 and 2050 for different parts of the world. In fact, declining yields relative to various dates in the past have been detected in some observational studies; that is, the peak has already passed. There is *medium confidence* that the peak response to twentieth and twenty-first century warming will fall within the twenty-first century in many inhabited glacierized basins, where society is currently benefitting from a transitory "meltwater dividend." When they are in equilibrium, glaciers reduce the year-to-year variability of water resources by storing water during cold or wet years and releasing it during warm years. As glaciers shrink, their diminishing influence may make the water supply less dependable. (Jiménez Cisneros et al. 2014).

Increased Risk of Floods and Droughts

Hydrological extremes—floods and droughts—are expected to increase in frequency and intensity in some parts of the world, affecting increasingly vulnerable populations.

Although global trends in precipitation from several datasets covering 1901 to 2005 are statistically insignificant (Jiménez Cisneros et al. 2014), regional observations show that most droughts and extreme rainfall events of the 1990s and 2000s have been the worst since the 1950s (Arndt et al. 2010). Certain trends in total and extreme precipitation amounts emerge from the data.

Floods. Temperature and precipitation changes could result in increased frequency of floods, according to the SREX report (IPCC 2012), but there is low confidence in the changes in frequency of fluvial floods (floods from overflowing rivers caused by intense rainfall). Recent work on global flood projections indicate flood hazards increasing in more than half the regions of the world, but with great variability at the scale of individual river basins. The ensemble of hydrology models reviewed in Jiménez Cisneros et al. (2014) indicate that flood hazards will increase in parts of South Asia, Southeast Asia, East Africa, Central and West Africa, northeast Eurasia, and South America. In contrast, a decrease in flood frequency is projected in parts of Northern and Eastern Europe, Anatolia, Central Asia, central North America, and southern South America. While there is agreement on the broad regions, there can be major differences at the local level, where even the direction of change may be subject to dispute.

Droughts. There is medium confidence that, since the 1950s, droughts have intensified and become longer in some regions of the world, in particular in southern Europe and West Africa, SREX (2012) concludes. However, in some regions, droughts have become less frequent, less intense, or shorter, such as central North America and North Western Australia. There is medium confidence that anthropogenic influence has contributed to some changes in the drought patterns observed in the second half of the twentieth century, based on its attributed impact on precipitation and temperature changes. There is, however, low confidence in the attribution of changes in droughts at the level of single regions because of inconsistent or insufficient evidence.

Looking to the future, studies conducted since the 4th assessment by the Intergovernmental Panel on Climate Change (IPCC) indicate a medium confidence in a projected increase in duration and intensity of droughts in some regions of the world, including southern Europe and the Mediterranean region, central Europe, central North America, Central America and Mexico, northeast Brazil, and southern Africa. Confidence is generally low for other regions because of insufficient agreement of projections of drought changes (dependent both on the model and dryness index). Definitional issues and lack of data limit confidence to a medium level in observations of drought changes, while these issues, plus the inability of models to include all the factors likely to influence droughts, preclude anything more than medium confidence in the projections.

Economic impacts of floods and droughts. Irrespective of the projected frequency and intensity of floods and droughts, their economic impacts are projected to increase even when the hazard remains constant because of increased exposure and vulnerability (Jiménez Cisneros et al. 2014). In Europe, for example, from 1961 to 1990, flood damage was €6.4 billion ($7.3 billion) and 200,000 people were exposed, on average, each year. This is expected to double by the 2080s under scenario B2 and triple under scenario A2.[2] Drought impacts at continental and smaller scales are difficult to assess because they vary greatly with the local hydrological setting and water management practices. More frequent droughts due to climate change may challenge existing water management systems; together with an increase of population, this may place even the domestic supply at risk in parts of Africa.

Increased Risks to Coastal Areas

The 5th Assessment Report WGII chapter on coastal systems and low-lying areas concludes that such areas will increasingly experience adverse impacts such as submergence, coastal flooding, and coastal erosion due to relative sea level rise. It is very likely that global mean sea level rose at a mean rate of 1.7 [1.5 to 1.9] mm/yr. between 1900 and 2010 and at a rate 3.2 [2.8 to 3.6] mm/yr. from 1993 to 2010 (WGI AR5, Section 13.2.2). Future rates are projected to exceed the observed rate for the period 1971–2010 of 2.0 [1.7 to 2.3] mm/yr. for all Representative Concentration Pathway (RCP) scenarios. From 2046 to 2065, the expected rate of rise is projected to be 12.0 [8.5 to 16.0] mm/yr. under the most optimistic scenario, RCP2.6. Under the least optimistic scenario (RCP8.5), the rate goes up to 14.5 [11.0 to 19.0] mm/yr. These figures now include a likely range of ice sheet flow contributions from Greenland and Antarctica (Wong et al. 2014).[3]

Sea level rise is not expected to be uniform in space and time. Natural modes of climate variability influence sea levels in different regions of the globe. This will affect the rate of rise from year to year and decade to decade. For example, in the equatorial Pacific, levels can vary from the global mean by up to 40 cm due to El Niño-Southern Oscillation. Regional variations in the rate of sea level rise on the coast can also arise from a number of other climate and ocean dynamic processes (Wong et al. 2014).

Severe storms such as tropical and extratropical cyclones (ETCs) can generate storm surges over coastal seas. There is *low confidence* regarding changes in tropical cyclone activity around the world during the twentieth century because of changes in observational capabilities, although it is virtually certain there has been an increase in the frequency and intensity of the strongest tropical cyclones in the North Atlantic since the 1970s (WGI AR5, Section 2.6). In the future, the frequency of tropical cyclones globally is likely either to decrease or remain unchanged, but global mean tropical cyclone precipitation rates and maximum wind speed will likely increase (WGI AR5, Section 14.6).

The trend of global average sea level rise is likely to continue throughout the twenty-first century, and at an accelerated pace. Sea level rise, combined with more intense tropical cyclones, will place coastal areas at greater risk.

Extreme sea levels arise from combinations of factors, including astronomical tides, storm surges, wind waves and swell, and year-to-year variability in sea levels. To date, observed trends in extreme sea levels have been mainly consistent with mean sea level (MSL) trends. Regarding future changes to storm surges, studies

Regions currently facing water scarcity are expected to experience worsening scarcity, with socioeconomic factors like population and economic growth as leading contributors.

show strong regional variability and sensitivity to the choice of Global Climate Model (GCM) or Regional Climate Model (RCM).

The effect of future tropical cyclone changes on storm surges has also been investigated in a number of regions using a range of different methods. In general, the small number of regional storm surge studies together with other uncertainties means there is *low confidence* in projections of storm surges due to changes in storm characteristics. However, observed upward trends in mean sea level, together with projected increases for 2100 and beyond, indicate that there is a *high confidence* that coastal systems and low-lying areas will increasingly experience extreme sea levels and their adverse impacts (see WGI AR5, Section 13.7).

Changes in sea water are also expected to have an impact on fisheries. Cheung et al. (2010) estimate that climate change may lead to a large-scale redistribution of global catch potential, with an average of 30-70 percent increase in high-latitude regions and a drop of up to 40 percent in the tropics. Moreover, maximum catch potential could decline considerably in the southward margins of semi-enclosed seas, while it is likely to increase in poleward tips of continental shelf margins. Such changes are most apparent in the Pacific Ocean. Among the 20 most important fishing Exclusive Economic Zone (EEZ) regions in terms of their total landings, EEZ regions with the highest increase in catch potential by 2055 include Norway, Greenland, the United States (Alaska), and Russia (Asiatic part).By contrast, EEZ regions with the biggest loss in maximum catch potential include Indonesia, the United States (excluding Alaska and Hawaii), Chile, and China. Many highly impacted regions, particularly those in the tropics, are socioeconomically vulnerable to these changes.

Worsening Water Scarcity

Despite the fact that the world only uses 10 percent of the available fresh surface and groundwater, water scarcity occurs because water availability is highly variable over time and space. The United Nations estimates that about 1.2 billion people, or almost one-fifth of the world's population, live in areas of physical water scarcity, and 500 million people are approaching this situation. An additional 1.6 billion people, or almost one-quarter of the world's population, face economic water shortage (where countries lack the necessary infrastructure to take water from rivers and aquifers).[4] By 2025, about 1.8 billion people will be living in countries or regions with absolute scarcity, according to the United Nations.

Hejazi et al. (2013) have estimated water scarcity using Raskin's definition of scarcity as the ratio of total water withdrawal (TWW) to total water availability (TWA). The index indicates no scarcity when it is below 0.1, low scarcity for values of between 0.1 and 0.2, moderate scarcity for values between 0.2 and 0.4, and severe scarcity for values greater than 0.4. They analyze future demand under a range of socioeconomic scenarios without climate change using the GCAM Integrated Assessment Model,[5] and find that by 2050, regions in China, India, the Republic of Korea, and the Middle East will be severely water stressed. When climate change is included in the analysis, Hejazi et al. (2014a) show that by 2095 similar or elevated water scarcity conditions are expected in these regions. More specifically, regions experiencing some level of scarcity are projected to experience even more scarcity, primarily due to mounting demands and changes in water availability. The largest increases in scarcity in the twenty-first century include regions in eastern China, India, Western Europe, and the Middle East. Some of that change is attributed to the large increase in population and the income effect in these regions, which raises water demand under the assumed socioeconomic developments. A number of other studies also predict an increase in demand for water due to climate change. Döll (2002) estimates that climate change may cause the global total irrigation requirement to increase by 5-8 percent until the 2070s. About two-thirds of the area equipped for irrigation in 1995 will experience an increase in irrigation demand. Fischer et al. (2007) find an even larger increase of 20 percent in global irrigation needs by 2080. About two-thirds of the increase results from higher irrigation intensity. These data form the basis of adaptation estimates discussed later in this paper.

The analysis by Hejazi et al. (2014a) is relevant in two respects. The first is the role of mitigation policies on water scarcity. The model considers two kinds of taxes: a uniform carbon tax (UCT), which includes all carbon emissions in all sectors (including land use emissions) and all regions of the world; and a fossil fuel and industrial emissions tax (FFICT) regime, which does not include a tax on land-use-related carbon emissions. Under both regimes, the carbon tax rises over time to limit atmospheric CO_2 concentrations to a prescribed stabilization level. The different types of policies lead to dramatically different outcomes for deployment of bioenergy, for emissions stemming from changes in land use, and consequently greenhouse gas emissions and climate change. The FFICT case is characterized by very high deployment of bioenergy and emissions associated with changes in land use, which lead to greater emissions and climate change than the UCT case.

There are also differences in water demand under the two regimes. The results depend on both the tax regime (UCT and FFICT) as well as the mitigation target chosen. The targets considered are scenarios A2 and B1 (resulting in best guess temperature increases by 2095 of 3.4°C and 1.8°C respectively). With the UCT regime, populations under severe stress decline by 2.0-2.4 percent by 2095 (depending on the mitigation target chosen). Under the FFICCT regime, they increase by 0.2 percent under scenario A2 and by even more (5.6 percent) under scenario B1. This unusual result arises because under scenario B1 demands for water when implementing the FFICT regime are particularly high.

The other important conclusion from the analysis is the small effect of climate change on scarcity relative to human factors. Figure 1 shows the percent of population under severe water stress due to climate (with different mitigation targets), to human factors, and to both. Clearly, the effect of climate is minor compared to that from socioeconomic factors.[6]

The Growing Need for Careful Management of Water Resources

Increasing water scarcity implies the strong need to manage water resources more carefully over the rest of this century.

Water pricing can play an important role in managing water resources. At present, the marginal value of water in different uses varies a great deal because the prices paid by industry, agriculture, and residential users often have no relation to each other. In the desert state of Arizona in the United States, for example, water prices vary from $27/acre-foot for agriculture to $3,200/acre-foot for urban uses, Olmstead (2013) finds.[7] While some of the variation can be explained by the difference in nature and quality of the product being delivered, most of it is a function of institutions that do not allocate water based on economic criteria.

Hejazi et al. (2014b) report ongoing research in which water withdrawal in each of the 235 river basins is tracked in the GCAM model previously discussed. They find that with no change in pricing, withdrawals will double over this century (from around 2,600 billion m^3/year in 2000 to around 5,000 billion m^3/year in 2100). By contrast, with a price to balance supply and demand, the increase is limited to between 3,100 to 4,000 billion m^3/year, depending on what amount of the stream flow is considered accessible. Thus even if only a part of water use is allocated based on a price that applies across users to bring supply and demand into balance, many of the problems of scarcity related to climate change and socioeconomic factors scarcity will be resolved.

Pricing is one method of conserving water use and increasing efficiency in its allocation, but other measures of a more technological nature should also make a contribution. Hertel and Liu (2015) notes the following possibilities, in particular:

a. *Evaporation from water storage.* Such evaporation accounts for a significant fraction in some regions. For example, reservoir evaporation in the semi-arid U.S. state of Texas amounts to about 61 percent of total agricultural irrigation use during the year 2010 (Wurbs and Ayala 2014). In Australia, Craig (2005) estimated this loss to be about 40 percent of the total storage volume. In many developing countries, storage rates are low because of inadequate water infrastructure. In Pakistan for example, only 9 percent of average annual flows are stored, while the world average is 40 percent. As a consequence, the country has limited opportunity to conserve flood waters, to be able to release water during periods of low river flow, such as Rabi (winter) (GOP and UNEP 2013). This evaporative loss could increase by about 15 percent by 2080, as surface temperatures rise in the face of climate change (Helfer, Lemckert, and Zhang 2012). Increasing total usable water storage by reducing this type of loss depends on the adoption of evaporation suppression technology, which is driven by the marginal value product of the water to be saved.

b. *Irrigation efficiency.* This refers to reliable and precise delivery of water to plants. One definition is the ratio of crop water requirement to irrigation water withdrawal. Average world irrigation efficiency was around 50 percent in 2005-2007, according to the United Nations Food and Agricultural Organization (FAO). In other words, about half of the water withdrawal is "lost" between the source and the destination. Among all the regions, Sub-Saharan Africa has the lowest irrigation efficiency, averaging about half of global efficiency (Alexandratos and Bruinsma 2012). A key driver of increased efficiency is the price of water relative to other inputs. Another factor is technological change that improves efficiency. The latter, however, is not enough to ensure a reduction in water use. As Hertel and Liu (2015) note, farmers tend to irrigate larger areas and increase irrigation intensity after adopting a more efficient technology. Hertel cites the example of the Upper Rio Grande Basin in the southwestern United States, an area studied by Ward and Pulido-Velazquez (2008). They find that adoption of the more efficient drip irrigation system through a subsidy for upstream irrigators reduces return flow, leading to larger depletion of downstream water. The overall withdrawal from the basin turns out to be larger than before the subsidy for drip irrigation was provided. The message is that technological efficiency needs to go hand in hand with water pricing to have a full effect on water conservation.

c. *Productivity of water.* Unlike irrigation efficiency, which measures the share of the diverted water finally applied to plants, water productivity refers to gaining more output per drop of water. This can be achieved either by raising yields (increasing the numerator) or by reducing non-beneficial consumptive water use (decreasing the denominator). Increasing water productivity places emphasis on agricultural practices. For example, limiting non-beneficial evaporative loss could boost yields from 1 to 3 metric tons/ha; limiting deep percolation of rainfall could further boost yields by another 2 tons/ha (Hertel and Liu, 2015). Other measures that contribute to raising yields relative to evapotranspiration are better pest and disease control and adopting drought-tolerant cultivars.

The literature indicates considerable room to improve water productivity. A number of recent findings confirm a nonlinear relationship between water productivity and yields. At a lower level of yield, even a small gain in yield can significantly increase water productivity. But when the farm moves to a higher level of yield, water use tends to rise in direct proportion to output, providing much less incentive for farmers to save water. The threshold for this nonlinearity is around 3 metric tons/ha. Most small-scale farmers in developing countries operate below this threshold, suggesting that they could significantly increase water efficiency (Hertel 2015).

Threats to Agricultural Production

A recent model, ENV-Linkages, was developed by the Organisation of Economic Co-operation and Development (OECD) to estimate the impact of climate change on 35 economic sectors and 25 regions throughout the world (see box 1 for a brief description of the model). The OECD project contains one of the most robust assessment of agricultural impacts from climate change published to date.

Changes in precipitation and river flows, as well as adverse climate-related shocks, will have a detrimental impact on agricultural production, particularly in some of the poorest and driest parts of the world.

The model finds that climate change affects crop yields heterogeneously in different world regions. Further, the effects are not the same for different crops. Figure 2 illustrates changes in crop yields for paddy rice and wheat at the global level in 2050. Falls in yields of paddy rice by 2050 are strongest in tropical areas,

BOX 1. Modelling the Economic Impacts of Climate Change

Estimates of the economic costs of climate change are generally conducted using Integrated Assessment Models (IAMs) with long-term perspectives, to the end of this century and beyond.[a] Most of these studies have a stylized, aggregated representation of the economy focusing on projections of climate change impacts over time. They often include highly aggregated integrated structures, in which climate change impacts in different sectors are aggregated and used to re-evaluate welfare in the presence of climate change. An IAM projection is presented in detail in the section on the Uncertainty of Cost Projections.

A smaller strand of literature uses computable general equilibrium (CGE) models to examine the economic implications of climate change impacts in specific sectors, often using a comparative static approach.[b] Because CGE models have a more disaggregated structure, they need more information to determine annual equilibria, and to run them forward, linking annual changes for more than 40 to 50 years, becomes very difficult. On the other hand, they can track the impacts of climate in a more detailed way than IAMs, which rely on reduced form functions linking impacts to temperature. Recent work at the Organisation for Economic Co-operation and Development (OECD 2015a) has attempted to address these issues by combining a CGE model to investigate the economic impacts of climate change to 2060 with an IAM model (AD-RICE) to look at impacts beyond that. Because their results are similar to a number of other models for the two periods, it is instructive to discuss them in some detail.

The OECD CGE model (ENV-Linkages) contains 35 economic sectors and 25 regions. It models trade flows as well as capital accumulation using capital vintages, in which technological advances trickle down only slowly over time to affect existing capital stocks. The model estimates the impacts of changes in different

box continues next page

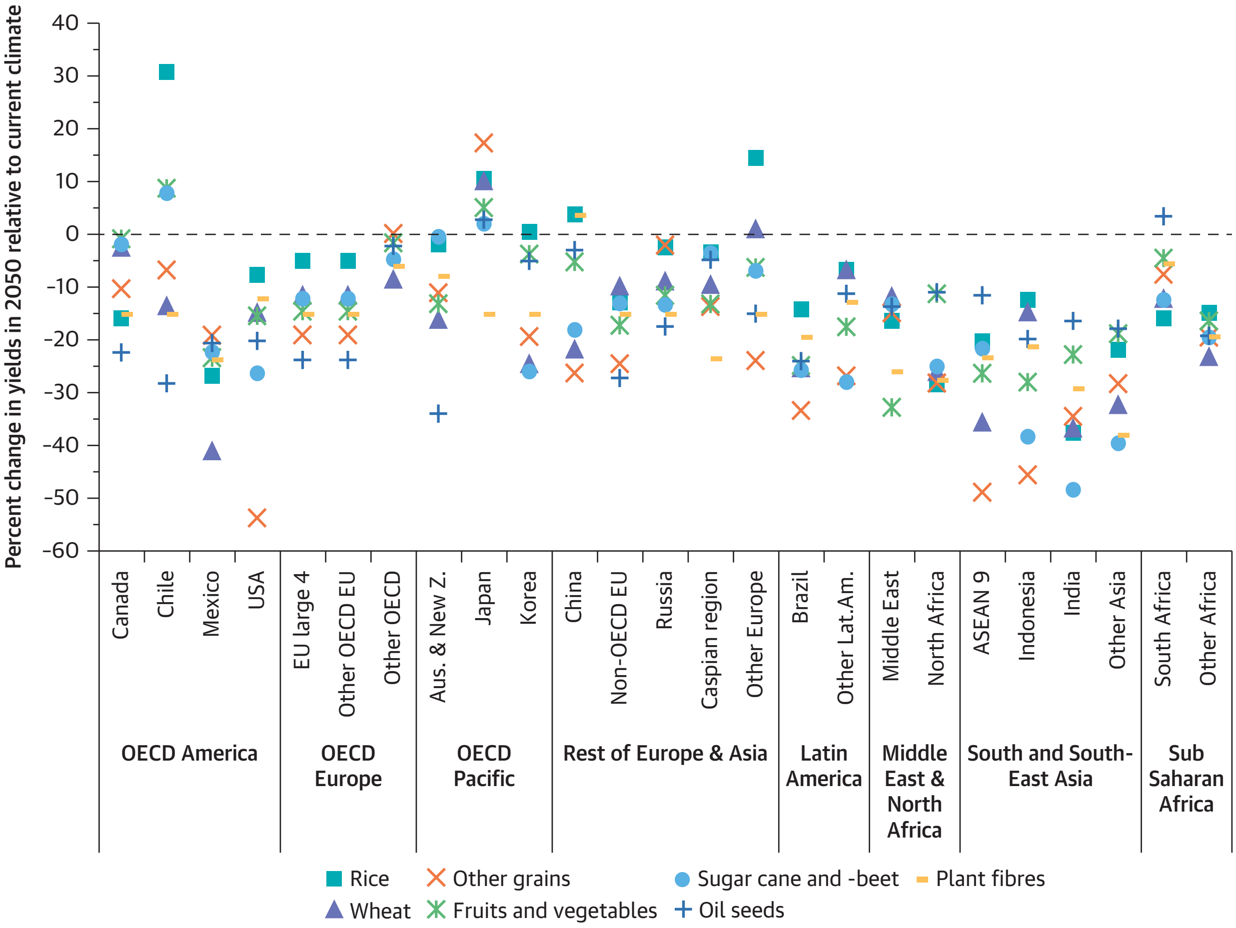
BOX 1. continued

inputs (including water) as a result of climate change using a production function that represents the activity of a specific industry or group of industries in the basic structure of the model. Climate impacts have the potential to directly affect sectors' use of labor, capital, intermediate inputs, and resources. They also affect the productivity of inputs to production. Adverse climate-related shocks to the economy therefore increase the need for more inputs to generate a given level of output. Compared to Integrated Assessment Models in which climate damages are subtracted as a total from GDP, the production function approach can also explain how the composition of GDP is affected over time by climate change: what sectors are most affected and what changes in production factors contribute the most to overall changes in GDP.

[a] See, for example, Nordhaus (1994, 2007, 2010); Tol (2005); Stern (2007); Agrawala et al. (2011).

[b] See, for example, Bosello, Roson, and Tol (2006); Bosello, Eboli, and Pierfederici (2012).

FIGURE 2. Impacts of Climate Change on Crop Yields by 2050



Source: OECD 2015a.

including Central American and Mexico, Sub-Saharan African countries, some parts of the Middle East, and a large part of South and Southeast Asian countries. Some regions experience large increases in paddy rice yields. In particular, the highest gains are estimated for the southern parts of Latin America (particularly Chile), in large parts of Africa (including Morocco, South Africa and other Sub-Saharan African countries), and in parts of Eastern Europe and continental Asia. Such heterogeneity in impacts suggests that climate change will cause major alterations in trade patterns in widely traded commodities such as rice.

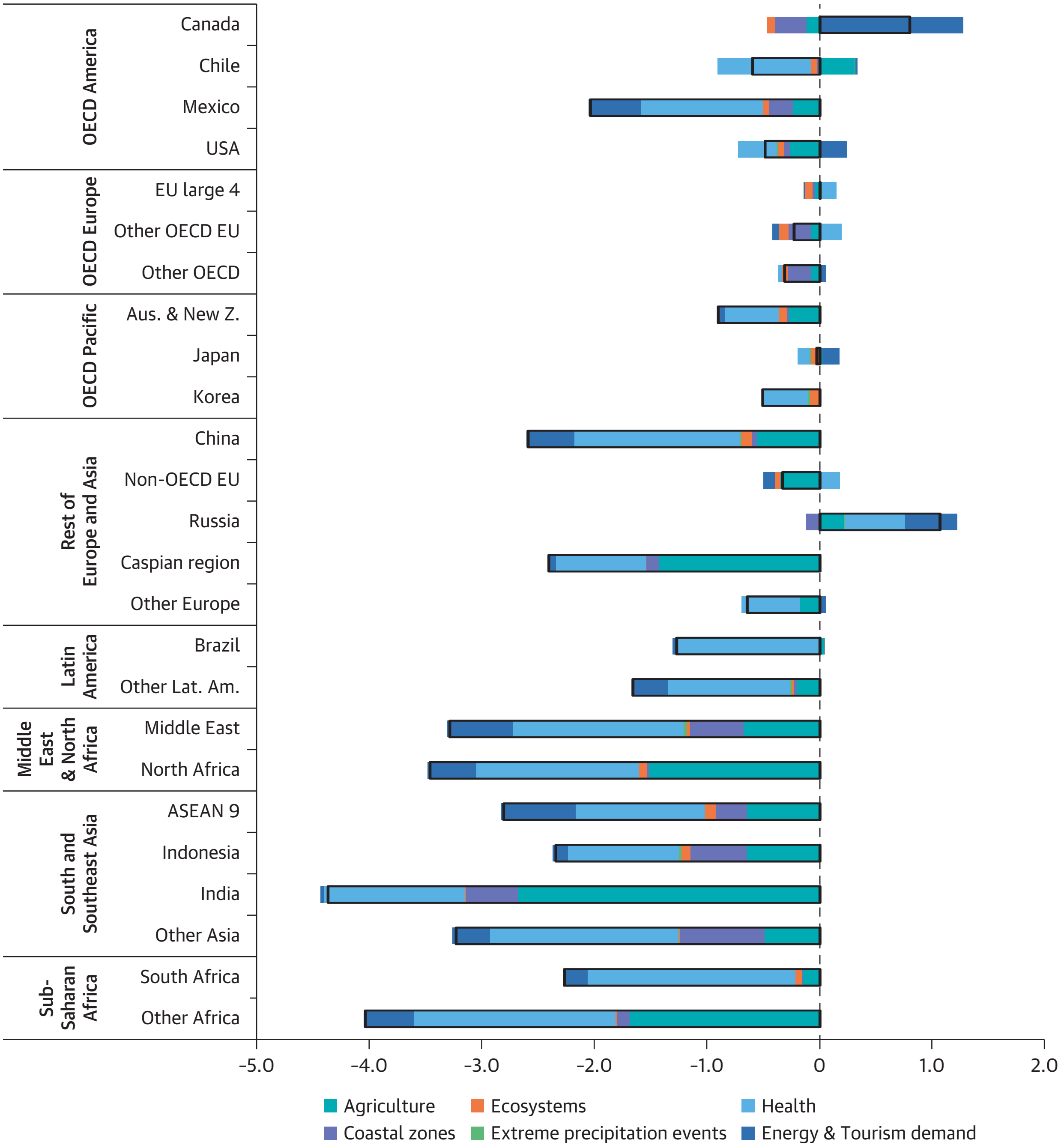
Changes in yields of wheat by 2050 are somehow less differentiated, and most regions are negatively affected. The most severe negative impacts take place in Mexico, Western and Eastern Africa, some Southern African countries such as Namibia and Lesotho, the Middle East, South and Southeast Asia, and some Western European countries, such as Belgium, the Netherlands, and Germany. While these are the most affected regions, negative impacts are widely spread and are also present in most of Europe, continental Asia, and North America. In a few regions, wheat yields are positively affected by climate change, particularly those with cold climates such as Canada, Russia, and the Scandinavian countries, most of Central America, Argentina, some countries in Eastern Europe and continental Asia, and a few African countries.

The estimated effects on GDP in 2060 are calculated as a percentage of "no damage" or baseline GDP in that year, which, of course, also needs to be estimated. The latest set of baseline growth estimates prepared by the community working on these issues (O'Neill et al. 2012) covers a range of growth rates by region, but they are all positive and imply a world that is considerably more affluent, with a minimum annual growth rate of 2.2 percent and a maximum of 4 percent between 2010 and 2060. The OECD study reviewed here took an intermediate value of 2.8 percent for world growth during this period. With such a baseline growth, the total loss of GDP due to changes in agriculture is around 0.7 percent of GDP in 2060, but with notable difference between countries and regions, as shown in figure 3. There are small gains for two countries (Russia and Chile), and modest losses for all the other countries and regions, with the largest impacts in "Other Africa," India, North Africa, and the Caspian region. The countries and regions with positive impacts are also the ones with the expected improvements in river water flow (Chile and Russia), while some of those with negative impacts are also the ones that will be water stressed (India and the Middle East). On the other hand, some of the countries and regions expected to be water stressed, such as China, have only a modest loss of agricultural output.

These predictions are of course subject to considerable uncertainty for several reasons, especially stemming from the assumed level of climate sensitivity as well as the model that predicts impacts due to changes in water stress. Nevertheless, the range of damage estimates when taking account of these factors remains relatively small up to 2060; the upper bound is at most three times the lower bound. This level of uncertainty increases, however, further out in time, when emissions scenarios also start to play a bigger role. The impact of longer time periods is discussed at the end of this section.

These estimates do not cover all the factors affecting agriculture. As noted, an important factor is the effect of higher carbon dioxide (CO_2) concentrations on crop growth—the so-called CO_2 fertilization effect. Including such an effect, which has been highly debated, would lead to higher agricultural productivity, especially for wheat and soybeans, although less so for maize. Rosenzweig et al. (2013) find "approximately ±10 percent yield change" by the end of the twenty-first century from CO_2 effects across a range of models and climate scenarios, but also note that there is wide variation between models and that "crop model parameterization of CO_2 effects remains a crucial area of research."

FIGURE 3. **Changes in GDP Due to Climate Change in 2060 by Region and Impact Category**



Source: OECD 2015a.

Note: ASEAN = Association of Southeast Asian Nations; Aus. & New Z = Australia and New Zealand; EU = European Union; Lat. Am. = Latin America; OECD = Organisation for Economic Co-operation and Development.

Livestock is also likely to be considerably impacted by climate change, but is not covered in this analysis. It is an important part of the agricultural sector for both OECD and non-OECD countries. Although the effects of climate change on livestock are much less exhaustively explored than crop production, the largest part of the literature finds negative effects of climate change, not least through heat and water stress on animal growth, animal health, and the commodities they produce, such as dairy (IPCC 2014). There is, however, a lack of studies with a global coverage of the impacts of climate change on livestock production (IPCC 2014).

Similarly, information on the effects of warming and other climatic drivers on aquaculture is limited. Pickering et al. (2011) conclude that climate change will likely be beneficial for freshwater aquaculture, except in coastal zones. No comprehensive economic study on the impacts of climate change on changes in aquaculture productivity currently exists.

Coastal Land Losses

Coastal land losses due to sea level rise are included in the economic modelling of the OECD study as changes in the availability of land, as well as losses to physical capital. Because information on capital losses is not readily available, changes in land and capital stock are approximated by assuming that changes in capital services match land losses, measured as a percentage change from baseline.

Estimates of coastal land lost to sea level rise are based on the DIVA model outputs (Vafeidis et al. 2008). DIVA is an engineering model designed to address the vulnerability of coastal areas to sea level rise and other ocean- and river-related events, such as storm surges, changes in river morphology, and altered tidal regimes.[8] It is based on a world database of natural system and socioeconomic factors for world coastal areas, reported with spatial details. Impacts are then assessed in terms of both physical losses (sq. km of land lost) and economic costs (value of land lost and adaptation costs).

The regions that are most affected by sea level rise are those in South and Southeast Asia, with the highest impacts in India and "Other Asia." The projected land and capital losses—expressed as a percentage of total regional land area in 2060 with respect to the year 2000—are, respectively, -0.63 percent for India and -0.86 percent for the Other Developing Asia. Other countries in the region are also affected, but to a smaller extent. Some impacts are also felt in North America, with Canada, Mexico, and to a lesser extent, the United States being affected. Canada has the highest loss in land (and capital) in this region (-0.47 percent in 2060 with respect to 2000). Smaller impacts occur in the Middle East (-0.35 percent) and in Europe, where the highest impacts are felt in the aggregate non-OECD Europe region (-0.37 percent), which includes Israel, Norway, and Turkey. Other world regions, such as Africa, South America, and continental Europe, are on balance hardly affected by sea level rise. Estimates of loss of GDP due to coastal zones are shown in figure 3.

Global sea-level rise threatens to flood costal lands in many regions of the world, destroying natural capital, and potentially swallowing up entire island nations in the Pacific Ocean.

This estimate of the impacts of climate change on coastal zones leaves out the loss of a number of nonmarket goods and services that these zones provide. Although scenic and recreational benefits are partly captured in the values of coastal properties, not all such benefits are capitalized in this way. OECD (2015a) also notes that sea level rise might also lead to the loss of entire nation states and their distinctive cultures. Low-lying island states such as the Maldives, Kiribati, Palau, the Seychelles, and Tuvalu are particularly at risk of being completely flooded. Apart from some case studies, evidence on the magnitude of these impacts in economic terms is very limited.

Shifts in Fisheries

As ocean waters warm, fishery ecosystems adapt and change. This will lead to global changes in the fisheries sector, with some warmer regions, such as North Africa and Indonesia seeing output decline, and some colder regions like Russia and North America benefiting.

A major water-related impact of climate change is on the fisheries sector, where there are some estimates of changes in catch potential. This is modelled as a change in the natural resource stock available to fishery sectors, which affects the output of that sector. The input data uses results from Cheung et al. (2010), which estimate maximum catch potential as dependent upon primary production and distribution. It considers 1,066 species of exploited fish and invertebrates. Future projected changes in species distribution are simulated by using a model (Cheung et al. 2008, 2010) that starts with identifying species' preference for environmental conditions and then links them to the expected carrying capacity. The model assumes that carrying capacity varies positively with habitat suitability of each spatial cell. Finally, the related change in total catch potential is determined by aggregating spatially and across species.

The input data for the fisheries sector is the percentage change in fish catch with respect to the year 2000. The most negatively affected regions by 2060 are North Africa (−27 percent) and Indonesia (−26 percent). Some European countries, the Middle East, Chile, and several countries in Southeast Asia have impacts ranging from −10 percent to −15 percent. Smaller negative impacts also take place in China, Korea, Brazil, and other Latin American countries, Mexico, and some European countries. In some countries, fish catches increase. The highest increases will occur in Russia (+25 percent) and in the five major European economies (+23 percent). Small positive impacts are seen in the United States, Canada, Oceania, and the Caspian region. Other world regions (India, other developing countries in Asia, South Africa, and the rest of Africa) are mostly unaffected.

Economic valuations of other water-related ecosystem services, such as wetlands, mangroves, coral reefs, and rivers and lakes (OECD 2015a), can be conducted by using a modified willingness to pay (WTP) approach (Bosello, Eboli, and Pierfederici 2012). The WTP to avoid a given loss in ecosystems is used to approximate the lost value in case these habitats are not protected. This is, for instance, the methodology applied in Stanford University's MERGE model (Manne, Mendelsohn, and Richels 1995).[9] In this approach, the monetized ecosystem losses related to a 2.5°C temperature increase above preindustrial levels is found to be approximately equal to 2 percent of GDP when per capita income is above $40,000. This calibration to 2 percent GDP loss for 2.5°C temperature increase represents the U.S. Environmental Protection Agency (EPA) expenditure on environmental protection in 1995. The strong implicit assumptions are that what is actually paid is reasonably close to the WTP, and roughly sufficient to preserve ecosystems and their services in a world with moderately increasing temperatures. Such an approach is also only partial; it does not pick up other losses of ecosystem services, such as those arising from the extinction of certain species.

By 2060, the countries with the highest WTP for all these ecosystem services are mainly the largest economies, including Canada, Japan, Korea, Mexico, South Africa, and the United States, as well as many European countries. These countries are willing to pay around 1 percent of GDP to protect these ecosystem services. The WTP is smaller (between 0.3 percent and 0.7 percent of GDP) in much of Latin America, China, Russia, the Middle East, and in OECD EU regions. Other regions have very small WTP; the smallest is in the group of Sub-Saharan African countries. This distribution of WTP values is not surprising because there is a strong connection between the willingness to pay for ecosystem services and average income in certain countries. Hence, it is natural that the WTP for ecosystem services is higher in high-income countries such as the United States or Canada, while being much lower in other areas of the world, such as continental Africa.

The total value of these losses in terms of GDP is shown in figure 3 (which includes losses from both fisheries and other ecosystem services). They are not large in any country or region, but are notable in Australia and New Zealand, the ASEAN 9, Canada, China, the largest four EU states, Indonesia, Korea and the United States and the.

Nevertheless, these estimates are only lower bounds, as they do not take into account non-use values of ecosystems and potential biodiversity loss, which could be a consequence of climate change. The assessment has also not accounted for possible changes in forest areas and the associated changes in services from the related ecosystems.

Increasing Flood Damages

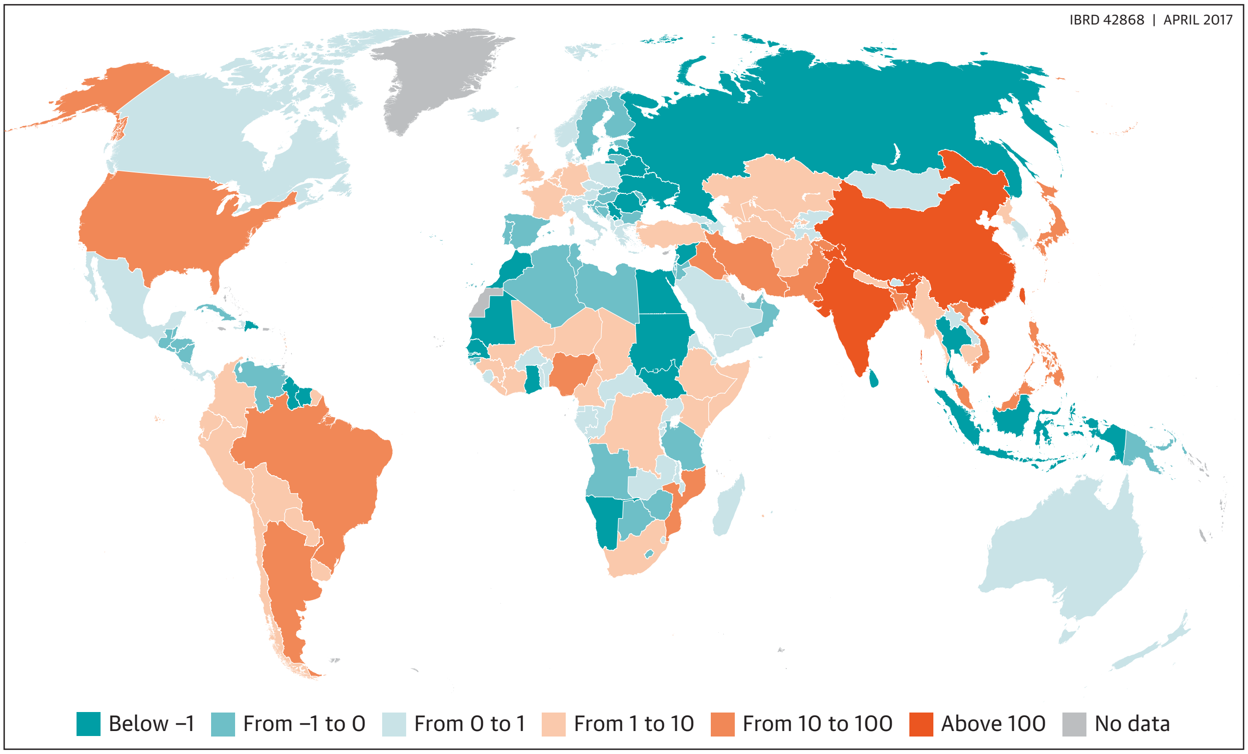
There are many types of extreme events and they affect the economy in different ways. Given the uncertainties involved in predicting the frequency and damages caused by these events, however, and the difficulties in attributing such events to climate change, the available data on how the economy will be affected are still scarce. The assessment by Mendelsohn et al. (2012) has provided some quantitative assessment and projections on damages from hurricanes. The authors stress that the regional damages are quite sensitive to the climate model that is used to project future climate conditions. They find overall that climate change is predicted to increase the frequency of high-intensity storms in selected ocean basins; the predicted extent depends on the climate models used. In value terms, Mendelsohn et al. (2012) find the current global damage from tropical cyclones to capital stocks to be around $26 billion, which is equivalent to 0.04 percent of global GDP. That is expected to roughly double by the end of the century under current climate conditions, due to changes in socioeconomic conditions not related to climate change. However, these damages are projected to double again by the end of the century due to climate change: that is, they are estimated to increase by a factor of 4. Most additional climate-induced damages are predicted to take place in North America, East Asia, and the Caribbean-Central American region, where the United States, Japan, and China will be most affected.

These estimates do not include damages from extreme events in the form of illness, disease and premature mortality. So far, there is no robust database to capture the impacts of climate change on river and other floods. As OECD (2015a) observes, flood risk models exist, which calculate indicators such as area at risk of flooding and population at risk of flooding, but these do not easily translate into economic costs. A groups of models, including GLOFRIS (Ward et al. 2013, 2014), can be used to compare projections of future flood risks with and without climate change (Winsemius and Ward 2015) and thus establish the additional damages due to climate change. Using the framework of Ward et al. (2013), the OECD (2015a) has estimated the excess urban flood damages from climate change.

Although the economic costs of tropical storms attributable to climate change are relatively small, flood damages are expected to increase significantly in some regions, with global urban damage estimates potentially reaching $1.8 trillion by 2080.

Map 2 shows the projected urban climate damages from floods for 2080 under the RCP 8.5 scenario, for data aggregated to the country level.[10] The two countries with by far the largest projected urban flood damages are India and China. The main driver for this is the huge increase in the urban assets that are exposed in these countries. The scale of flood risks is so large in these countries that the additional damages from climate change are also huge. Bangladesh is also high in the ranking of most affected countries, but in this case the role of climate change is substantially larger. The opposite is true for Indonesia, Russia, Thailand, and the main Nile countries, where flood risks are

MAP 2. **Urban Climate Change Damages from Floods by 2080**



Source: OECD 2015a, based on Winsemius and Ward 2015.

currently relatively high, but the additional damages from climate change are projected to be negative. For OECD countries, the climate-induced urban flood damages are limited to less than $50 billion a year by 2080. That does not mean that total urban flood damages— either climate-induced or not—are much smaller than in non-OECD regions. For example, the annual damages by 2080 amount to $170 billion in the United States, $58 billion in Mexico, $20 billion in Germany, and $17 billion in the Netherlands. But the climate-induced component of these damages is substantially smaller than for many non-OECD countries.

Given the importance of the projected regional precipitation patterns for these simulations, and the large uncertainties surrounding them, these results can only be considered as indicative. As table 2 shows, there are significant differences depending on which climate models are adopted to make these projections. For instance, only the HadGEM model projections imply a reduction in urban flood damages in Indonesia; the other models all predict increased damages for this country. For the OECD region, the largest uncertainty is in the projections for Mexico. Nonetheless, there are also some consistent patterns across the models, including the fact that the largest climate-induced urban flood damages are in Asia in general and in India in particular, and that the flood damages in Russia decrease due to climate change. Using climate scenarios from the HadGEM model, global annual urban flood damages are projected to amount to between $0.7 and $1.8 trillion in 2080.

TABLE 2. Urban Flood Damages by Region and Model

($US billion, 2005 PPP exchange rates)

	HadGEM			GFDL	IPSL	MIROC	NorESM
	2010	2030	2080	2080			
OECD America							
Canada	0.0	0.5	0.0	1.5	−3.6	1.9	0.8
Chile	0.0	0.3	2.0	−3.4	−3.1	−3.4	−0.4
Mexico	0.0	−0.5	0.7	66.3	−49.7	−15.6	−29.9
USA	0.0	2.3	19.4	10.2	16.6	5.4	3.5
OECD Europe							
EU large 4	0.0	1.9	11.2	0.8	3.9	4.8	2.2
Other OECD EU	0.0	1.6	8.8	1.6	5.8	4.6	2.6
Other OECD	0.0	−0.2	1.5	−6.2	−5.2	−4.5	0.1
OECD Pacific							
Aus. & New Z.	0.0	−0.3	1.3	−4.2	1.4	1.2	0.4
Japan	0.0	0.6	3.4	2.6	1.2	0.9	1.5
Korea	0.0	0.2	0.9	1.1	0.4	2.0	0.7
OECD	0.0	6.2	49.2	70.3	−32.1	−2.8	−18.5
Rest of Europe and Asia							
China	0.0	48.0	427.9	343.0	88.8	102.5	184.4
Non-OECD EU	0.0	−0.8	−3.6	−1.7	−2.3	4.4	0.7
Russia	0.0	−5.4	−32.6	−7.6	−7.8	−4.7	−44.8
Caspian region	0.0	1.9	17.6	2.6	−4.6	2.9	−6.4
Other Europe	0.0	−2.6	−13.5	−7.9	−6.8	2.1	−12.6
Latin America							
Brazil	0.0	0.9	12.6	6.7	98.1	−15.1	−40.3
Other Lat. Am.	0.0	−0.7	15.2	−10.5	10.5	−16.6	−26.9
Middle East & North Africa							
Middle East	0.0	−0.3	39.8	−60.9	−32.2	−34.2	9.4
North Africa	0.0	−2.5	−44.9	128.0	243.2	47.2	25.0
South and Southeast Asia							
ASEAN 9	0.0	−0.7	65.1	185.2	139.1	57.9	196.1
Indonesia	0.0	−2.7	−29.0	5.2	152.8	11.2	38.4
India	0.0	51.5	1,094.9	432.7	718.3	362.2	207.8
Other Asia	0.0	2.4	184.0	153.9	148.9	117.8	114.1
Sub-Saharan Africa							
South Africa	0.0	0.1	3.3	4.8	2.2	−2.0	−1.4
Other Africa	0.0	3.1	59.3	85.6	178.4	225.1	76.1
World	0.0	98.4	1,845.3	1,329.4	1,694.3	857.9	701.2

Source: OECD 2015a, based on Winsemius and Ward 2015.

Note: HadGEM, GFDC, IPSL, MIROC, and NorESM are specific climate models that are used to project precipitation and temperature patterns (see Winsemius and Ward 2015 for more details). PPP = purchasing power parity. ASEAN = Association of Southeast Asian Nations; Aus. & New Z = Australia and New Zealand; EU = European Union; Lat. Am. = Latin America; OECD = Organisation for Economic Co-operation and Development.

It is also important to note that these calculations provide an estimate of potential damages, without any adaptive behavior to deal with increased flood risks. Hence, the numbers presented here should be interpreted as an upper bound of the costs that will occur when such adaptation is taken into account. On the other hand, urban damages are only one element of flood damages, and the local disruption effects are excluded here. These are likely to have severe consequences for local communities, even if their economic effect may be relatively small (compared to the damages from hurricanes).

Increases in Water-borne Diseases and Water-related Deaths and Injuries

Climate change will have water-related impacts on health, with increases in water-borne diseases and deaths and injuries caused by flooding.

The health impacts of climate change are generally divided into those arising from climate-related diseases, effects of heat stress, and the effects of extreme events. Effects that can be attributed to heat stress and climate-related diseases are not particularly water-related and they are not discussed further, except for diarrhea. For water-borne diseases, estimates of the costs are generally measured in terms of the additional expenditures needed to treat the cases arising from climate change. Ebi (2008) estimated the costs of specific interventions for treatment of additional cases of malaria, diarrhea, and malnutrition that are expected to occur between 2000 and 2030 because of climate change. Her projections show increases of 5 percent in malaria disease, 3 percent in diarrhea, and 10 percent in malnutrition. Ebi's projections for diarrhea are a little lower than those of Kolstand and Johansson (2011), who project an increase of 8-11 percent in the risk of diarrhea in the tropics and subtropics due to climate change using the A1B scenario (see description above in footnote 1). Ebi estimates the additional annual costs of treating diarrhea in 2030 to be between $1.7 and $9.0 billion.

The costs of extreme events in the form of deaths, illnesses, and injuries from floods and sea level rise due to climate change are not available on a systematic basis. According to the EMDAT disaster database,[11] there have been an annual average of 16,117 deaths worldwide between 2000 and 2014 from floods and storms. In addition, an average of 75.4 million people have been affected every year. Most, but not all, of these impacts have been in developing countries. In the future, with climate change such losses can be expected to increase, but reliable estimates are not available. Hinkel et al. (2014) estimate the number of people who may be displaced during this century due to sea level rise under different modelling assumptions, but do not estimate deaths and injuries. There are also estimates of people at risk from flooding for some regions,[12] but they also do not estimate deaths or injuries. Even if estimates are available, converting these into monetary terms would require valuing loss of life, which is controversial.

Increase in the Cost and Decrease in Reliability of Power Supply

Water plays an important role in the supply of energy, not only in the generation of hydropower but also in providing an input into the generation of thermal and nuclear power. A number of studies have highlighted the increased cost of reduced water availability from climate change for supplying electrical energy. Under higher temperatures, the efficiency, output, and reliability of thermal power plants is expected to suffer as a consequence of reduced water volume and higher water temperature—two factors that are crucial for cooling of most of these plants (alternative processes, such as dry cooling, typically consume more electricity and require higher investment costs). Climate change could raise the costs of power plants in areas where climatic factors increase water scarcity. China could be particularly affected by this development, given that much of the existing and planned coal power capacity is located in regions with high risks of water stress.

Cost increases in India are expected to be smaller, given that Indian coal mines, power stations, and industrial demand are located mostly in areas with lower risks of water scarcity (IEA 2015; WRI 2014). A case study by Hurd et al. (2004) has assessed the likely welfare costs of climate change impacts on water use in electric power generation in the United States, projecting losses of about $622 million per year up to 2100 due to changes in cooling water for combustion in coal, natural gas, and other thermal power stations. The study assumed warming of +2.5°C above preindustrial levels and a drop of 10 percent in monthly average precipitation. Water shortage can also negatively affect the operation of hydropower plants (IPCC 2014).

There is also an issue with hydropower, where low flow rates will create difficulties in maintaining the current and proposed levels of generation. In Europe, for example, recent warm, dry summers have shown the vulnerability of the European power sector to low water availability and high river temperatures. Climate change is likely to affect electricity supply, in terms of both water availability for hydropower generation and cooling water usage for thermoelectric power production. Van Vliet, Vogel, and Rubbelke (2013) estimate the impacts of climate change and changes in water availability and water temperature on European electricity production and prices. Using simulations of daily river flows and water temperatures under future climate in power production models from 2031 to 2060, they show declines in both thermoelectric and hydropower generating potential for most parts of Europe, except for the most northern countries. Gross hydropower potential of Europe is estimated to decrease on average by 4–5 percent for 2031-60 (SRES B1-A2) relative to 1971-2000, with decreases of around 16-20 percent in Bulgaria and 15-21 percent in Spain. Based on changes in power production potentials, they assess the cost-optimal use of power plants for each European country by taking electricity import and export constraints into account. Higher wholesale prices are projected on a mean annual basis for most European countries (except for Sweden and Norway), with the strongest increases for 2031–60 for Romania (31-32 percent), Bulgaria (21–23 percent), and Slovenia (12–15 percent), where limitations in water availability mainly affect power plants with low production costs.

The implications of water scarcity will need to be taken into account more fully when choosing energy options for mitigating CO_2. The World Bank's Energy Sector Management Assistance Program (Ebinger and Vergara, 2011) produced figure 4, which shows both the water intensity (M^3/kWh) and CO_2 (kg/kWh) intensity of different electricity options. Several low-carbon options such as nuclear, solar, thermal, and geothermal have a high water intensity, which may determine where they can be located.

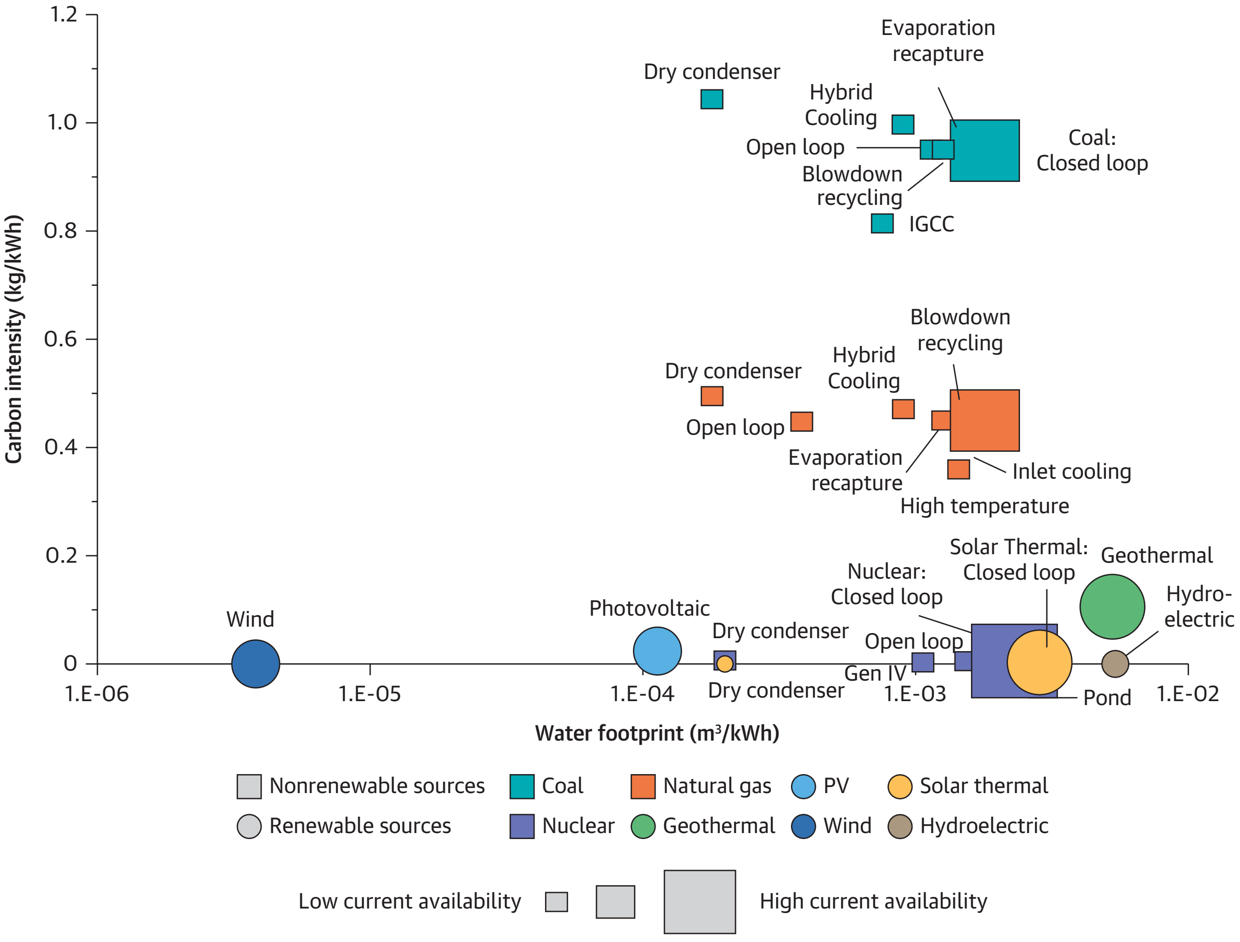
Stress on Municipal Water Supplies and Quality

In addition to negative economic consequences for water-intensive economic activities, reduced water availability from climate change will likely also be felt by households and municipalities through impacts on the availability and quality of drinking water (OECD 2013, 2015a; IPCC 2014). However, economic values of these impacts are not available.

A changing hydrological environment will also put stress on municipal water supplies and affect water quality at the household level.

A recent study by Henderson et al. (2015) attempted to estimate the economic impacts of climate change on water resources in the United States, covering several other types of water use beyond irrigation and cooling. The study suggests annual damages of approximately $2.1 billion by 2050 and $4.2 billion by 2100 without new climate change policies. The largest impacts are projected to affect non-consumptive activities, such as hydropower and environmental flows. Agriculture and other consumptive uses will be impacted by climate

FIGURE 4. **Water and Carbon Intensity of Different Fuel Cycles**



Source: Ebinger and Vergara 2011.

change less negatively. Similarly, Strzepek et al. (2014) suggest negative welfare consequences for the United Sates in the order of $6.5 to $15 billion by the end of the century in their assessment of the impacts of climate change on water supply, management, and use of water resources. For the year 2050, results are more ambiguous, with one scenario suggesting positive effects on welfare from climate change and two others suggesting negative effects.

Although climate and economic models universally agree that damages from the effects of climate change on water will be costly, the precise magnitude of the costs are uncertain and projections should be treated with caution.

The Uncertainty of Cost Projections

The expected damages discussed in the preceding sections are small relative to the expected GDP in 2060; they amount to about 1.5 percent of GDP in that year. That figure, however, is misleading in a number of respects. First, as can be seen from figure 2, there are significant variations between regions, with Northern Europe and North America having much lower damages and South Asia and Sub-Saharan Africa having much higher damages.

Second, there is considerable uncertainty in the estimates. If the upper bound turns out to be right, the figures could be two to three times higher. A key source of uncertainty is the equilibrium climate sensitivity (ECS): the amount by which temperature will increase with a doubling of GHG concentrations.

Third, the process for making the estimates is strongly driven by the underlying growth in the economy, which is assumed to be around 2.8 percent per year. All the models that make projections to 2050 and beyond assume some global growth rates of at least 2 percent per year, which decreases the importance of more climate-related sectors such as agriculture in the structure of the economy. Furthermore, scarcity of water in the coming decades may make these projections infeasible, as discussed.

Fourth, the CGE model assumes relatively easy substitution between factors. When there is a shock and an input such as land or water is reduced, the model assumes that the input can be replaced with other factors such as capital, and any displaced labor can be absorbed by other sectors of the economy in a painless fashion. In practice, such substitution will take time and will involve transition costs that are not accounted for. Some ongoing work indicates that allowing for imperfect substitution will raise the cost of climate change, but the adjustment does not appear to be huge.

Fifth, the scenarios modelled in the CGE part of the analysis are based on relatively small increases in temperature (around 2 degrees Celsius). If higher increases occur, then the assumptions of the model in terms of climate impacts may not hold, and there is no experience on which to base the sectoral changes. These higher increases are discussed in the next section.

Lastly, the estimates of losses are incomplete. They do not include all impacts, nor do they value losses of life. All these factors would raise damage estimates from climate change through a number of pathways, of which water is an important one.

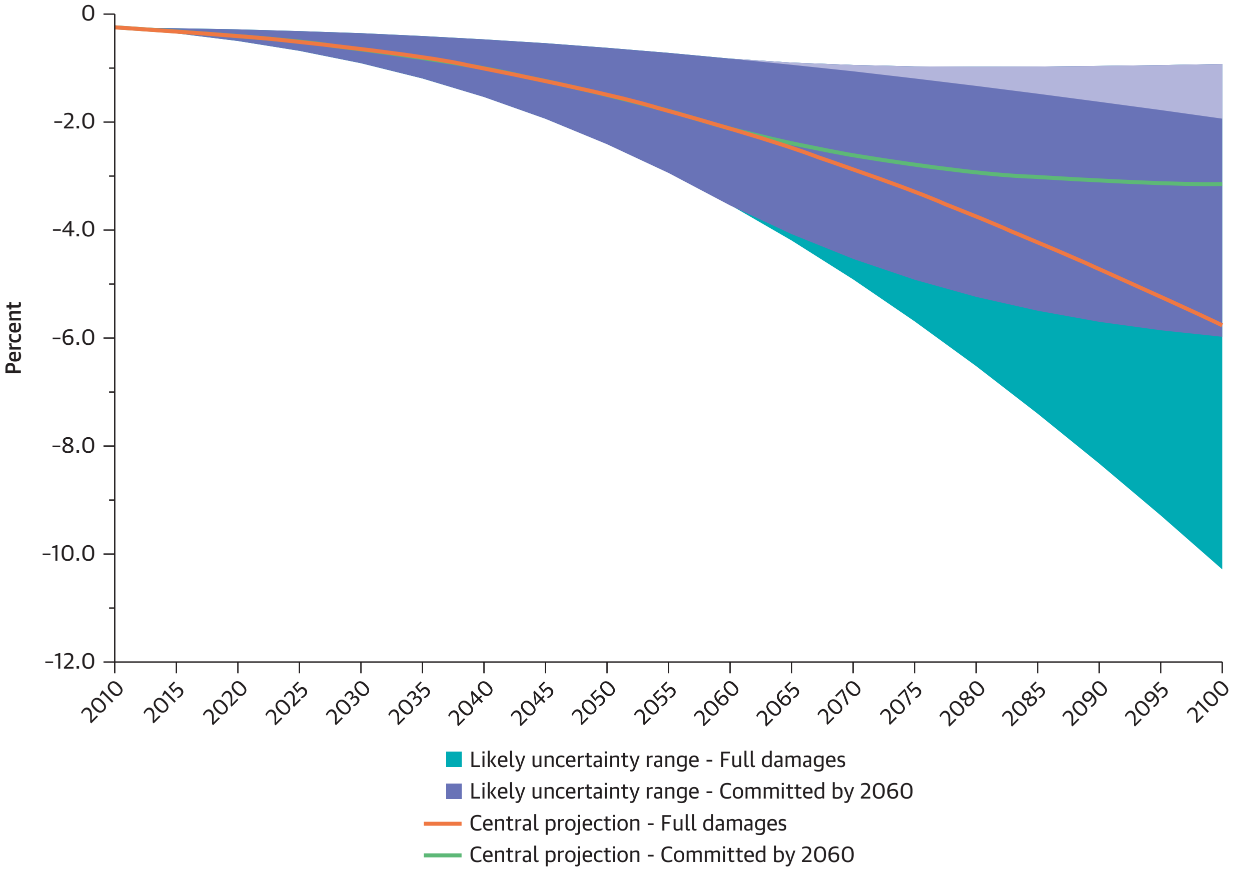
Alternative ways to look at the link between factors such as water and the economy under climate change is thorough their direct impact on growth. These are examined in the next section.

When estimating climate change damages beyond 2060, uncertainty increases, but it is likely that the rate of damage will accelerate.

The damages or costs of inaction in the face of climate change will not stop in 2060. The modelling indicates an increase in the rate of damage after that date, at the same time as an increase in the level of uncertainty in the projections and underlying data. This applies to all sources of damages, including those related to the water sector. Figure 5 shows the annual damages from 2010 to 2100 relative to a no-damage baseline for all damages (not just from water-related sectors). The main estimate increases from around 2 percent of GDP in 2060 to around 6.8 percent by the end of the century. These projections are based on the AD-DICE model, which is one of the IAMs with estimates in the middle of the range generated by such models.[13] In the long term, the equilibrium climate sensitivity (ECS) has even more impact on the estimated damages. Within the range of values of this parameter, the corresponding range of damages by 2100 is between 2 percent and 10 percent of GDP. With a wider interval for ECS that is plausible, damages can vary from 1 percent to 15 percent of GDP, with a corresponding range of temperature increase under inaction of 2.4 to 5.5 degrees Celsius (OECD 2015a). The figure also shows the extent to which damages beyond 2060 are committed as a result of emissions produced by 2060. If emissions are assumed to stop completely in 2060, damages will continue to 2100 as a result of the inertia in the system. This is especially true for sea level rise damages, which respond very slowly to a change in emissions. Consequently, damages that were around 2 percent of GDP in 2060 will rise to around 3 percent by 2100. Thus, the case for action on emissions now is partly to forestall damages in the future.

As noted, these long-term estimates are uncertain because of the unknown ECS, but also because the

FIGURE 5. Climate Change Impacts in the Very Long Run



Source: AD-DICE model.

damage functions linking temperature and precipitation to damages are crude and not well determined (up to 2060, the use of such a function is avoided in the reported figures by using direct links between impacts and sector-level production functions).[14] As noted, continuing the projections to 2100 with no action may result in very high increases in temperature. There is no basis for estimating damages for such scenarios. An alternative to the "standard" function used in the AD-DICE model is one proposed by Weitzman (2013), in which damages at high temperature increases are modelled using higher power terms in the damage function. The result is an increase in potential damages by 2100 that increases from the figure of 6.8 percent previously discussed to as much as 18 percent of GDP.

A main message from the longer-term analysis therefore is that the costs of inaction in terms of economic damages rise substantially beyond 2060, as the world approaches 2100. At the same time, so does the uncertainty, making the case of action now much more one of applying the precautionary principle. The second message is that action now will affect the future path of damages to a significant extent because of the inertia in the system. This also makes a case for reducing emissions significantly in the period to 2060.

Other Models

An alternative approach to looking at the nexus of water, climate change, and the economy is through the effects of climate change on water and thereby on the growth of the economy. There is an emerging literature that takes the view that an important pathway for climatic impacts is through the damage they do to the capital stock and to the capacity of the economy to increase total factor productivity and thereby growth.

This literature is in part motivated by empirical studies that show how historic climate-related events have in fact reduced growth in some economies. Dell, Jones, and Olken (2012) were the first to investigate the effects of climate variability (temperature and precipitation), on GDP per capita, agricultural value added, industrial value added, and investment. The study also assesses the lagged effects of climate variability for periods of 1, 5, and 10 years. It finds that for Sub-Saharan Africa, a one-degree increase in temperature has been statistically significantly associated with a 1.8 percent decline in the growth rate. In poor countries, as a group, the effect of a one-degree increase is to reduce growth by 1.4 percent.

While Dell, Jones, and Olken (2012) do not find a significant link between precipitation and GDP growth, Brown et al. (2013) do. They apply a similar regression model, allow for temporal and spatial variation in precipitation, and use a more sophisticated index for precipitation variability. The analysis for a panel dataset of 133 countries showed that an increase of 1 percent in the area of a country exposed to a drought for a given period results in a decline in GDP per capita of 2.7 percent, and an increase of 1 percent in the area of a country exposed to a flood is associated with a reduction in GDP per capita of 1.8 percent. More recently, Moore and Diaz (2015) take the results from Dell, Jones, and Olken (2012) and use them to project growth rates with different mitigation polices, concluding that growth could be significantly reduced with a business-as-usual policy.

Another interesting study that looks at the historic link between economic performance and growth is Hsiang and Jina (2014). Using meteorological data, they reconstruct every country's exposure to the universe of tropical cyclones from 1950 to 2008 and estimate the causal effect such events have on long-term growth. Comparing each country's growth rate to itself in the years immediately before and after exposure, the data reject the hypothesis that disasters stimulate growth or that short-term losses disappear following migrations or transfers of wealth. Instead, they find "robust evidence that national incomes decline, relative to their pre-disaster trend, and do not recover within twenty years." The conclusion holds both for developed and developing countries. They note: "Income losses arise from a small but persistent suppression of annual growth rates spread across the fifteen years following disaster, [generate] large and significant cumulative effects: a 90th percentile event reduces per capita incomes by 7.4 percent two decades later, effectively undoing 3.7 years of average development." Based on these results, they estimate that projections of future cyclone activity would result in a discounted present value cost that is about $10 trillion larger than previous estimates.

Several other types of models exist for predicting climate change and water's effect on future economic growth, which provide alternative and sometimes different predictions.

These studies are valuable in pointing to a pathway by which climate change could have bigger impacts and need to be taken seriously. Yet there are some difficulties with them. First, the econometric estimates can be criticized on a number of grounds, such as: using linear functions where nonlinearity is more likely to be the case; not taking account of year-to-year variability of temperature and rainfall (in the case of Dell, Jones, and Olken 2012); and not allowing for individual country effects. Second, in terms of economic structure, they do not indicate how the causality works. This leaves open the possibility that the common observations of climate variability and GDP changes are the result of some other factors such as a structural shift to lower growth in Sub-Saharan Africa countries during a period when an increase in temperatures has been observed. More work is needed to confirm these results and to understand the causality.

One way to understand the growth impacts of climate change is to link the changes caused by climate not only to flows of goods and services but also to the capital stock and the productivity of that stock. The latter can come through changes in the rate of technological change of the economy, measured in terms of total factor productivity (TFP). It is possible to incorporate the capital effects by allocating part of the damages estimated in the previous section to the capital stock. An estimate for the share to be allocated is around 30 percent (Dietz and Stern 2014). Alternatively, it can be assumed that this 30 percent of damages affects not the capital stock but the growth rate of TFP. If either path is followed, the level of damages does increase, but not dramatically. By 2060, expected damages rise about 1 percentage point under the assumption that residual damages are allocated to TFP growth. If they are allocated to the capital stock, the total damage goes up by only 0.2–0.3 percent. By 2100, the differences are more pronounced, with the effects via TFP growth damages increasing by about 2 percentage points and with the effects operating via the capital stock increase by about 0.5 percent.

Another way to look at the growth issue is to model it explicitly in a CGE model. Some work is ongoing in that direction. Taheripour et al. (forthcoming) have developed a version of the GTAP model with detailed modelling of biofuel supply as well as water demand and supply through the GTAB-BIO-W Model, and applied it to the South Asia region (Bangladesh, India, Pakistan, Sri Lanka and the rest of South Asia).[15] This model retains the multilevel constant elasticity of substitution (CES) structure and irrigated/rain-fed crop production of the existing GTAP-W model, but overcomes some of its shortcomings. The most marked difference is that GTAP-BIO-W permits competition for resources to take place at two different levels: competition for water within river basins and competition for land within agro-ecological zones (AEZs). This design significantly improves the adaptability of the model. For example, the irrigated and rain-fed production functions operate independently from one another. That means irrigated crop production can be completely removed from a certain part of the country if water supply for irrigation falls short. Moreover, in GTAP-BIO-W, intersections between different river basins and agro-ecological zones are featured by different technologies (production functions) that reflect water availability, growing conditions, and soil quality peculiar to that area.

Because a computable general equilibrium (CGE) model requires detailed specification of individual sectors of the economy, it is not possible, for reasons explained earlier, to provide long-term projections. Thus the exercise is limited in time—in this case, to 2050. In that time frame, the study investigates the consequences of the expected growth in GDP and population and how economic output by sector may be affected by constraints on water supply, including those resulting from climate change.

Given the strong baseline projected growth in GDP and population in the region, and the water scarcity that has already been noted, it is not surprising that such scarcity could compromise the baseline projections. The modelling shows that climate change adds to the effects of the expected scarcity of water. With the two taken together, losses of GDP by 2050 relative to the baseline are now 5.2 percent in Bangladesh; 1.8 percent in India; 0.8 percent in Nepal; 5.6 percent in Pakistan; 0.6 percent in Sri Lanka; and 0.5 percent in Rest of South Asia. If, however, water for agriculture were to be available (that is, the non-climatic uncertainty were to be removed), the effects of climate change on GDP would be very small; they would be reduced by more than an order of magnitude.

The main implication of water scarcity then is one of addressing the scarcity problem, through improvements in water and land productivity as much as possible. In general, water efficiency use in irrigation is relatively low in this region. It can be improved substantially, but this requires additional investments and changes in water allocation rules.

Reducing Future Damage through Investment in Adaptation Technology

The damages assessed to 2060 and beyond make a strong case for action on adaptation; up to 2060 these actions are more or less independent of the mitigation policies undertaken, but beyond that date, the mitigation and adaptation policies are interrelated. The higher the level of mitigation, the lower the damages in the future and the less is needed in the way of adaptation expenditure to reduce these damages. The two become substitutes for each other. At a more specific level, however, adaptation and mitigation can work against each other, particularly over water use. Adaptation to changing hydrological regimes and water scarcity, for example, takes place through increasing reuse of wastewater and the associated treatment, through deep-well pumping, and possibly large-scale desalination. These adaptation measures increase energy use in the water sector, leading to increased emissions and mitigation costs (Klein et al. 2007).

Adaptation costs are made up of proactive (or anticipatory) adaptation (taken in anticipation of expected damages often by the public sector), reactive adaptation (take after the impacts have occurred so as to minimize their consequences), and innovative activity (undertaken to make adaptation responses more effective) (Bosello, Carraro, and De Cian 2013). The anticipatory and reactive adaptations are also referred to in the literature as stock and flow forms. The former often involve an investment in capital, while the latter consist of sector-related periodic expenditures (OECD 2015a).

Estimates of the amounts of adaptation expenditure should be determined by the point at which the marginal damages reduced are equal to the additional expenditure on a particular type of adaptation. These levels will depend of course on the level of baseline damages and will vary over time. Bosello, Carraro, and De Cian et al. (2013) have summarized the outlays on proactive adaptation, reactive adaption, and innovation activity for a situation in which concentrations of CO_2 double.[16] The figures are based on the literature. In the case of water, they consist of additional costs for agriculture– largely for irrigation, for providing water for other uses in areas where scarcity is expected to increase, for dealing with flood risks in river systems, and for expenditure on coastal protection. Their data are given in table 3, in both billions of U.S. dollars and as a percent of GDP.

Investments in adaptation technology and capital can significantly reduce future impacts from water damages induced by climate change.

The table indicates about 60 percent of all adaptation expenditures as allocated for water-related impacts, with the greatest amounts going to the Middle East and North Africa (MENA), East Asia, and South Asia, for agriculture and other vulnerable areas; and to Latin and Central America and the Caribbean (LACA), East Asia, and Western Europe for coastal protection. As a percent of estimated GDP in the year of calibration (2050), the costs are modest, ranging from 1.5 percent (MENA) to 0.2 percent (Canada, Japan, and New Zealand, CAJANZ). In absolute terms, they amount to $613 billion, which is a much greater amount than the current finance for adaptation—estimated at around $26 billion to $32 billion by Buchner et al. (2014)—but recall that the figures in the table are for 2060.

Although the table provides some of the best available estimates, it should be viewed as only a rough guide to the likely adaptation needs. The underlying studies are quite crude; they are not based on a detailed bottom-up assessment, and for some categories, such as early warning systems, the figures appear to be merely a placeholder. Furthermore, it is not clear what is

TABLE 3. Annual Adaptation Costs in Response to a Doubling of CO_2 Concentrations in 2060

	Water in agriculture (Irrigation)	Water in other vulnerable markets	Early warning systems	Coastal protection	Settlements	Cooling expenditure	Disease treatments	R&D for adaptation	Total	Total as % of GDP
USA	5.0	2.1	5.0	3.6	31.3	1.1	2.9	2.9	53.9	0.1
W. Europe	7.8	3.3	5.0	5.0	63.3	−0.7	2.4	2.4	88.5	0.2
E. Europe	12.3	5.3	5.0	0.3	2.4	−0.1	0.0	0.0	25.2	0.7
KOSAU	0.1	0.1	5.0	1.8	3.7	1.9	0.3	0.3	13.2	0.5
CAJANZ	2.7	1.1	5.0	2.9	23.1	3.0	1.7	1.7	41.2	0.2
TE	16.9	7.2	5.0	1.7	2.0	0.1	0.1	0.1	33.1	0.5
MENA	79.1	33.9	5.0	1.2	3.2	2.1	0.1	0.1	124.7	1.5
SSA	16.1	6.9	5.0	2.7	4.0	0.5	0.0	0.0	35.2	0.9
SASIA	28.4	12.2	5.0	1.3	12.8	1.1	0.0	0.0	60.8	0.6
CHINA	12.5	5.4	5.0	1.3	9.7	0.3	0.2	0.2	34.6	0.3
EASIA	31.2	13.4	5.0	4.3	6.0	4.7	0.0	0.0	64.6	0.9
LACA	7.2	3.1	5.0	7.7	15.0	5.7	0.1	0.1	43.9	0.2
Total	219.3	94.0	60.0	33.8	176.5	19.7	7.8	7.9	619.0	0.4%
As %	35.4%	15.2%	9.7%	5.5%	28.5%	3.2%	1.3%	1.3%	100.0%	

Source: Adapted from Bosello, Carraro, and De Cian (2013).

Note: CAJANZ = Canada, Japan, New Zealand; EASIA = East Asia; KOSAU = Korea, South Africa, Australia; LACA = Latin and Central America and the Caribbean; MENA = Middle East and North Africa; SASIA = South Asia; SSA = Sub-Saharan Africa; TE = transition economies.

assumed about future changes in the pattern of use of existing resources such as water. Earlier, it was observed that major inefficiencies in water use exist, and that removing these would increase water availability significantly, without further investment in irrigation. The adaptation options included in most analysis tend to focus on engineering alternatives and give less weight to changes in behavior and current practices of water use, as well as on other softer alternatives involving the use of ecosystems and the like. For these reasons, estimates of adaptation cost could be on the high side, although this needs further investigation.

The study by Bosello, Carraro, and De Cian (2013) (which uses the adaptation calibration in table 3 in the framework of the AD-Witch model),[17] as well as other similar studies, note that the amount of damage reduced by adaptation is never 100 percent or close to it. The marginal costs of reducing damages through adaptation increase as the percentage rises. The estimates in table 3 are based approximately on the level at which the marginal reduction in damages is equal to the marginal cost. Table 4 shows the reduction in damage that is estimated to be achieved from the expenditures given in table 3.

For the water sector, damage reductions from the adaptation expenditures range from 36 percent (water in agriculture) to 60 percent (water in other vulnerable markets). Reductions are lower from early warning systems for extreme events. Variations by region show higher levels of damage reduction in developed regions relative to developing ones.

An alternative way to look at the amount of damages reduced is to divide adaptation into stock and flow. Stock adaptation refers to measures that require

TABLE 4. **Percentage of Damages Reduced as a Result of Adaptation Costs Presented in Table 3**

	Water in agriculture (Irrigation)	Water in other vulnerable markets	Early warning systems	Coastal protection	Settlements	Disease treatments	Weighted total
USA	48.0	80.0	10.0	75.0	40.0	90.0	25.0
W. Europe	43.0	80.0	10.0	54.0	40.0	90.0	20.0
E. Europe	43.0	80.0	10.0	63.0	40.0	60.0	34.0
KOSAU	27.0	80.0	10.0	62.0	40.0	81.0	24.0
CAJANZ	38.0	80.0	10.0	37.0	40.0	69.0	25.0
TE	38.0	40.0	10.0	37.0	40.0	70.0	20.0
MENA	33.0	40.0	10.0	55.0	40.0	60.0	38.0
SSA	23.0	40.0	0.1	30.0	40.0	20.0	21.0
SASIA	33.0	40.0	0.1	47.0	40.0	35.0	19.0
CHINA	33.0	40.0	10.0	76.0	40.0	40.0	22.0
EASIA	33.0	40.0	1.0	25.0	40.0	40.0	19.0
LACA	38.0	40.0	0.1	46.0	40.0	90.0	38.0
Average	35.8	60.0	6.8	50.6	40.0	62.1	25.4

Source: Adapted from Bosello, Carraro, and De Cian (2013). Additional material from the report was provided by the authors.

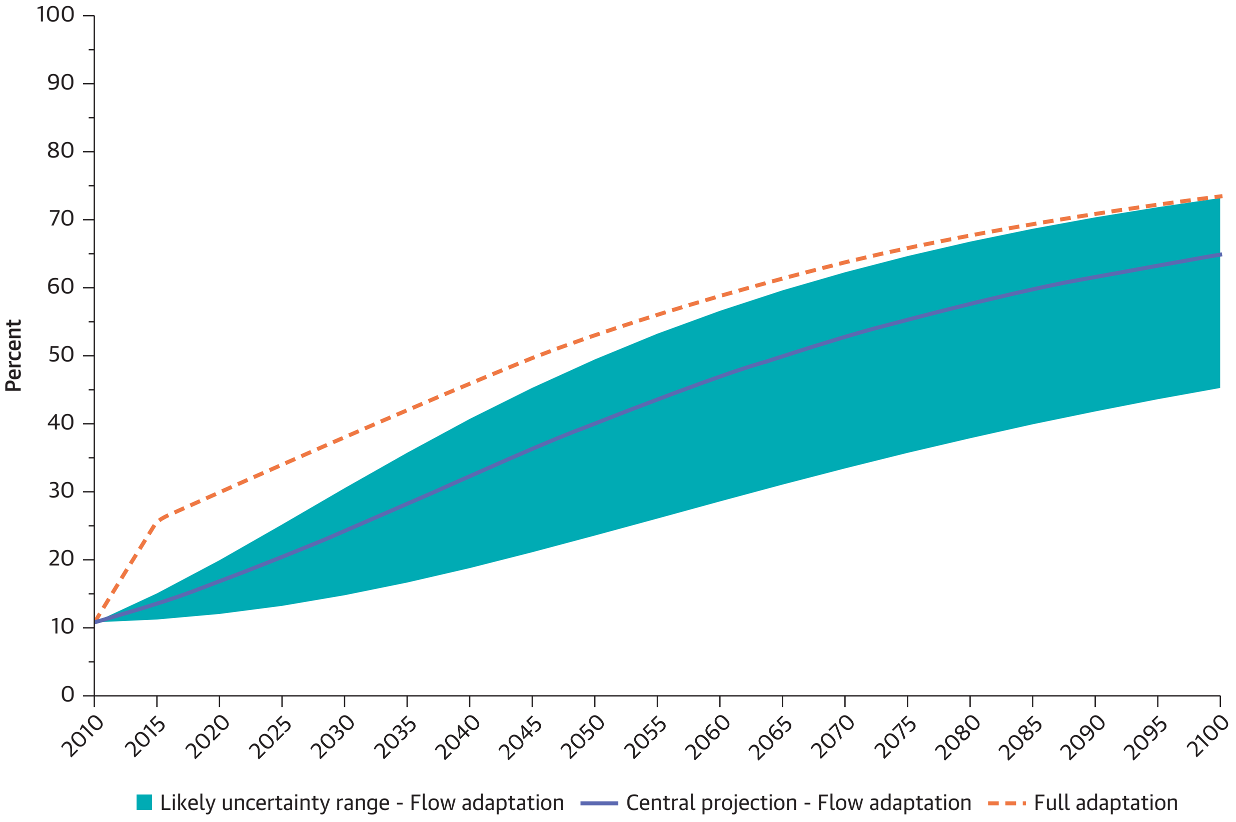
Note: CAJANZ = Canada, Japan, New Zealand; EASIA = East Asia; KOSAU = Korea, South Africa, Australia; LACA = Latin and Central America and the Caribbean; MENA = Middle East and North Africa; SASIA = South Asia; SSA = Sub-Saharan Africa; TE = Transition Economies.

investments beforehand to build adaptation capital. This adaptation stock reduces the damages of climate change in the future. Flow adaptation refers to adaptation measures that do not require investments beforehand but where benefits are reaped almost instantaneously. Government involvement can facilitate the efficient application of this adaptation (for example, by overcoming knowledge barriers), but is not necessary for its implementation. As a crude approximation, OECD (2015a) assumes stock adaptation to be driven by the public sector and the market and would hence require government coordination for its successful implementation. Flow adaptation is assumed to be private and market driven. Using a calibration similar to that in Bosello Carraro and De Cian (2013) but in the framework of the AD-DICE model, they estimate the optimal level of each type of adaptation over time. If adaptation is undertaken to minimize total damage costs, it takes the form shown in figure 6. The figure shows the percentage of damages avoided rising over time, with the share of reduction attributed to flow adaptation also increasing. In 2015, stock adaptation accounts for more than half the reduction in damages, but by 2100 it accounts for only around 14 percent of the reduction. Total damages reduced rise from around 27 percent in 2015 to 70 percent in 2100.

The benefits of adaptation, therefore, are to reduce damages significantly by the end of the century. Equally valuable, the adaptation also reduces the risks of climate change. Even though the benefits of adaptation are in themselves also uncertain, the range of damage uncertainty is considerably lower with adaptation than it is without it.

This discussion demonstrates the shortcomings in the analysis of adaptation in the context of global climate policy. The appropriate level of adaptation as calculated in the Integrated Assessment Models depend on macro-level functions linking damage reduction by

FIGURE 6. **Percentage of Damages Reduced By Adaptation (No Mitigation)**



Source: OECD 2015a AD-DICE model.

sector to adaptation expenditure. The basis of these assumptions and this analysis needs to be strengthened, with more account taken of soft measures and improvements in efficiency of resource use. This is particularly the case for water. Even without climate change, water scarcity is likely to be a problem in many parts of the world, and action will be needed to address that. More work is needed to determine the detailed policies and measures that could reduce damages—especially in the areas of public (stock) adaptation—and how these can complement actions in the area of private (flow) adaptation.

Nevertheless, the analysis shows how important adaptation is in reducing future damages, at a cost that is considerably lower than the reduction in damages (notwithstanding all the qualifications about the options chosen). As tables 3 and 4 indicate, adaptation expenditures are modest as a percentage of GDP, while they reduce damages to a significant extent; a 70 percent reduction of damages in 2100 would amount to a reduction in GDP loss of around 6-7 percent. Globally, therefore, adaptation expenditures amounting to around 0.4 percent of GDP would help avoid damages that would represent a GDP loss of around 6-7 percent in 2100. Inexpensive strategies with high benefit-cost ratios could be considered in priority.

Conclusions and Next Steps

Water is a key channel for climate change to affect the economy and society. The current state of knowledge on climate change and water points to predominantly negative effects. Studies indicate variations in precipitation and run-off, but with many regions facing negative effects, on balance. Changes in river flow favor some regions and reduce flow rates in others, with possible negative impacts on groundwater and on water quality. The models also predict a shrinking of most glaciers and increases in frequency and intensity of floods and droughts, but with notable regional differences. In terms of marine areas, predictions of sea level rise and storm surge increases are made with some confidence, with variations in space and time. The global catch potential of fisheries is likely to increase in high latitude regions and drop in the tropics. A major exacerbating factor is an increased frequency of extreme events (flood and droughts) in several parts of the world (though not all).

In all these projections, there is a considerable element of uncertainty, which is reflected in statements of different levels of confidence in the data and in the likelihood of the events. Nevertheless, strong economic impacts can be expected from the changes in water availability, through the role of water in coastal areas and through floods and droughts at the local level.

Importantly, these effects will occur on top of a water scarcity situation that already prevails in many parts of the world. Studies indicate an increase in demand for water due to climate change, which will be overlaid on a background of increasing scarcity resulting from growing demand and inefficient allocation of scarce water. The impact of climate change on water scarcity is present but small in general, compared to the impact of the socioeconomic factors. Changes in efficiency of water use could make a big contribution to water problems, including those caused by climate change. Pricing is one method of conserving water use and increasing efficiency in its allocation, but technological measures should also make a contribution. These include measures to reduce evaporation from water storage, increases in irrigation efficiency, and increases in the productivity of water. Research shows there is considerable room for such actions to reduce water demand, especially in developing countries. To be effective, however, they will in some cases need to be combined with water pricing.

In-depth estimates of damages from climate change related to water have been made to 2060 using a computable general equilibrium model, and to 2100 using integrated assessment models that are less able to capture links between climate and economic output. The 2060 estimates indicate that the impacts from water supply changes or changes in water-related extreme events and marine flows add up to about 1.5 percent of GDP in 2060 in the absence of mitigation or adaptation. This average figure, however, may be misleading for a number of reasons: there is a large uncertainty range, with big differences between regions; a number of impacts are not covered; the estimates depend to some extent on achieving a strong underlying growth in the economy; shifts in the structure of the economy may not be as easy as is assumed in the modelling; and modelling of changes for extreme temperature changes is not based on any real experience. Taking these factors into account makes damage estimates larger, with increased regional variations and higher uncertainty.

Estimates to 2100 of potential damages in economic terms are even more uncertain, but there are strong reasons to believe they will be greater as a percentage of GDP—perhaps around 10 percent globally, and possibly even higher. The long-term projections are particularly sensitive to the assumed value for equilibrium climate sensitivity (ECS)—the amount by which temperature will increase with a doubling of GHG concentrations. In addition, damages depend more on the emissions scenario that is realized. Lastly, the future path for damages depends to a significant extent on actions taken now: the less that is done to reduce emissions by 2060, the greater is the estimated damage in 2100.

Alternative approaches of linking climate impacts to the economy work through their effects on growth, rather than output. There is some empirical evidence in support of this path, but the results are not firmly established and it is difficult to see the causal pathways. Nevertheless, some attempts have been made to estimate damages through their impacts on the capital stock. They indicate an increase in damage relative to the computable general equilibrium (CGE) model approach, but not a large one. Further work is needed in this area.

Adaptation can make a major contribution to reducing damages from climate change for all mitigation scenarios, and more so when mitigation is absent or limited. Adaptation will require both private and public actions. Public action may need to be at least as large as private action initially, but by 2100 the main focus will be on private action. If undertaken optimally, at a cost of less than 0.5 percent of GDP, adaptation could remove up to around 70 percent of damages by the end of the century, at a cost that would leave net damages considerably reduced. But adaptation options need further analysis to include more of the softer options, such as those involving ecosystems, and approaches that incorporate increased efficiency in the use of scarce water, among other resources.

In terms of next steps, work is needed on how economic growth in the future could be affected by the effects of climate change on water and on water-related extreme events. In addition, a better understanding of how increases in the efficiency of water use could affect the water-energy-economic nexus under climate change is needed. Most models of climate change assume a more-or-less constant level of efficiency in water use: if this can be changed, the predictions of losses could be significantly reduced. Finally, a better estimate of the likely reduction of damages from adaptation is needed, based on a detailed bottom-up assessment rather than a top-down one.

Notes

1. Scenario A1B represents a world with describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies with a balance between fossil and non-fossil energy. In Scenario B2, the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than the A scenarios, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 storylines. The scenario is also more oriented toward environmental protection and social equity. See https://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html.
2. Scenario B1 represents a world with significant reduction in emissions and a mean temperature increase by the end of the century of 1.8°C. In Scenario A2, emissions rise more or less as at current rates, population increases are greater, and mean temperature increases by 3.4°C by the end of the century. See https://www.ipcc.ch/publications_and_data/ar4/wg1/en/spmsspm-projections-of.html.
3. The RCPs are pathways for radiative forcing developed by the research community to model different changes in climate. RCP2.6 is the most optimistic with CO_2 emissions staying at today's level until 2020, then declining and becoming negative in 2100. RCP8.5 is a pessimistic scenario, with CO_2 emissions rising to three times present levels by 2100. See https://www.sei-international.org/mediamanager/documents/A-guide-to-RCPs.pdf. Under RCP2.6 temperature increases by 2081-2100 are likely to be in the range of 1°C, while under RCP8.5 they are likely to be in the range of 3.7°C. See Table SPM-2 in: http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf.
4. http://www.un.org/waterforlifedecade/scarcity.shtml.
5. The Global Change Assessment Model (GCAM) is an integrated assessment tool for exploring consequences and responses to global change developed primarily by the Joint Global Change Research Institute. For more information, visit http://www.globalchange.umd.edu/gcam/.
6. In figure 1 the mitigation scenarios are shown in terms of radiative forcing, measured in Watts per square meter. The Scenario A2 corresponds to a radiative forcing of $7.7W/m^2$, Scenario B2 corresponds to a radiative forcing of $5.5W/m^2$ and scenario B1 to a radiative forcing of $4.2W/m^2$. Recall that the scenarios correspond to an expected temperature increase by 2095 of 3.4°C (A2), 5.5°C (B2) and 1.8°C (B1). The case of radiative forcing of $8.8W/m^2$ represents Business as Usual.
7. One acre foot is equal to 1,233.5 cubic meters.
8. For more information about the DIVA model, visit http://www.diva-model.net/.
9. MERGE stands for a Model for Evaluating the Regional and Global Effects of GHG Reduction Policies. For more information, visit http://web.stanford.edu/group/MERGE/.
10. See note 3 for descriptions of the scenarios.
11. The Emergency Events Database (EM-DAT) is maintained by the Centre for Research on the Epidemiology of Disasters (CRED). For more information, visit http://emdat.be/advanced_search/index.html.

12. For estimates for Europe, see Feyen et al. 2015.

13. The AD-DICE and its sister model AD-RICE are integrated economic and geophysical model of the economics of climate change developed at Yale University. For more information, visit http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm.

14. Pindyck (2012) makes the telling comment that these are "arbitrary functions made up to describe how GDP goes down when temperature goes up."

15. The GTAP is named after the Global Trade Analysis Project at Purdue University. The standard GTAP model is a multiregion, multisector computable general equilibrium model. The GTAP-W model is expands the GTAP model to include more details on the demand and supply of water and The GTAP-BIO-W model takes the GTAP-W further to include land use for energy and its implications for water demand. For more information, visit https://www.gtap.agecon.purdue.edu/models/current.asp.

16. Further details of the adaptation modelling, and a comparison across different integrated assessment models is available in Agrawala et al. (2011).

17. The WITCH (World Induced Technical Change Hybrid model) is a modelling tool developed within the Mitigation, Innovation and Transformation Pathways research programme of the Fondazione ENI Enrico Mattei (FEEM), Milan. For more information, visit http://www.witchmodel.org/.

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