MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY of GLOBAL CHANGE

2014 Energy and Climate Outlook

Exploring Global Changes

The 2014 Energy and Climate Outlook continues a process, started in 2012, of providing an annual update on the direction the planet is heading in terms of economic growth and the implications for resource use and the environment. We use the MIT Integrated Global System Model (IGSM), a framework developed in the Joint Program on the Science and Policy of Global Change, to provide an integrated look at energy, land, water, climate, atmosphere, and oceans. As in the previous editions of the Outlook, we provide a projection of the future based on an assessment of current policies, while recognizing that our projections of environmental change indicate that further policy measures are needed to stabilize our relationship with the planet. This scenario is a description and certainly not a prescription or recommendation.*

* Previous Outlook reports are available on our website: http://globalchange.mit.edu/research/publications/other/outlook

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

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

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

This Energy and Climate Outlook Report is intended to communicate research results and improve public understanding of global environment and energy challenges, thereby contributing to informed debate about climate change and the economic and social implications of policy alternatives.

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About the 2014 Outlook

New in this edition of the Outlook are estimates of future water supply and use, including identification of water basins that are subject to increases in potential water stress as demands for water grow with population and economic activity while the water supplies change with climate. We also take an updated look at economic growth and other drivers of energy and land use change, and have continued to update our modeling of atmosphere, ocean, and terrestrial systems. In this summary, we report results for three broad country groups: *Developed* countries (USA, Canada, Europe, Japan, Australia and New Zealand); an approximation of *Other G20* nations (China, India, Russia, Brazil, Mexico and several fast-growing Asian economies); and the *Rest of the World* (see **Box 1** for regional classification details).

As in the 2013 Outlook, we incorporate the emissions targets in the Copenhagen-Cancun pledges agreed upon under the United Nations Framework Convention on Climate Change (UNFCCC) (UN, 2009; 2010). These pledges focused on targets for 2020, which we extend through the horizon of the study. One exception is that for the EU, we include further reductions beyond 2020 to reflect targets proposed in their Emissions Trading Scheme (EU, 2013). To represent these targets, we reduce the emissions cap from power stations and other fixed installations by 1.74% every year. Our population projections are drawn from the UN's 2012 Revision (UN, 2013) which projects a global population of 10.8 billion by the end of the century.

In addition to the central emissions scenario, we include a short section where we speculate on the possible outcome of the efforts of the UN Conference of the Parties (COP) to forge an agreement on post-2020 actions, since the Copenhagen-Cancun pledges formally are only through 2020. As yet, few details are available on what countries may put forward, but based on what is happening within countries it is possible to offer some ideas as a way of starting a conversation on the adequacy of those measures.

Box 1.

Regional Classification Details

The IGSM modeling system used to generate the projections in this Outlook divides the global economy into 16 regions. These regions do not align exactly with the membership in international organizations such as G20. In particular, the *Other G20* grouping includes a *Dynamic Asia* region, comprised of Indonesia and South Korea (both G20 members), as well as Malaysia, Philippines, Singapore, Taiwan, and Thailand. Conversely, South Africa, Argentina, Saudi Arabia, and Turkey are G20 countries, but are part of other regions in our model, and thus are included in the *Rest of the World* grouping.

Several other regions deserve further explanation as well. *EUR* is the EU-27, plus Norway, Switzerland, Iceland and Liechtenstein. The *Middle East* region includes Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Palestine, Qatar, Saudi Arabia, Syria, the United Arab Emirates, and Yemen. Egypt, Libya, Tunisia, Algeria and Morocco are included in Africa.

A full list of countries in each IGSM region is provided in the Appendix. Supplementary projection tables are available online: http://globalchange.mit.edu/Outlook2014.

For the reporting in this Outlook, the regions are further aggregated into 3 broad groups: *Developed*, *Other G20*, and *Rest of the World*.

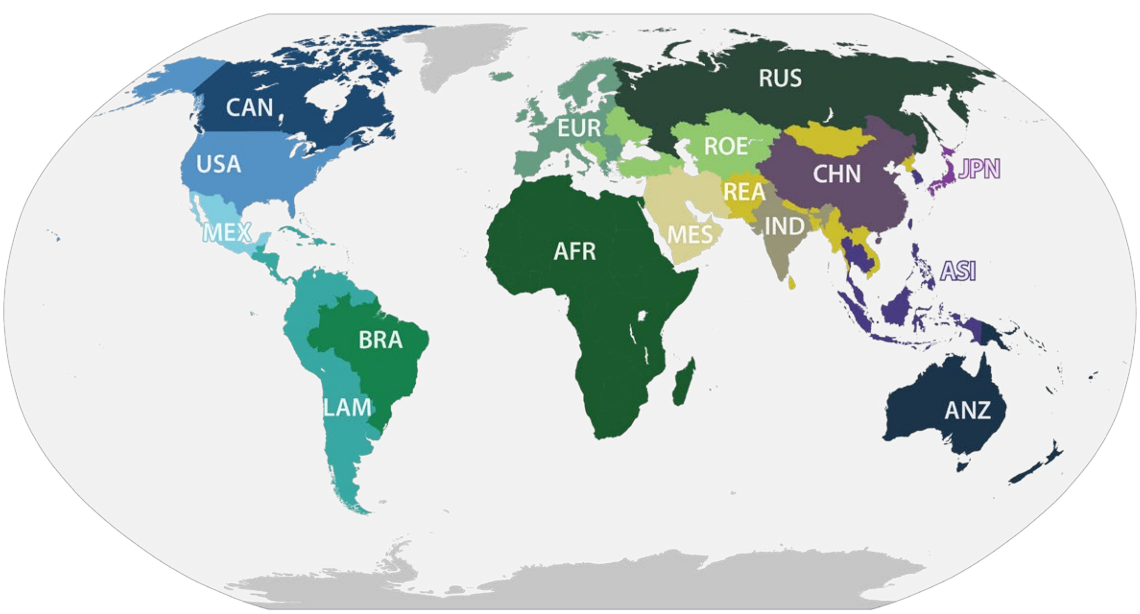

Figure 1. IGSM regions: Africa (AFR), Australia & New Zealand (ANZ), Dynamic Asia (ASI), Brazil (BRA), Canada (CAN), China (CHN), Europe/EU+ (EUR), India (IND), Japan (JPN), Other Latin America (LAM), Middle East (MES), Mexico (MEX), Other East Asia (REA), Other Eurasia (ROE), Russia (RUS), United States (USA).

Key Findings

Changes in Energy and Emissions

With emissions stable and falling in developed countries, on the assumption that Copenhagen-Cancun pledges are met and retained in the post-2020 period, future emissions growth will come from the *Other G20* and developing countries.

- Growth in global emissions results in 77 Gt (gigatons) carbon dioxide equivalent (CO_2-eq)[1] emissions in 2050, rising to 92 Gt by 2100—nearly double the emissions in 2010. By 2050 the developed countries account for about 15% of global emissions, down from 30% in 2010.
- CO_2 emissions from fossil fuels remain the largest source of GHGs, but other greenhouse gas emissions and non-fossil energy sources of CO_2 account for almost 33% of total global GHG emissions by 2100 (slightly down from 35% in 2010, and 43% in 2050).
- In 2050, electricity and transportation emissions will together account for nearly 52% of global CO_2 emissions from fossil fuel use, decreasing slightly from 56% in 2010.
- Fossil fuel energy continues to account for over 80% of primary energy through 2050 (despite rapid growth in renewables and nuclear), in part because the natural gas share of primary energy also increases.

Changes in Climate

Global change will accelerate with changes in global and regional temperatures, precipitation, land use, sea level rise and ocean acidification.

- Global mean surface temperature increase ranges from 1.6 to 2.6°C (central estimate 1.9°C) by mid-century relative to the 1901–1950 mean, and 3.3 to 5.6°C (central estimate 3.9°C) by 2100.
- Global mean precipitation increase ranges from 4.1 to 5.3% by 2050 relative to the 1901–1950 mean, and 7.5 to 12.4% (central estimate 8.5%) by 2100.
- Thermal expansion and land glacier melting contribute 0.08 to 0.12 meters to sea level rise from present (2014) by 2050, and 0.25 to 0.44 meters (central estimate 0.30 meters) by 2100.
- More carbon in the ocean leads to increasing acidity—average pH drops from 8.03 in 2010 to about 7.85 pH by 2100.

Changes in Water Flows

Annual freshwater flow increases globally by about 15% by 2100.

- By the end of the century, total water withdrawals are projected to increase by about 19%. We estimate current withdrawals of 2,700 billion cubic meters (bcm) rising to 3,200 bcm in 2100. At this level, withdrawals would account for about 6% of the annual freshwater flow.
- Our projections assume no changes in irrigated lands and, as a result, withdrawal for irrigation falls slightly (from the current 1,551 bcm to 1,389 bcm in 2100). Withdrawals for domestic use of water doubles (from 348 to 698 bcm) and industrial use of water increases by almost 45% (from 763 to 1,098 bcm).
- We distinguish between *consumption* of water (the amount lost to evaporation or consumed and not returned to the basin) and *withdrawals*, which include consumption plus return flow. In terms of consumption, annual irrigation is projected to use nearly 1,000 bcm in 2100, while industrial and domestic uses are each about ⅕ of that amount—just over 200 bcm. Globally, this level of consumption is 2.5% of total annual freshwater flow in 2100.
- Withdrawals and consumption as a percentage of total annual flows can provide a misleading picture of the adequacy of water resources, because location and timing of flows is important. Similarly, the seasonality of precipitation often means the timing of flows does not match needs.
- By 2100, our scenarios show reductions in potential water stress in some parts of North America, China and the Middle East. Despite abundant global supply, they also show increased water stress in parts of India, China, Pakistan, Turkey, North Africa, South Africa and the U.S.
- Based on more extensive simulations, water requirements increasing with population and GDP can have a stronger effect than climatic changes on water stress, especially in developing countries, where economic and population growth can be strong drivers of water requirements. Where growth occurs, inter-basin transfers, added water storage, and conservation and efficiency measures can be a response to increased stress.
- Projections of regional precipitation patterns, and the processes that control runoff and water requirements, are highly uncertain and have strong interannual and decadal variability. More rigorous uncertainty analysis is needed to fully understand likelihoods of specific water resource outcomes.

Expectations for the 2015 UN Climate Agreement

- Likely efforts will further bend the curve of emissions growth, with an estimate of 68 Gt CO_2-eq emissions in 2050—about 9 Gt less than our Outlook estimate for 2050.
- Unless the post-2020 agreement is significantly more stringent than we speculate, the emissions path will diverge further from what the Intergovernmental Panel on Climate Change (IPCC) Working Group III shows to be consistent with stabilization of GHG concentrations to 530–580 CO_2-eq by 2100.
- On this emissions path, by 2030 the world will be within about 7 years of hitting cumulative emissions levels that the IPCC Working Group I shows to be consistent with a 50% chance of holding temperature increase to less than 2°C.

Progress on climate change mitigation through international agreement has been slow, and efforts appear to be falling well behind the ambitious long-term goals set by the international community. Whether those goals are achieved or not, any hope of averting considerable climate consequences by stabilizing atmospheric GHG concentrations will require significant emissions reduction. Another 20 or 30 years of increasing emissions suggest substantial risks of dangerous climate change.

This Outlook provides an overview of the details by which we have reached these broad conclusions. A principal product

[1] CO_2-eq is a calculation that allows comparison of the warming effect among greenhouse gases with different lifetimes and radiative forcings.

[2] Tables available at: http://globalchange.mit.edu/Outlook2014

of our process is a set of detailed tables containing economic, energy, land use, and emissions results for each of 16 global regions.[2] We provide detailed regional projections up to 2050 and show global results through 2100 (useful for providing long-term climate implications of our near-term emissions policy choices). The nature of the climate change issue—(1) the long-term accumulation of gases with long lifetimes; (2) a climate system with inertia so that it takes some decades to millennia, in the case of sea level, to see the full effect of current concentrations; and (3) the added inertia in the energy system due to long-lived capital investments and the institutions that can be slow to change—all mean that much of our climate future for the next few decades has already been determined; we are just waiting to see how uncertainties about the climate response resolve themselves.

Box 2.

Major Updates in the 2014 Outlook

Updates to Model Inputs

Economic Growth: Regional economic growth assumptions reflect the latest International Monetary Fund Outlook (IMF, 2014) through 2015 and our own long-term projections. The IMF's projection shows slightly slower recovery from the recession, with the global average annual GDP growth rate from 2010 to 2015 only 0.08% lower compared to the 2013 Outlook, mostly attributed to 1.1% slower growth in China during that period. After 2015, the most substantial changes are in China (where the average annual GDP growth rate through 2050 is reduced by 0.5%) and India (where the average annual GDP growth rate through 2050 is increased by almost 0.15%).

Slower Energy Efficiency Improvement in China: New estimates of energy efficiency improvement are based on our Energy Outlook for China (2014) developed by the China Energy and Climate Project in collaboration with Tsinghua University. That work suggests slower efficiency improvement in industry than in our 2013 Outlook, somewhat counterbalancing the effect of slower GDP growth on energy use. The 2013 Outlook assumed an annual improvement of nearly 2.5% per year in energy intensive industries, other manufacturing and the service sector, now reduced to just under 1.6% per year.

Additional Outlook Reporting

- Economic output reporting is provided in 2010 US dollars.
- Water stress index for 2010 and 2100.
- Global water supply and use for 2010 and 2100.
- Water supply and uses for Indus River basin for 2010 and 2100.

Additional Policy Scenario

A first look at implications for emissions of a post-2020 international agreement on mitigation.

Our Changing World

This 2014 Outlook relies on the same population forecasts as the 2013 Outlook (**Figure 2a**). These latest UN estimates (UN, 2013) have the world's population passing 9.6 billion by 2050 and reaching 10.8 billion by the end of the century. The UN projections show that much of the growth will happen in developing regions like the Middle East, Africa and Latin America.

Population is a key driver of the future as it determines the labor force, which—together with changes in labor, land, and energy productivity—is a source of continued growth in gross domestic product (GDP). Productivity improvements along with the availability of advanced energy supply technologies more than offset the effects of resource depletion, such as that of fossil fuels, or limits on renewable resources such as arable land. Labor is the single largest resource in terms of contribution to GDP growth; hence, we can use labor productivity to target GDP growth, especially in the near term. In particular, near-term GDP growth has been adjusted to reflect the most recent International Monetary Fund Outlook (IMF, 2014) through 2015. In general, GDP shows further recovery from the recession, but slightly slower than previously projected—between 2010–2015, the global average annual GDP growth rate decreased by 0.08% compared to our 2013 Outlook. We attribute this mostly to a 1.1% reduction in the growth rate in China during that period. Longer-term growth rates were also re-evaluated, which led to 0.5% lower growth for China and 0.15% increased growth for India through 2050. **Figure 2b** shows our projection of GDP.

We project individual country and regional growth in market exchange rates, in large part because we model international trade, which occurs at market exchange rates. Other forecasts sometimes adjust GDP across regions, taking account of the purchasing power of income in different currencies to generate a better comparison of well-being across the world. Such a practice generally adjusts GDP up in many poorer countries, and such an adjustment would result in, for example, the *Other G20* and *Rest of the World* representing a larger initial share of GDP. Moreover, since our projections show those regions growing more rapidly, global GDP would grow more rapidly. Such an adjustment can be made with the data tables

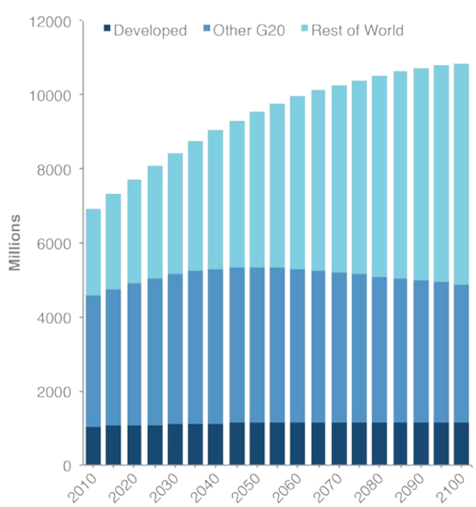

Figure 2a. World population forecast, in millions.

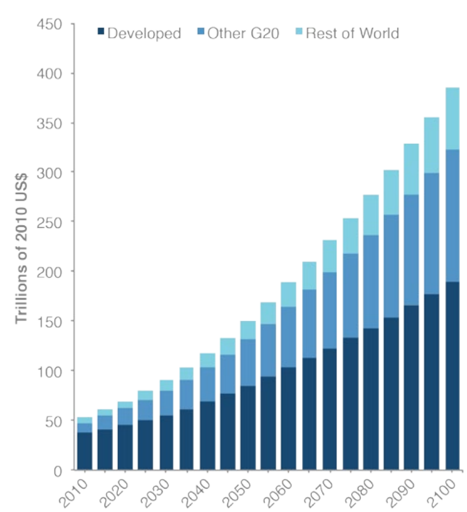

Figure 2b. World GDP, in trillions of 2010 USD.

Table 1. Average Annual Growth Rates for GDP and GDP *per Capita*.

	2010–2050	2010–2100
GDP		
Developed	2.1%	1.8%
Other G20	3.9%	2.9%
Rest of World	3.3%	2.8%
World	2.7%	2.2%

	2010–2050	2010–2100
GDP per Capita		
Developed	1.8%	1.7%
Other G20	3.5%	2.8%
Rest of World	1.8%	1.7%
World	1.8%	1.7%

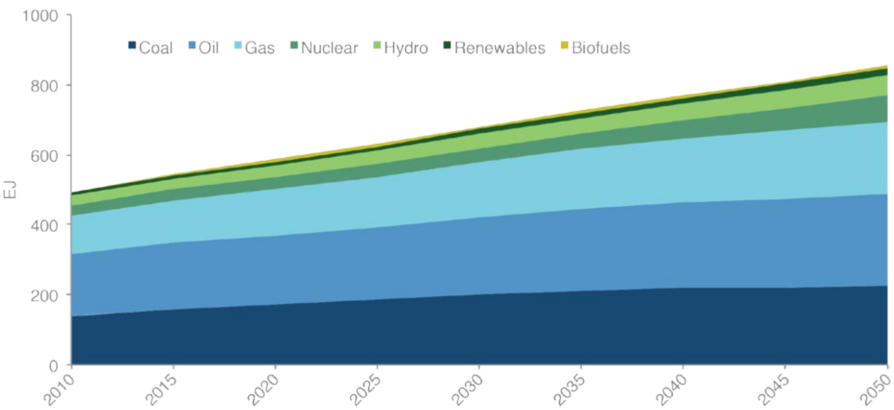

Figure 3. Global primary energy use, in exajoules (EJ).

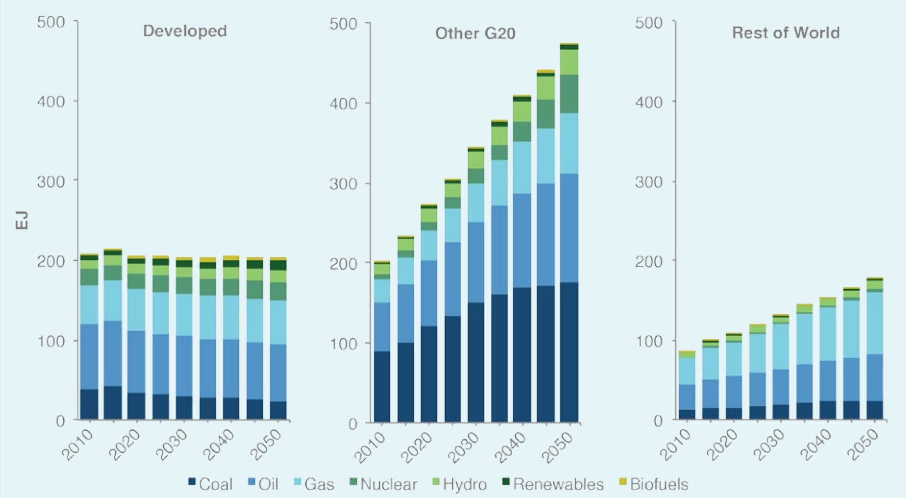

Figure 4. Primary energy use by major group, in exajoules (EJ).

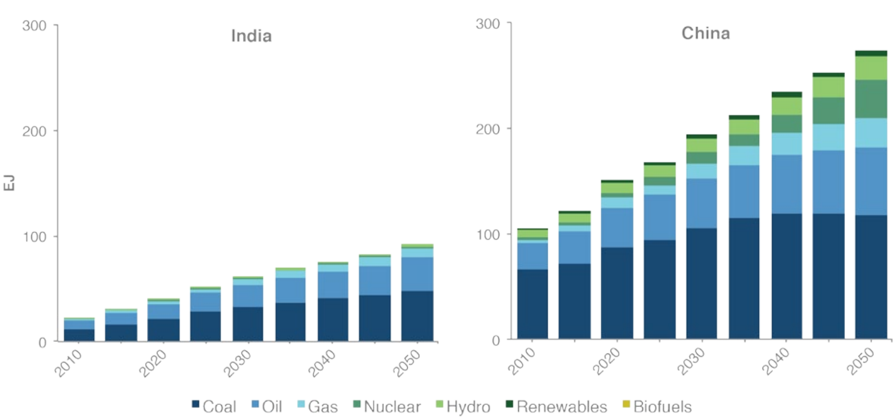

Figure 5. Primary energy use in India and China, in exajoules (EJ).

we present. Here we report GDP aggregated using market exchange rates. The resulting global GDP is projected to nearly triple between 2010 and 2050, and increase by another 2.5 times by 2100 (corresponding to an average annual growth rate of 2.2%). Through 2050 the average growth rate is 2.65% per year—about 0.08% lower than the 2013 Outlook because of adjustments, particularly in China and India. While this difference in the growth rate is small, it reduces global GDP by over $4.5 trillion in 2050. While *per capita* income will grow in all regions, this income growth is projected to be generally more rapid in *Other G20* countries, especially through 2050 (**Table 1**).

With higher incomes, we find that global energy use almost doubles by 2050 (**Figure 3**), similar to our 2013 Outlook. In fact, total global primary energy use is nearly identical here compared to the 2013 Outlook (856.9 exajoules (EJ) vs. 857.2 EJ), as along with the changes in income there were changes in resource availabilities for fossil resources and advanced technologies. That said, there have not been disruptive changes in energy or world economy over the past year, and thus it is not surprising that any changes are incremental. This overall growth in energy use occurs despite assumptions of substantial improvements in energy efficiency and conservation spurred by higher prices. In developed countries, our projections show that energy use will stabilize and fall slightly, in part because of the assumption that these countries will meet their Copenhagen-Cancun pledges and, for Europe, additional EU ETS reductions for the post-2020 period (**Figure 4**). Emissions policies are strong drivers of limiting energy growth, although slower economic and population growth, other pollutant policies, and energy efficiency trends all contribute to slower energy growth than in rapidly developing countries.

As in the 2013 Outlook, growth in energy use in our projection is led by the *Other G20* nations, again reaching close to 500 EJ (the level of global energy use in 2010) by 2050. While growth in the *Other G20* countries is dramatic, the *Rest of the World* energy use is also projected to be substantial, by 2050 approaching what is used today in the developed world. Global energy use by fuel also remains dominated by fossil fuels. Even in developed countries where carbon-emissions policies exist, we still see

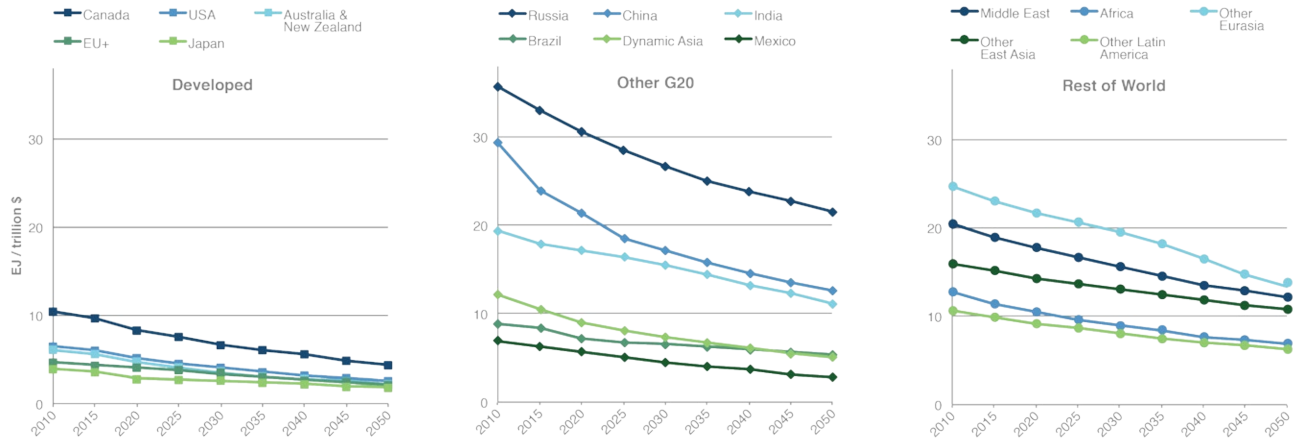

Figure 6. Energy intensity by region, in EJ per trillion $.

the dominance of fossil fuels. These policies have a stronger effect on overall energy use, and the mix among fossil fuels, with coal use falling while oil and gas are relatively stable.

The *Other G20* countries are already as important in terms of energy use as *Developed* countries. In terms of energy and emissions, the two most important countries are China and India. Due in part to our collaboration with Tsinghua University through our China Energy and Climate Project (http://globalchange.mit.edu/CECP), we have brought additional focus on these regions. In our projections, by 2050 primary energy use grows to nearly 300 EJ in China and 100 EJ in India (**Figure 5**). China's projected 2050 consumption alone is 50% more than the total consumption of *Developed* countries today. While India's energy consumption is only about ⅓ that of China, India remains almost entirely fossil energy-based. In contrast, China has extensive plans to diversify energy supply, expanding nuclear, hydro, renewables and gas, which leads to coal use flattening out.

As we noted earlier, energy use is increasing even with improvements in technology and rising projected prices that provide further incentives to improve efficiency or conserve on use. The factor countering these drivers of less energy use is growth in overall activity, GDP. GDP includes the effect of both a larger and a wealthier population. A useful way to summarize the effects opposing growth in GDP is to calculate the energy intensity of GDP—exajoules per trillions of dollars (or, equivalently, megajoules per dollar). Actual projected energy use includes the effects of exogenous improvements in efficiency, conservation and efficiency spurred by price or policy changes, and structural change in the economy.[3]

Energy price increases due to depletion of high-grade resources are offset in part by advancing technology and availability of alternative resources like shale gas and oil. The exception has been in some of the poorest countries embedded in our aggregated groups, where structural change involves developing energy-intensive infrastructure, or where resource endowments cause the economy to draw in significant energy-intensive industry and export the goods. In principle, energy price decreases would lead to higher energy use, but in general we show price increases for fossil fuels, as advancing technology and availability of alternative resources like shale gas and oil do not fully offset the effect of depletion of high-grade resources.

Accounting for all of these factors, our projections show continued decreases in energy intensity across the world (**Figure 6**). Global energy intensity decreases by about 40% from 2010 to 2050. Energy intensity improvements range from about 50–65% in *Developed* countries, 40–60% in *Other G20* countries, and 30–45% in other developing countries. This trend reflects the continuing improvement in energy use per unit of output that we have observed for decades for much of the world, as well as reductions from rising energy prices caused by fossil resource depletion and carbon policies in regions where they are implemented.

As with the 2013 Outlook, we focus on the transportation and electricity production sectors, which together in 2010 accounted for about 56% of CO_2 emissions and 57% of primary energy use. We find that total electricity production in 2050 is about 141 EJ (6% lower than in the 2013 Outlook), reflecting about a 91% increase from 2010 levels (**Figure 7**). Global coal generation levels off by 2040, and natural gas generation increases. Nuclear and hydro-power generation increases throughout the period. The largest percentage increase for 2010 to 2050 is from renewable generation (132%), followed closely by gas (127%) and nuclear (124%). Somewhat less growth is seen in hydropower (76%). Even with this growth, however, between 2010–2050 coal's share of generation only drops from about 40% to 35%.

Electricity generation currently contributes about 11.2 gigatons per year of CO_2—about 36% of total global CO_2 emissions. Given the projections, power generation emissions rise to about 16.8 Gt of CO_2 (about 34% of total global CO_2 emissions) by 2050. This represents a 50% increase in electricity emissions from 2010–2050; however, because global generation increases by 56%, this indicates a decline in the carbon intensity of generation.

The *Developed*, *Other G20* and *Rest of the World* regions all show growth in electricity use (**Figure 8**). From 2010–2050, the share of coal use falls from about 33% to 23% in the *Developed* regions and from 56% to 47% in the *Other G20*. The *Rest of the World* starts at just 20%, but stays about constant,

[3] Structural change is not necessarily energy-reducing, but in general we observe for most economies that historically, energy intensity of GDP is falling.

only falling to 18%. Renewables expand most in the *Developed* region, rising to 11% of generation in 2050; nuclear and hydro expand the most in the *Other G20*, growing by about 7.1 and 2.3 times, to 18% and 13% of generation, respectively; natural gas grows most rapidly in the *Rest of the World*, from 39% in 2010 to 47% of generation by 2050.

Highlighted in the 2013 Outlook was the rapid growth of vehicle use and its potential implication for energy use and greenhouse gas emissions. Our 2014 projections continue to show rapid expansion of vehicle use, especially in *Other G20* nations (**Figure 9**)—we project about 3.3 times more automobiles on *Other G20* roadways in 2050 than in 2010. There is also substantial increase in the *Rest of the World*, rising over 2.7 times. Growth is particularly fast in *Other G20* nations, because income levels increase such that personal vehicle use becomes more affordable for many. Meanwhile, vehicle use in *Developed* nations increases only about 30%—population growth is slow or negative in some areas and markets are near saturation. For the world as a whole, vehicle stock almost doubles by 2050.

There is considerable variation in projected trends in vehicle ownership among the countries and sub-regions comprising our three global regions (**Figure 10**). Among *Rest of the World* regions, vehicle growth is slow in Africa, where the rate of ownership is low, because income does not reach levels that support widespread vehicle ownership. Vehicle ownership is higher in *Other East Asia,* where we project faster economic growth. The *Other G20* stands out with large increases in vehicle ownership: nearly five times in China, and more than five times in India. Other countries in the *Other G20* have more modest increasing trends. There is a mix among countries in the *Developed* region. In the U.S., population grows by 30% and vehicle use by about 45%, with the increase in vehicle use being largely due to the increase in population. In Europe (EU+), population increases by only 2% and vehicle use by 21%, reflecting the fact that countries in Europe remain diverse in terms of income distribution and vehicle saturation.

Currently, transport contributes 6 Gt of CO_2 emissions per year. Given these projections, emissions from transport rise to 9.1 Gt of CO_2 by 2050. While this represents about a 52% increase in transport emissions from 2010

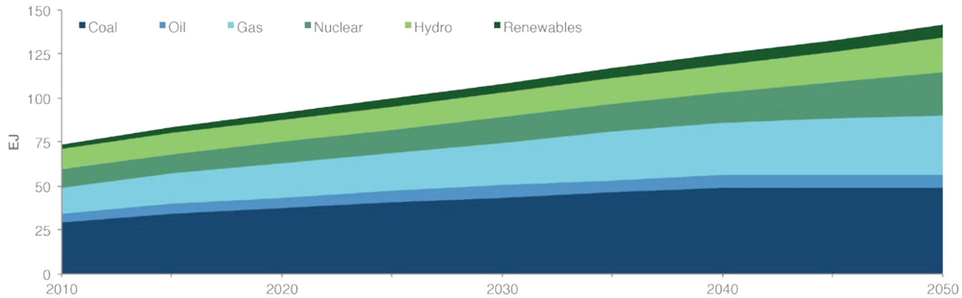

Figure 7. World electricity production, in exajoules (EJ).

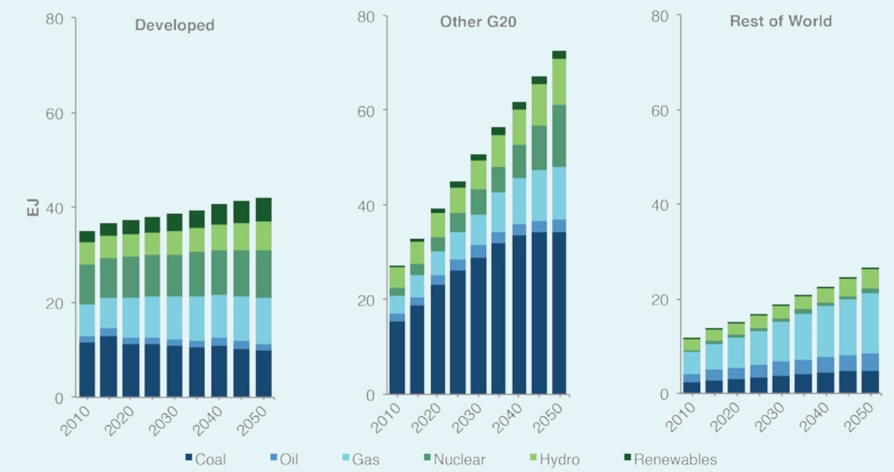

Figure 8. Electricity production by major group, in exajoules (EJ).

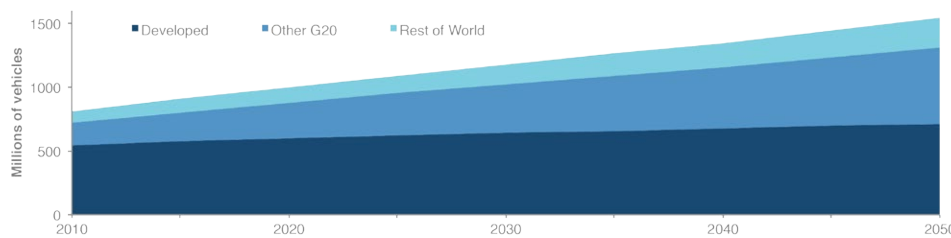

Figure 9. World private vehicle stock - millions of private cars and light trucks.

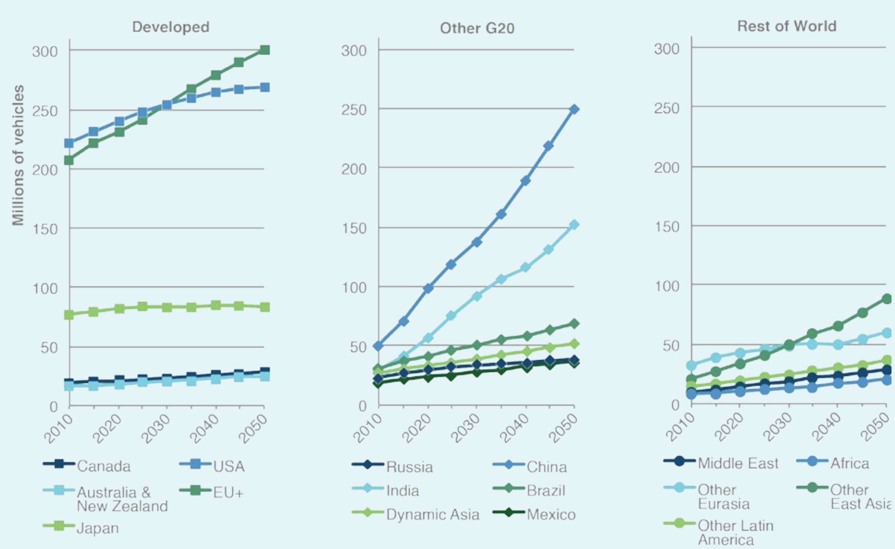

Figure 10. Regional private car and light truck stocks - millions of vehicles.

to 2050, the emissions share from transport in 2010 and 2050 is about the same (around 20% of total CO_2 emissions). Even though electricity generation contributes a large share of emissions, and we often focus on transport because it is very visible and growing rapidly, other energy use and emissions are increasing as well. We project that the combined share of emissions from transportation and electricity generation will fall to 52% of total CO_2 emissions in 2050. While it seems obvious to focus on policies targeting these visible sectors, that may overlook significant opportunities elsewhere, ultimately frustrating attempts to reduce emissions.

An advance in the 2014 Outlook is a closer coupling among our economic projections of land use, terrestrial emissions of greenhouse gases, and the impacts on climate. A first component of this analysis is economic projections of land-use change at the 16 region- and country-level aggregations in our economic model. As with energy efficiency, land productivity is subject to exogenous rates of improvement and price driven improvement via substitution of other inputs for land. The improvement in productivity limits the need for increased cropland to feed a wealthier and larger population. Overall we see about a 50% increase in cropland between 2010 and 2050, trailing off after 2050 as population growth slows and stabilizes (**Figure 11**). The cropland increase is at the expense of all other land uses, which contract slightly by 2050—natural forestland and pasture decrease from 2010 levels, by about 10% and 5% respectively. The small exception is land devoted to biofuels, which nearly doubles from 2010 levels by 2030, due to increasing demand for biofuels, but declines back to 2015 levels by 2050, as productivity of biofuel crops continues to increase. While the doubling between 2010 and 2030 may at first seem concerning, even at its highest level, biofuels account for less than 4% of global cropland (emphasized by Figure 11, where the biofuel bar is barely visible).

Dramatic differences in patterns of land-use change exist among the broad regional groups we define. Whereas for energy the dramatic change was in the *Other G20*, for land use the *Rest of the World* region shows the biggest changes (**Figure 12**). The underlying reasons are related to income and population growth, as they were with energy use. The *Rest of World* group includes some of the poorest countries where a substantial share of increased income will continue to be devoted to food consumption; even in the *Other G20* regions the income driver of consumption begins to taper off by mid-century as much smaller shares of additional income are devoted to food consumption.

Population growth is also expanding more rapidly in the *Rest of the World* region. The *Rest of the World* region also still has substantial amounts of potential agricultural land, and there are fewer restrictions on converting unmanaged land to other uses. While trade in agricultural goods is an important component of global agriculture in that it generates price linkages for commodities among regions, most countries still produce a very large share of the food they consume domestically. Hence, the regional expansion of population and income growth is a relatively accurate predictor of changes in cropland.

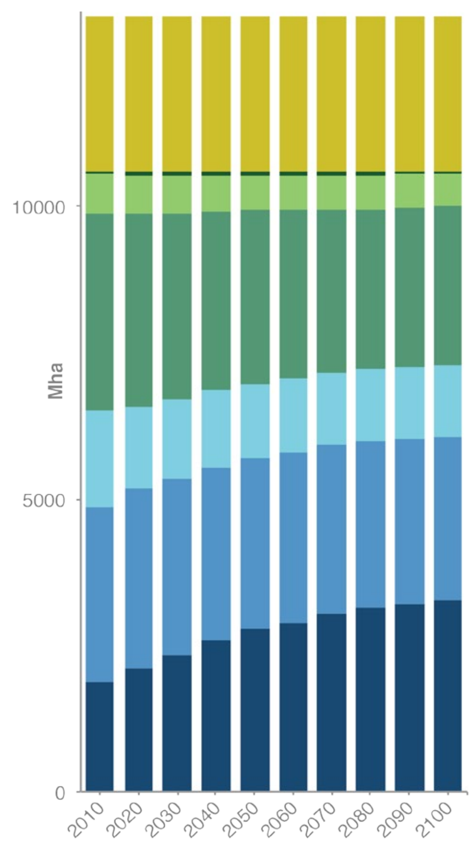

Figure 11. Global land use, in megahectares (Mha).

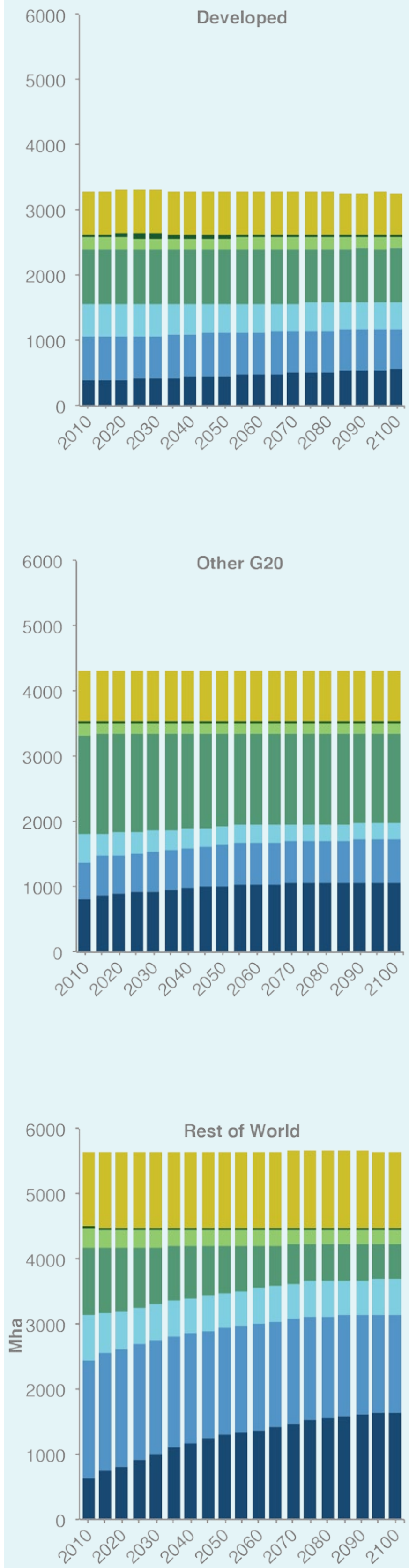

Figure 12. Land use by major group, in Mha.

Cropland · Pasture · Natural grassland · Natural forest · Managed forest · Biofuels · Other

Current World Development Path: GHG Emissions Implications

Total GHG emissions from all sources of human activity (energy, industry, agriculture, waste, and land-use change) in 2100 are projected to reach 92 Gt CO_2-eq, which is almost 70% higher than in 2010 (**Figure 13**). Total fossil fuel CO_2 emissions reach 62 Gt by 2100, doubling from 2010. Fossil fuel CO_2 emissions at the end of this century still constitute a majority of total GHG emissions on a CO_2-equivalent basis (about ⅔). Of course, that leaves almost ⅓ from other CO_2 sources and other gases. Compared to the 2013 Outlook, cumulative global CO_2 emissions over the century are about 2% higher. Cumulative CH_4, N_2O, PFC, HFC and SF_6 emissions are lower, by 2%, 1%, 9%, 3% and 5% respectively. Part of these differences in total emissions reported in CO_2-eq is due to our use of new GWPs reported by the IPCC in its 5th Assessment Report (AR5; see **Box 3** below).

Changes in regional emissions (**Figure 14**) to a large degree reflect energy projections, and to a lesser extent reflect land-use change and agriculture projections. The projected emissions in *Developed* countries decrease slightly (by about 20% in 2050 relative to 2010) because of the Copenhagen-Cancun pledges and domestic policies, but they remain roughly constant after 2020 (reflecting our policy assumptions). In the *Other G20* nations, Copenhagen-Cancun pledges result in slow growth in GHG emissions. However, unless emissions targets are extended and increased, emissions are projected to

Box 3.

Changes in GHG Emissions

The radiative forcing of greenhouse gases varies by factors of 1000, as does their atmospheric lifetime. This makes it meaningless to directly add together the radiative effect of tons of CH_4, SF_6, and CO_2: the estimated lifetime of CH_4 is 12.4 years, with 36×10^{-5} $Wm^{-2}ppb^{-1}$ radiative forcing; SF_6 has a lifetime of 3200 years, with $57{,}000 \times 10^{-5}$ $Wm^{-2}ppb^{-1}$ radiative effect; and CO_2 has an effective lifetime of approximately 200 years[a], with 1.4×10^{-5} $Wm^{-2}ppb^{-1}$ radiative forcing.

Global warming potentials (GWPs), as reported by the IPCC, integrate the warming effect of each GHG over a given time period to produce an index (CO_2=1.0 by definition)which, multiplied by the number of tons of that GHG, approximates how many tons of CO_2 would create an equivalent amount of warming (traditionally designated as tons of CO_2-eq). For example, methane's GWP is 28, so 1 ton of methane is "equivalent" to 28 tons of CO_2. In addition to allowing tons to be more sensibly added together, GWPs also offer an improved guide to policy and economic decision-making; if one is willing to pay $10 per ton to abate CO_2 emissions, then one should be willing to pay up to $280 per ton for methane abatement, as the same reduction in warming is achieved.

Unfortunately, these indices are necessarily an approximation. One issue is the time period of integration. The IPCC reports 20-, 100-, and 500-year GWPs—policy makers have focused mostly on the 100-year values. Even the 500-year values truncate the effects of gases that will remain in the atmosphere for thousands of years, and so the shorter the integration period, the higher the GWP for shorter-lived species. As reported in the IPCC's 4th Assessment Report, methane's 20-year GWP is 72, its 100-year GWP is 25, and its 500-year GWP is 7.6.

Scientists calculating GWPs also have revised their calculations to include some of the gases' indirect effects, especially in the case of methane. Methane's 100-year GWP was 21 in early IPCC reports and has now risen to 28. We have used the most recent IPCC GWP estimates—a revision from our previous Outlook, which used GWP estimates adopted by the US Environmental Protection Agency and included in the IPCC's First Assessment Report. In the table below we compare the IPCC's AR5 estimates to the AR4 estimates.

Gas	IPCC AR4	IPCC AR5
CH_4	25 GWP	28 GWP
N_2O	298 GWP	265 GWP
PFC	7390 GWP	6630 GWP
SF_6	22800 GWP	23500 GWP
HFC	1430 GWP	1300 GWP

We only use GWPs for reporting purposes such as in Figure 12, and to represent the relative economics of abatement. We use GWPs without climate-carbon feedback, as they reflect better our model setting where nitrogen limitation and changes in terrestrial and ocean uptake are explicitly represented in the IGSM. For simulating the climate effects of emissions, the IGSM does not use GWPs as it includes the physical processes that determine the lifetime and fate and the radiative effect of each gas. Our use of the new IPCC AR5 GWPs results in differences in reporting of CO_2-eq emissions, but is not a source of difference in our simulation of climate effects.

[a]CO_2 does not have a lifetime *per se* and its residence time in the atmosphere varies; 200 years is a rough approximation of the effective residence time.

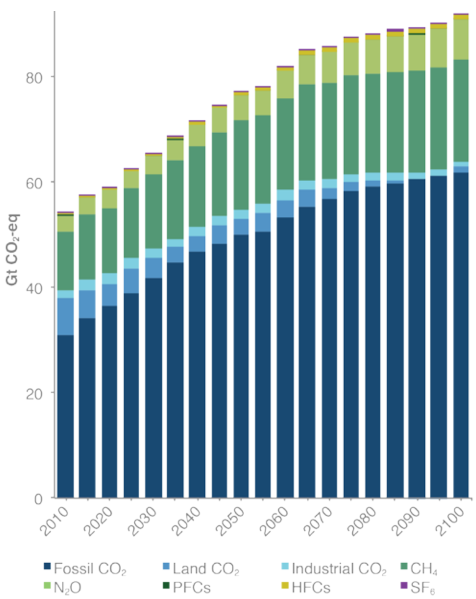

Figure 13. Global greenhouse gas (GHG) emissions.

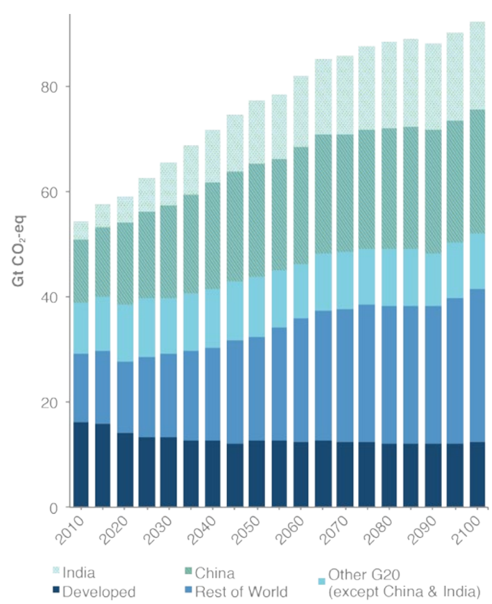

Figure 14. GHG emissions by major group.

increase substantially (by about 100% over the century) and the G20 nations become the world's largest source of emissions—contributing about 55% of global emissions by 2100 (up from 46% of the total in 2010). At the same time, due to population growth in places such as the Middle East and Africa, and the absence of any climate policy, the emissions in the *Rest of the World* are projected to more than double by 2100.

Our projections regarding the *Other G20* regions are partially a result of how the Copenhagen-Cancun pledges are extended in our analysis. Since the pledges are emissions-intensity targets for China and India, the commitments become non-binding as improvements in energy efficiency occur. Over time, countries may subsequently decide to lower their intensity targets. Our results demonstrate the importance of lowering these targets, so that—rather than simply slowing emissions growth—their emissions will begin to decline absolutely. Even if developed nations reduce their emissions to zero, global emissions would still increase as developed nations' emissions by 2050 have dropped to about 13 Gt CO_2-eq, while emissions in other regions of the world have increased by nearly twice that (see Figure 13). Our projections show that the global share of both fossil fuel and greenhouse gas emissions that developed nations release are cut by more than half—from 38 to 16% for carbon dioxide, and from 32 to 13% for other greenhouse gases.

Expectations for a New Climate Agreement

Our 2014 Outlook follows previous Outlooks by assuming that the Copenhagen-Cancun international agreement on emissions reductions would be achieved, and that the agreed emissions levels or policies would remain in place through the end of the century. The actual commitments were technically only through 2020, with the assumption that countries would make new (and likely stronger) commitments for the post-2020 period. International negotiations have now begun focusing on this new climate agreement, to be reached at the 21st meeting of the Conference of Parties (COP-21) in Paris during November/December of 2015. With the objective of stimulating timely and open discussion of the adequacy of potential new commitments, we have speculated on what countries might propose, introduced those measures into our economic model, and simulated what they mean for future emissions. This exercise is documented in a recent report (Jacoby and Chen, 2014; *MIT Joint Program Report 264*). The report assumes that the architecture of the agreement will likely involve voluntary pledges and *ex-post* review (akin to the Copenhagen Accord), with a broad mix of policies directed toward reducing coal use in power generation, improving vehicle efficiency, reducing land-use emissions, and similarly diverse measures rather than numerical emissions targets to be met with nationwide cap-and-trade programs.

The analysis shows that an agreement likely achievable at COP-21 will succeed in a useful bending of the curve of global emissions. It will not, however, reduce global emissions to a trajectory that aligns with the "tolerable windows" to 2050 that are consistent with frequently proposed climate goals. This raises questions about follow-up steps in the development of a climate regime. **Figure 15** illustrates the key finding for emission profiles in the no climate policy scenario (*Reference*), Copenhagen pledges (*Copenhagen*), this Outlook (*JP Outlook 2014*), expected emissions based on COP-21 agreements (*Expected*) and the IPCC's emissions windows consistent with about a 2.5°C temperature increase (relative to pre-industrial levels) by 2100. Policies in the Copenhagen scenario in Jacoby and Chen (2014) do not include any additional policies after 2020, while this Outlook assumes extension and tightening of EU ETS after 2020.

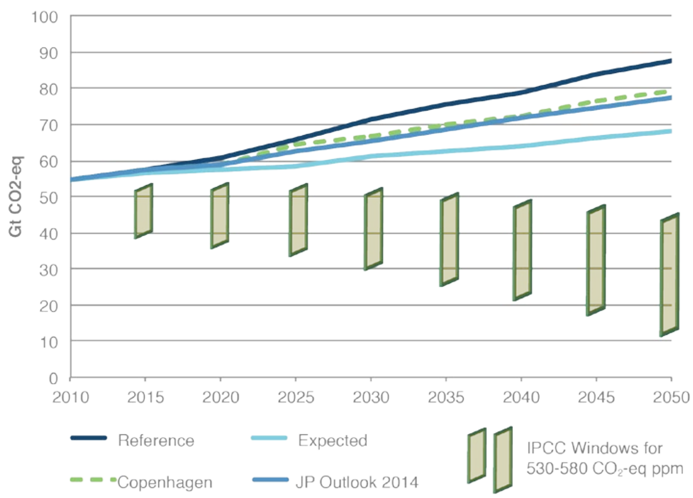

Figure 15. Emissions implications of possible measures under a new international agreement.

(For comparability, land-use emissions are adjusted in the results of Jacoby and Chen here, as in this Outlook we use more advanced modeling of land-use change.)

On this emissions path, by 2030 the world will be within about 7 years of hitting the cumulative emissions level the IPCC estimates as consistent with there being a 50% chance of holding the temperature increase below 2°C. As noted, this is largely speculation on our part, meant to stimulate discussion; countries may propose more (or less) stringent measures. However, a recurring conclusion we have found in this and other research is that a wide variety of measures directed at different sectors often achieves much less than expected because: (1) important sources of GHG emissions are not targeted at all; (2) the measures are often not as effective as hoped, even in the target sectors, because they fail to assume behavioral change (e.g., a rebound effect when vehicles are forced to be more efficient, or slower replacement of old vehicles); and (3) various channels of leakage exist— e.g., measures in target regions and sectors reduce fuel prices, spurring higher emissions in uncovered regions and sectors; reductions are achieved by cutting back on production of energy intensive goods, which are then produced somewhere else and imported.

Greenhouse Gas Concentrations and Climate Implications

To meet the temperature and GHG concentrations goals discussed broadly amongst nations, global emissions need to peak very soon, if not immediately. Many analyses have focused on the target of 450 parts per million (ppm) as the limit for avoiding temperature increases of 2°C. Current atmospheric concentrations for Kyoto gases[4] (**Figure 16**) already exceed 450 ppm CO_2-eq, while CO_2 concentrations approach 400 ppm. When all major GHGs, including CFCs, are included, concentrations are currently above 480 ppm, as shown in Figure 16, labeled *CO_2-eq (IPCC)*. The use of chlorofluorocarbons (CFCs) has been almost entirely phased out under the Montreal Protocol because they destroy protective ozone in the stratosphere. While new CFCs are not being produced and emitted, concentrations will remain in the atmosphere for a very long time because their lifetimes are thousands of years. The seasonal cycle of concentrations, due largely to strong CO_2 effects of northern hemisphere vegetation, is smoothed to show the underlying trend (for details, see Huang et al. [2009], from which Figure 16 is updated). Note that CO_2-eq concentrations do not use GWPs as they are intended to show the relative radiative effect of concentrations at a point in time, rather than over their expected lifetime in the atmosphere (see **Box 4**).

Even though we have exceeded the 450 ppm level we have not yet seen warming of 2°C. Two important reasons are: (1) the offsetting cooling effect of sulfate aerosols (airborne particles), which is not included in Figure 15; and (2) due to the inherent inertia in the climate system, it will take decades to see most of the warming to which we are already committed. There have been strong efforts to control sulfate emissions in wealthier countries to reduce the source of acid precipitation, and because the aerosols are considered a health hazard. Sulfate aerosols remain in the atmosphere for only a few days to a week or so; if they were controlled worldwide, concentrations would fall almost immediately, and their substantial cooling effect would no longer mask GHG warming. Inertia in the climate system may spare us some of the warming for some decades, but not forever. Thus, there is little comfort in the fact that we have exceeded 450 ppm CO_2-eq without seeing a large impact on global temperature.

The implications of our emissions projections are that CO_2 concentrations approach 750 ppm by 2100 with no sign of stabilizing (**Figure 17**). The figure also shows the four Representative Concentration Pathways (RCP) scenarios (van Vuuren et al., 2011) in dashed lines, the scenarios A1FI, A1B, A2 and B1 from the special

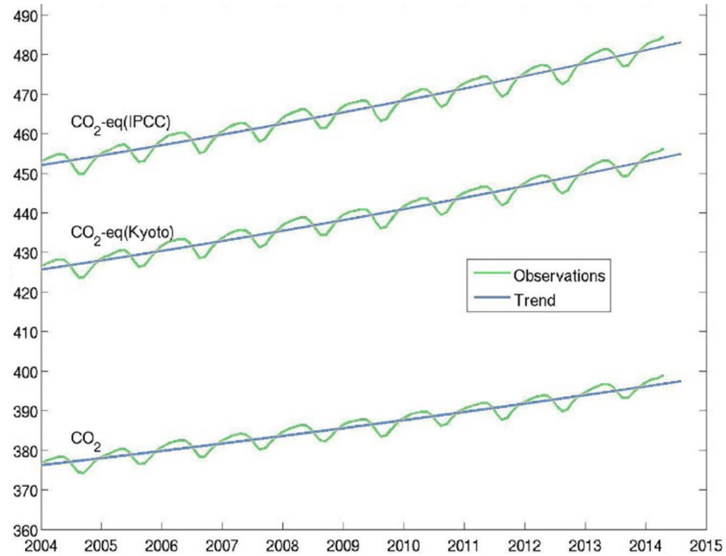

Figure 16. Current greenhouse gas (GHG) concentrations.

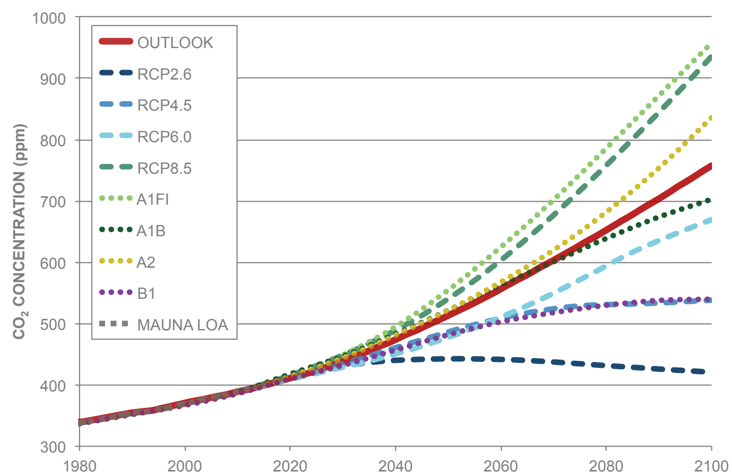

Figure 17. Projected CO_2 concentrations.

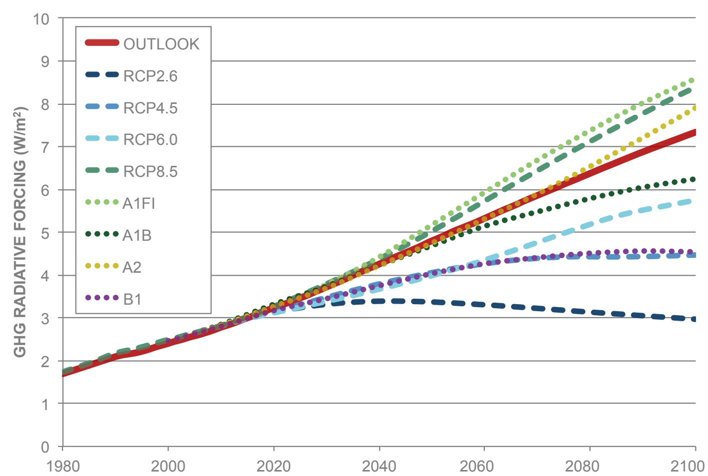

Figure 18. Projected greenhouse gas (GHG) radiative forcing.

Box 4.

CO_2-equivalent Concentrations of GHGs

As discussed in Box 3, GWPs provide an approach to aggregate emissions because, in part, the lifetimes of the gases in the atmosphere differ. CO_2-eq concentrations of gases are calculated differently—in the case of concentrations, we know the concentration of the gas (historically, or the predicted level in a particular future scenario). CO_2-eq concentrations are calculated by multiplying the instantaneous radiative forcing by the atmospheric concentration of the gas at any point in time. This metric is less subject to uncertainties because of lifetimes and feedbacks, and is intended to show how important different gases are in terms of the forcing they are causing at any given time.

[4] We refer to Kyoto gases to denote those included in the emission targets specified under the Kyoto Protocol.

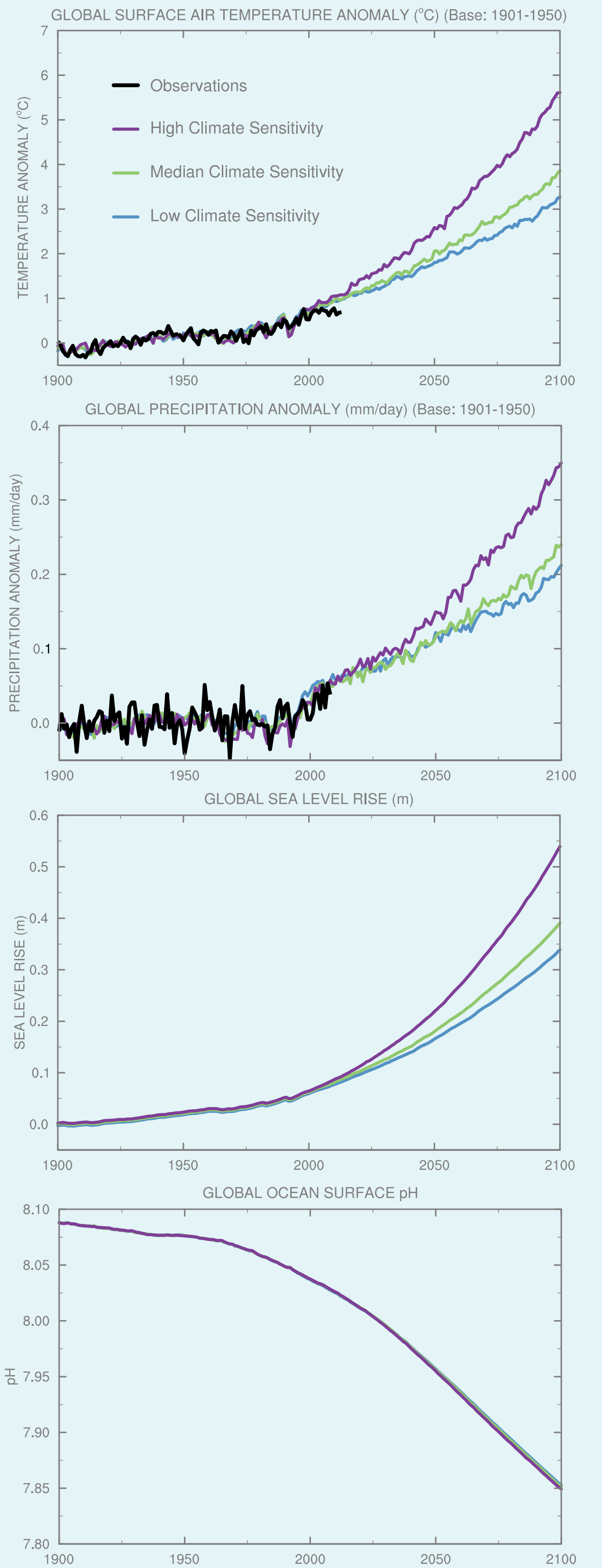

Figure 19. Global mean temperature and precipitation changes from the 1901–1950 mean and sea level rise and ocean surface acidity.

report on emissions scenarios (SRES) (Nakicenovic et al., 2000) in dotted lines, and CO_2 concentrations observed at Mauna Loa until 2012, as annual averages, smoothing out the annual cycle shown in Figure 16. The RCP and SRES scenarios were developed by the IPCC, and we provide them for comparison with our policy scenario. The 2014 Outlook scenario lies between the SRES scenarios A2 and A1B, and between the RCP scenarios RCP6.0 and RCP8.5. Compared to the 2013 Outlook, projected CO_2 concentrations in 2100 are 0.3% lower. Climate results can also be shown in terms of GHG radiative forcing (**Figure 18**). Our 2014 Outlook scenario increases from 2.8 W/m^2 in 2010 to 7.3 W/m^2 in 2100. RCP scenarios approach 8.5, 6.0, 4.5, and 2.9 W/m^2 by 2100. SRES scenarios reach 8.6 (A1FI), 8 (A1B), 6.2 (A2), and 4.5 W/m^2 (B1) by 2100.

What does this mean for the world's climate? To answer this critical question, we developed three climate scenarios that take into account the uncertainty in the Earth system's response to changes in aerosols and GHG concentrations. In our modeling framework, the MIT IGSM-CAM (Monier et al., 2013), the climate response to given emissions is essentially controlled by three climate parameters: the climate sensitivity, the ocean heat uptake rate and the strength of aerosol forcing. To limit the number of simulations presented, we limit our analysis to one particular ocean heat uptake rate, which lies between the mode and the median of the probability distribution of ocean heat uptake rate from Forest et al. (2008). We choose three values of climate sensitivity (CS) that correspond to the 5^{th} percentile (CS=2.0°C), median (CS=2.5°C), and 95^{th} percentile (CS=4.5°C) of the probability density function. The lower and upper bounds of climate sensitivity agree well with the conclusions of the IPCC's 5^{th} Assessment Report (AR5), which finds that climate sensitivity is likely to range from 1.5–4.5°C (IPCC, 2013). The value of the net aerosol forcing is then chosen with the objective to provide the best agreement with observed 20^{th} century climate change. The values for net aerosol forcing are -0.25 W/m^2, -0.55 W/m^2 and -0.85 W/m^2, corresponding to the CS=2.0°C, CS=2.5°C and CS=4.5°C values respectively. For each set of climate parameters, a five-member ensemble is run with different representations of natural variability, represented by random sampling of observed surface wind over the ocean and different initial conditions in the atmosphere and land components (by choosing different states consistent with the radiative forcing at the beginning of the simulation). In the remainder of this Outlook, we refer to these different representations of natural variability as "different initial conditions."

Using these three sets of climate parameters, the Earth's global mean temperature (**Figure 19**) is projected to increase from about 1°C above the 1901–1950 mean temperature (a base level close to the pre-industrial) in 2010, to 3.3–5.6°C above by 2100. Blue, green and purple lines in Figure 19 are the means of ensembles with different initial conditions for, respectively, the low, median and high climate sensitivity scenarios. Under the median climate sensitivity scenario, temperature increases by 3.9°C by 2100. Comparing the new result to the year 2000 shows a temperature increase of 3.2°C, which is 0.6°C lower than in the 2013 Outlook. This reflects a combination of factors, including updates to the Earth system components of the model to better reflect its response to GHG and aerosol forcing. In a

Note: The version of IGSM used in this study, like most climate models, does not simulate precisely the timing and phase of natural climate variability as it affects mixing and transport of heat into the deep ocean. Much of the recently observed hiatus in atmospheric temperature change is explained by the observed anomalously high post-1998 heat uptake by the deep ocean (see Balmaseda et al., 2013). Hence, the global surface air temperature projections (upper left panel) over-predict warming for the recent observed period; however, the land-only mean surface temperature simulations match well the observations (see Monier et al., 2013).

similar figure in the 2013 Outlook, we included individual ensemble members illustrating the effects of different initial conditions. The exclusion of the individual ensemble members simplifies the graphics here, but the core message remains the same. While the ensemble average helps to better show the climate change trend by reducing the noise of natural variability, we will not live in an ensemble-mean world—we will experience much greater variability. In that regard, the global mean changes in any one ensemble are somewhat misleading in that local and regional variability will be much greater than seen in the global mean, which by its nature smooths the regional variability (see, e.g., Monier et al., 2014).

Figure 19 shows an increase in global precipitation anomaly, from 0.05 mm/day in 2010 to a range of 0.21 to 0.35 mm/day in 2100. The precipitation changes represent increases of 4.1–5.3% by 2050 relative to the 1901–1950 mean, and 7.5–12.4% (central estimate 8.5%) by 2100. Global precipitation increases with warming are projected by all climate models as warming speeds up the hydrological cycle, increasing both evaporation and precipitation. Because evaporation and evapotranspiration from plants is increasing and the patterns of precipitation are changing, the increase in precipitation does not necessarily mean that vegetation and water resources are less stressed everywhere.

Figure 19 also shows that thermal expansion and land glacier melting contribute 0.08–0.12 meters to sea level rise from present (2014) by 2050, and another 0.25–0.44 meters (central estimate 0.30 meters) by 2100.[5] Both thermal expansion and glacier melting—and even more so, ice sheet melting—have very strong inertia effects. The full extent on sea level rise of warming at any given time will not be observed for hundreds to thousands of years. Sea level rise is thus nearly irreversible, short of interventions that would actually create cooling. If emissions ceased completely, radiative forcing and global temperature could reverse and would continue to drift downward slowly (see Paltsev et al., 2013). More aggressive interventions in addition to halting all emissions, such as some CO_2 absorption process (tree planting, biomass energy with carbon capture and storage) or geoengineering, could reverse warming more substantially. Given the current trajectory of emissions growth, imagining that we could have zero emissions from fossil energy—and negative emissions if we added tree plating or biomass energy with CCS—any time soon seems far-fetched, and geoengineering carries its own risks and uncertainties.

The time series of temperature changes from the 1901–1950 mean for each continent are shown in **Figure 20**. Green bands represent the range over all climate sensitivity scenarios and initial conditions for projections over the 21st century; white dotted lines show the mean of the model runs, with five different initial conditions for the median climate sensitivity; blue bands show the range of simulations over the historical period; black lines represent observations. All continents are projected to experience large increases in temperature. By 2100, temperature increases in Africa, Australia, and South America exceed 3°C while increases exceed 4°C in North America, Europe, and Asia. The range of warming is very large, indicating that there is a large uncertainty in the projected warming, and this uncertainty is increasing over time.

Spatial results for projected temperature and precipitation changes from the 1901–1950 mean are presented in **Figure 21** for the three climate sensitivity scenarios for the periods 1991–2010, 2041–2060 and 2091–2110. As with all climate model projection in response to GHG forcing, polar regions display the largest warming, as do land areas. By 2100, in the high climate sensitivity scenario, some regions show warming as large as 12°C compared to pre-industrial (e.g., Northern Canada and Siberia). In all climate sensitivity scenarios, the warming by the end of the century is expected to be greater than 4°C in most inhabited regions of the world.

Patterns of precipitation change vary geographically, with many higher latitude and tropical land areas projected to become wetter. Exceptions are mainly in the subtropics, western North America,

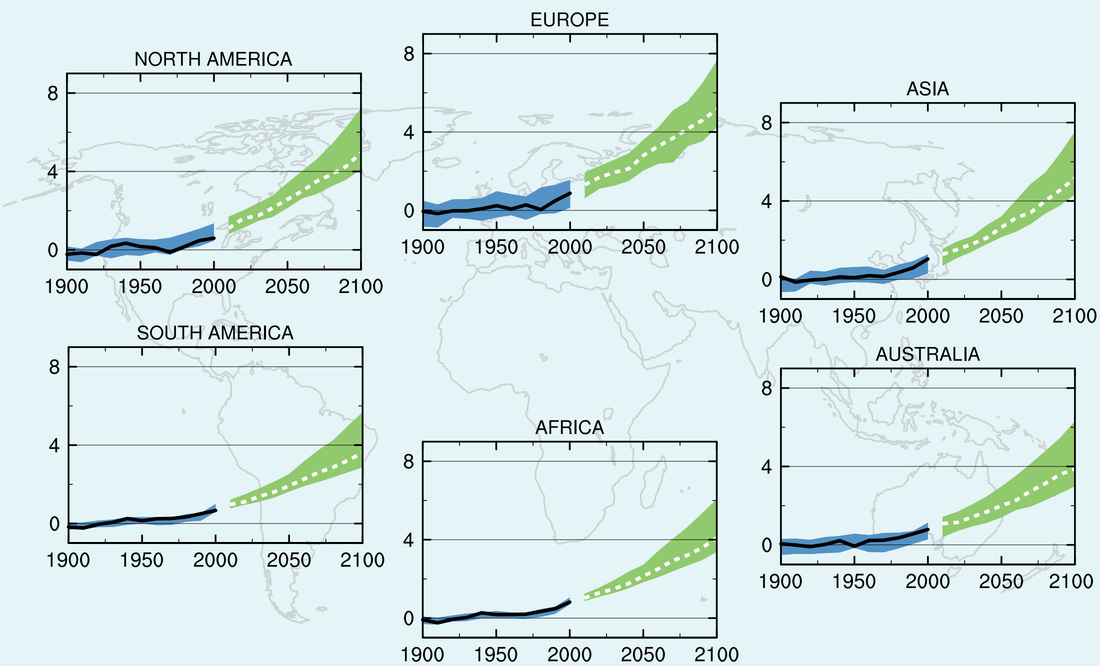

Figure 20. Regional temperature change, 1900–2100.

[5] Melting of large ice sheets will contribute significantly to sea level rise, but we do not have the capability in our modeling system to project those effects.

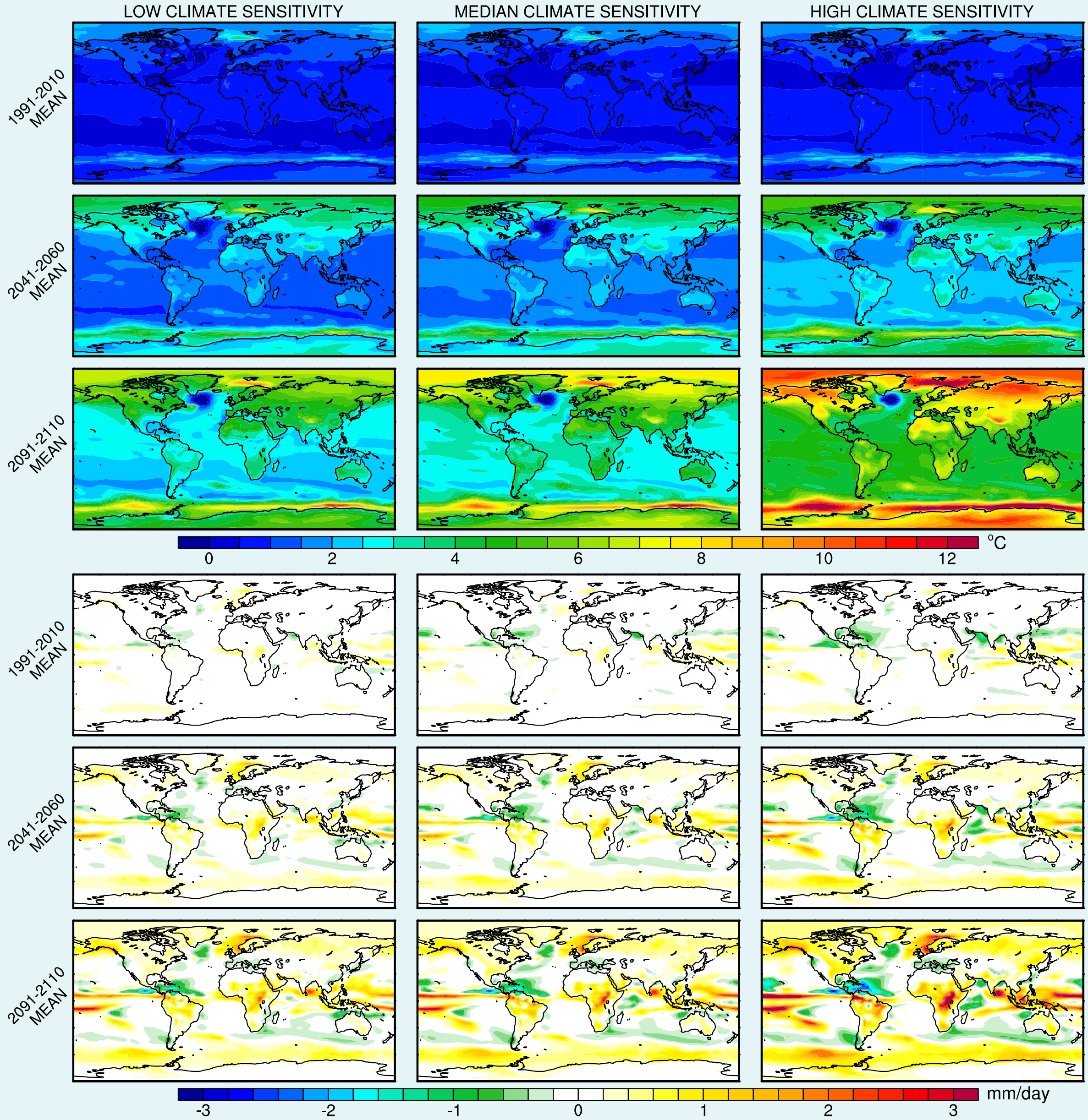

Figure 21. Mean surface temperature (top panels) and precipitation (bottom panels) anomalies for the periods 1991–2010, 2041–2060 and 2091–2110 from 1901–1950 means.

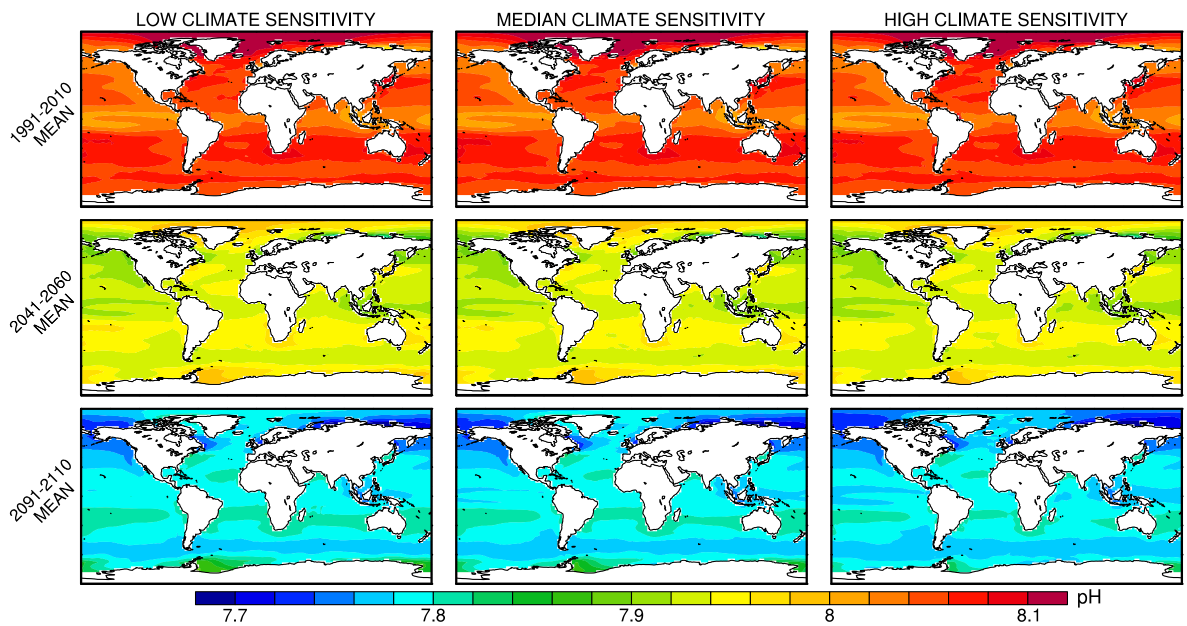

Figure 22. Ocean surface level pH for the periods 1991–2010, 2041–2060 and 2091–2110.

Europe, North Africa and central Asia, where there is little change—or in some cases, decreases. There is also little increase or even substantial decrease over large parts of the world's oceans. With overall global increased precipitation concentrated on land (and only a portion of the land), the increases would likely be accompanied by an increase in extreme precipitation events, leading to flooding with potentially damaging consequences. Anomalies described in mm/day can also be somewhat misleading because in regions of already high average precipitation (such as tropical areas), an anomaly may be a small *relative* change; in other regions that are currently relatively dry, the same mm/day anomaly is a large proportional change. Areas that receive little increase, no increase, or a decrease may also suffer much greater drought conditions than the precipitation change alone would indicate, because with higher temperatures evapotranspiration will very likely increase—so water availability, relative to needs of vegetation growing in those regions, will actually decrease.

While there is much concern about the climate effects of increasing atmospheric CO_2 concentrations, a less appreciated accompanying environmental implication is that the world's oceans are becoming more acidic. The oceans serve as significant sinks when atmospheric CO_2 increases, but dissolved CO_2 in the ocean becomes carbonic acid. Acidity in the ocean is measured by seawater pH, with lower pH indicating higher acidity. Maps of ocean pH for the ensemble mean of the three climate sensitivity scenarios are presented for the periods 1991–2010, 2041–2060, and 2091–2110 (**Figure 22**). By 2100 most locations are projected to reach a critical range of 7.7 to 7.8 pH. The reduced pH would strongly affect marine organisms like corals and mollusks, as 7.7 pH is considered a level of acidity at which corals are likely to cease to exist. These results are largely unchanged for different values of climate sensitivity because increases of CO_2 in the atmosphere—and thus its uptake by the ocean—are overwhelmingly controlled by the emissions scenario. If we had varied ocean heat uptake, which is a key uncertainty in the Earth system response, that would have led to different levels of carbon uptake by the ocean and, as a result, a wider variation in pH.

Impacts on Water

To summarize the impacts of climate change and economic growth on water resources, we employ a Water Stress Index (WSI). This index is defined as a ratio of total water requirements (municipal, industrial, and irrigation) to freshwater flow (water from upstream sources and basin runoff). We further characterize our calculation as *potential* water stress, as our current framework does not consider adaptation to changes in flow, which would inevitably occur. The index can take values from 0, for no water withdrawal requirements in the basin, to values greater than 1.0 if the combination of growth and changing resources leads to an estimate of water requirements greater than average annual flow. The water resource literature considers a Water Stress Index larger than 0.6 as indicating serious water stress. At first it may appear overly conservative that serious water stress conditions exist when as much as 40% of the annual freshwater flow in a basin is unused. However, at least three factors must be considered: (1) most water basins have wet and dry seasons; if 60% or more of the annual flow is being used, shortages are likely during the dry season; (2) there is increasing concern about the downstream environment of water systems, with regulations or guidance on maintaining a minimum flow level to preserve freshwater systems that depend on river flows; and (3) most regions are subject to large inter-annual and even decadal variability in river flows, so utilizing a large proportion of the average annual flow can create vulnerability during year-long or multi-year droughts.

Our projections of stress on water resources are shown in **Figure 23**. The top left panel shows estimates for 2010 among the 282 river basins in our newly developed Water Resource System (WRS) (Strzepek et al., 2013; Schlosser et al., 2014). The top right panel shows the same Water Stress Index for 2100. The bottom left panel shows the changes between 2100 and 2010—the difference between the top two panels—to highlight water stress is increases or decreases. These projections are all based on the mean of multiple initial-condition ensembles for the median climate sensitivity (i.e. the green line climate projection in Figure 19). As previously discussed, a focus on the ensemble mean can be misleading. Thus, in the lower right panel we show the Water Stress Index range across the different ensemble members, to illustrate at least a partial impact of natural variability.

Given the spatially varying precipitation patterns, it is no surprise that the changes to water stress vary geographically. Specifically, by 2100 we see a substantial increase in water stress in parts of India, China, Pakistan, Turkey, North Africa, South Africa and USA, while water stress decreases are projected in some parts of North America, China and Middle East. Water availability projections also depend on natural variability. In the lower right panel of Figure 23 we see that the Water Stress Index differences across ensemble members reach up to 0.25 for certain river basins. Most of the differences are observed in Mexico, Western parts of USA, North Africa, South Africa, Middle East, Pakistan, India, and China. This difference is notable, as a Water Stress Index of 0.3–0.6 is considered as moderately exploited water conditions, and a difference of 0.25 is almost the full range of this water-stress regime. The difference among ensemble members—caused by climate variability—can therefore move a region from slightly exploited water conditions toward the high end of moderately exploited.

Within each basin, the WRS considers total runoff (generated from precipitation), groundwater recharge, withdrawals, return flows, and water consumption (withdrawals that are evaporated or not directly returned to the basin). This allows us to compare water withdrawals and consumption to total annual available freshwater supply. **Figure 24** shows global water sources, withdrawals, uses, and return flows in 2010

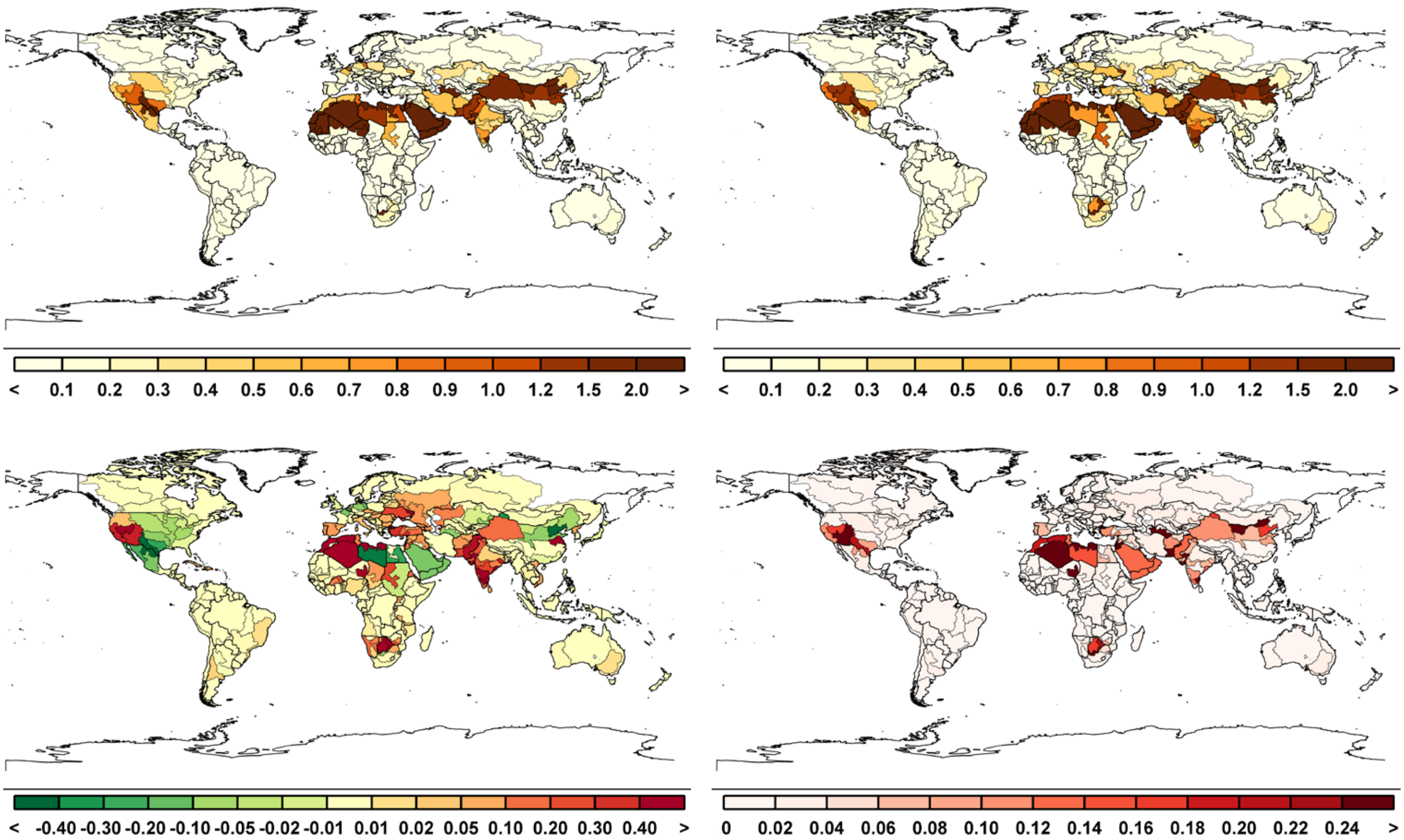

Figure 23. Water stress index maps. Top left: Water Stress Index (WSI) in 2010. Top right: WSI in 2100. Bottom left: WSI difference, 2010–2100 (mean of different initial conditions). Bottom right: range of WSI differences in 2100 for different initial conditions.

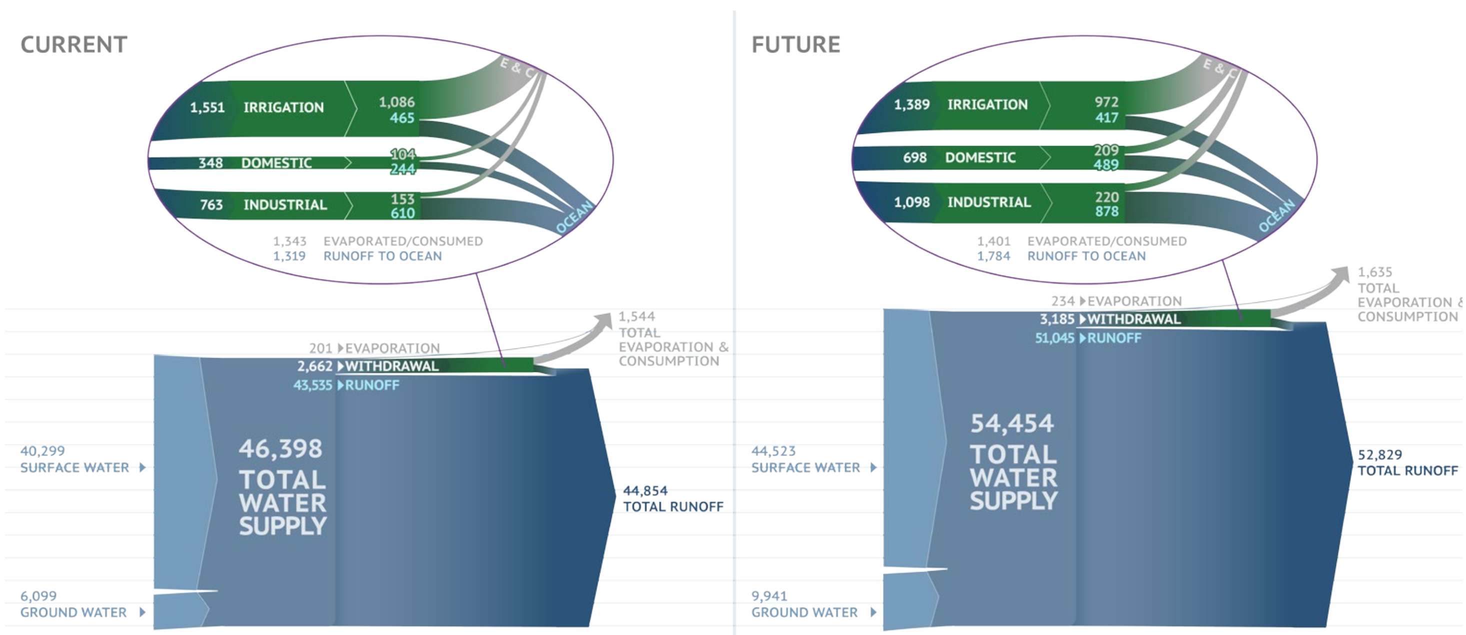

Figure 24. Global water sources and uses in 2010 and 2100, in billion cubic meters.

(*Current*) and 2100 (*Future*) in billion cubic meters (bcm) of water (see also **Box 5** for further discussion). Several features are worth mentioning. First, withdrawals and consumption as a percentage of total annual flows can provide a misleading picture of the adequacy of water resources because the location and timing of flows is important. Rivers such as the Amazon and the Mississippi are extremely large flows but are in areas with little development or with limited storage, and so much of the flow ends up in the ocean, while other regions have serious water shortages. Similarly, the seasonality of precipitation often means the timing of flows does not match needs, requiring extensive storage. By one estimate, about 70% (30,000 bcm) of total water supply from freshwater flow is not available to human use and goes directly to oceans (Niemczynowicz, 2000). In addition, a majority of the remaining water is needed to sustain natural ecosystems. Thus, water resource experts have estimated that only about 10% of total water supply (as freshwater flow) is actually available for human withdrawal.

In considering Figure 24 further, we note that—globally—freshwater appears abundant, with only about 2.9% of the annual flow currently used. However, given that only 10% of the annual flow is readily available to humans, then that use is about 30% of the realistically available global supply. We project global freshwater supply to increase by 17%, a direct result of our projected increased precipitation over land. On the demand side, total water withdrawals are expected to increase from the current levels of about 2,700 bcm to 3,200 bcm in 2100 (about a 19% increase). Domestic use of water is projected to double from 348 bcm in 2010 to 698 bcm in 2100, industrial use of water is expected to increase by almost 45% from 763 bcm in 2010 to 1,098 bcm in 2100, and irrigation needs are lower by about 10% from the current 1,551 bcm to 1,389 bcm in 2100. A current feature of the WRS is that we do not consider potential increases in irrigated areas—and any expansion could offset or overturn the reduction into an increase.

Presenting the results at a global level can give a misleading impression of regional challenges. As shown in Figure 23, some areas may experience substantial shortages of surface water. For example, in **Figure 25** we use the same style of diagrams as in Figure 24, focusing on the Indus River basin in India and Pakistan, where water withdrawals constitute a substantially larger portion of the total water supply. In this region, total withdrawals exceed the amount of available surface water by 2100. That would imply, of course, an unsustainable situation and therefore water requirements would need to be met by a transformation of current water management practices in the region, including the water supply provided by groundwater extraction.

Box 5.

Water Resource Estimates

The results presented in Figures 24 and 25 are based on simulations with the IGSM-WRS framework. As such, the flows of water are a result of model-derived values of precipitation as well as the runoff generated in the natural and managed land areas of the globe. Moreover, water demands of agriculture and subsequent withdrawals are determined by the IGSM simulated atmosphere—namely precipitation and temperature. This is done with the goal to achieve consistency between natural and managed land systems in the IGSM framework. However, given the challenges in climate modeling to accurately simulate precipitation and other key meteorological variables (such as clouds), biases can result. The international water community provides other estimates (similar to those depicted in Figure 24) that are based on a global integration of national surveys, whose values were bias-corrected with data gaps filled by model estimates without the constraint of running a globally consistent human-earth system model (such as the IGSM). As a result, our estimates of global withdrawals shown in Figure 25 are found to be typically lower than most of these survey-based reports. For example, the latest FAO report (available at http://www.fao.org/nr/aquastat) indicates that global withdrawals of freshwater around the year 2006 were approximately 3,750 bcm, which is higher than our estimate of 2,700 bcm in 2010. Each of these methods face unique challenges in quality control of observation, data synthesis, and model fidelity in order to provide a global compilation. Our ongoing efforts in the IGSM's development in this regard is to narrow the disparity among our assessments and those provided by the community at large, keeping a balanced perspective between improved observations and model advances.

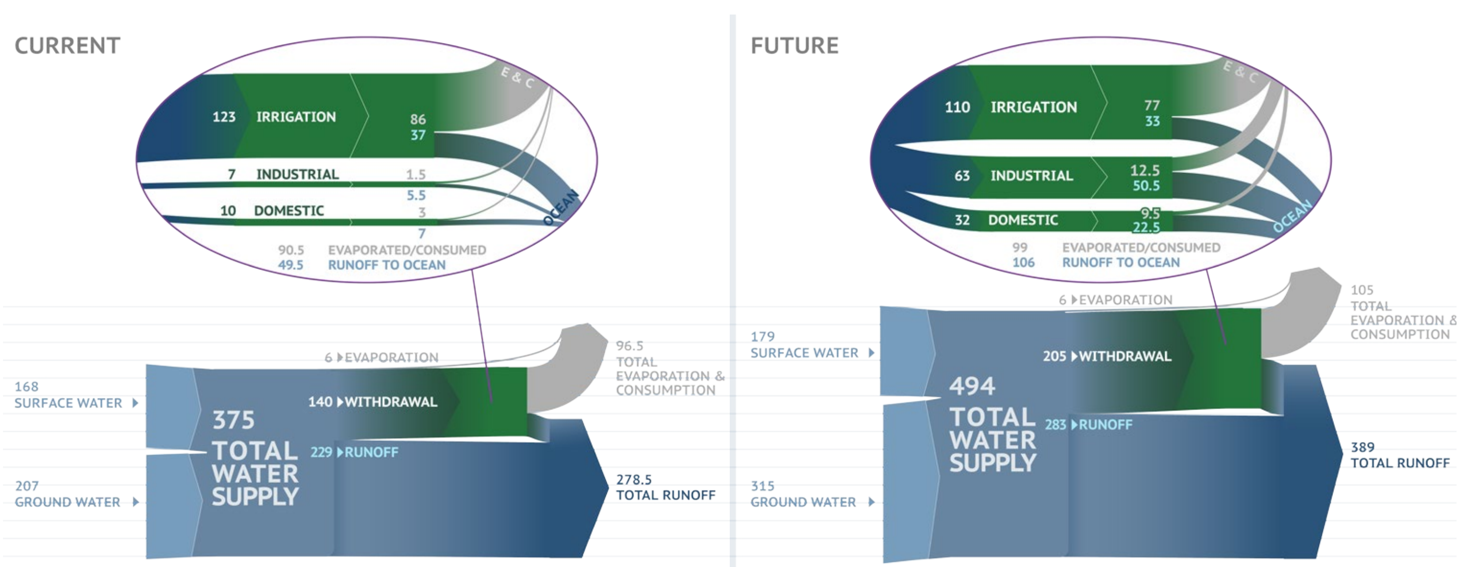

Figure 25. The Indus River basin water sources and uses in 2010 and 2100, in billion cubic meters.

Preparing for Tomorrow Today

This Outlook provides a view into the future as we project it in 2014. From this research effort, it is clear that the Copenhagen-Cancun pledges do not take us very far in the energy transformation ultimately needed to avoid the risk of dangerous warming. Even if policy efforts in developed countries are successful in holding emissions constant, as other nations grow and industrialize, their emissions will contribute to further increases in greenhouse gas concentrations and climate change. Our initial speculation on the outcome of ongoing international climate negotiations for the post-2020 period show further progress, but an emissions path that still remains far above any "windows" that would lead to stabilization of concentrations of GHGs in the atmosphere.

References

Outlook References:

Balmaseda, M., K. Trenberth, and E. Källén, 2013: Distinctive climate signals in reanalysis of global ocean heat content, *Geophysical Research Letters*, 40, 1754–1759.

Energy Outlook for China, 2014: *Energy Outlook for China*, Tsinghua-MIT China energy and Climate Project, MIT Joint Program on the Science and Policy of Global Change. http://globalchange.mit.edu/files/document/CECP_2014_Outlook.pdf

EU [European Union], 2013: The EU Emissions Trading System (EU ETS), European Commission, European Union. http://ec.europa.eu/clima/publications/docs/factsheet_ets_2013_en.pdf

Forest, C.E., P.H. Stone and A.P. Sokolov, 2008: Constraining climate model parameters from observed 20th century changes. *Tellus A*, 60(5): 911–920, doi:10.1111/j.1600-0870.2008.00346.x, available at: http://globalchange.mit.edu/hold/restricted/Forest-Stone-Sokolov-TellusA-2008.pdf

Huang, J., R. Wang, R. Prinn and D. Cunnold, 2009: A semi-empirical representation of the temporal variation of total greenhouse gas levels expressed as equivalent levels of carbon dioxide, MIT Joint on the Science and Policy of Global Change Program Report Series, *Report 174*, http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt174.pdf

IPCC, 2013: Summary for Policymakers, in: *Climate Change 2013: The Physical Science Basis.* Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nakicenovic, N., et al., 2000: *IPCC special report on emissions scenarios.* Cambridge University Press, Cambridge, UK and New York, NY, USA

Niemczynowicz, J., 2000: Present challenges in water management, *Water International*, 25: 139–147.

Paltsev, S., J. Reilly and A. Sokolov, 2013: What GHG Concentration Targets are Reachable in this Century? MIT Joint on the Science and Policy of Global Change Program Report Series, *Report 247,* http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt247.pdf

Schewe, J., et al., 2014: Multimodel assessment of water scarcity under climate change, *Proceedings of the National Academy of Sciences*, 111(9): 3245–3250.

UN [United Nations], 2009: Copenhagen Accord, United Nations Framework Convention on Climate Change. http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php

UN [United Nations], 2010: Cancun Agreements, United Nations Framework Convention on Climate Change. http://cancun.unfccc.int/

UN [United Nations], 2013: World Population Prospects: The 2012 Revision, Population Division, United Nations Department of Economic and Social Affairs. http://esa.un.org/unpd/wpp/Excel-Data/population.htm

van Vuuren, D., J. Edmonds , M. Kainuma, K. Riahi and J. Weyant , 2011: A Special Issue on the RCPs. *Climatic Change,* 109(1-2): 1–4.

Wada Y., et al., 2013: Multimodel projections and uncertainties of irrigation water demand under climate change, *Geophysical Research Letters*, 40: 1–7.

Publications describing the basic structure of the IGSM:

Monier, E. and X. Gao, 2014. Climate Change Impacts on Extreme Events in the United States: An Uncertainty Analysis. *Climatic Change*, online first, doi: 10.1007/s10584-013-1048-1, available at http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_14-3.pdf

Monier, E., X. Gao, J.R. Scott, A.P. Sokolov and C.A. Schlosser, 2014. A Framework for Modeling Uncertainty in Regional Climate Change. *Climatic Change,* online first, doi:10.1007/s10584-014-1112-5, available at: http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_14-10.pdf

Monier, E., J.R. Scott, A.P. Sokolov, C.E. Forest and C.A. Schlosser, 2013: An integrated assessment modeling framework for uncertainty studies in global and regional climate change: the MIT IGSM-CAM (version 1.0). *Geoscientific Model Development*, 6, 2063–2085, doi:10.5194/gmd-6-2063-2013 (http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_13-28.pdf)

Paltsev, S., J.M. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker, 2005: The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4. MIT Joint Program on the Science and Policy of Global Change, *Report 125*, http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf

Prinn, R.G., 2012: Development and application of earth system models. *Proceedings of the National Academy of Sciences*, 110(S1): 3673–3680, available at http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_12-12.pdf

Schlosser, C.A., K. Strzepek, X. Gao, C. Fant, E. Blanc, S. Paltsev, H. Jacoby, J. Reilly and A. Gueneau, 2014: The Future of Global Water Stress: An Integrated Assessment. *Earth's Future*, 2(8): 341–361, doi:10.1002/2014EF000238, available at: http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_14-16.pdf

Sokolov, A.P., C.A. Schlosser, S. Dutkiewicz, S. Paltsev, D.W. Kicklighter, H.D. Jacoby, R.G. Prinn, C.E. Forest, J. Reilly, C. Wang, B. Felzer, M.C. Sarofim, J. Scott, P.H. Stone, J.M. Melillo, and J. Cohen, 2005: The MIT Integrated Global System Model (IGSM) Version 2: Model Description and Baseline Evaluation. MIT Joint Program on the Science and Policy of Global Change, *Report 124*, http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt124.pdf

Strzepek, K., A. Schlosser, A. Gueneau, X. Gao, E. Blanc, C. Fant, B. Rasheed and H.D. Jacoby, 2013: Modeling water resource systems within the framework of the MIT Integrated Global System Model: IGSM-WRS. *Journal of Advances in Modeling Earth Systems*, 5(3): 638–653, doi:10.1002/jame.2004, available at http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_13-26.pdf

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Appendix

This appendix contains projections for global economic growth, energy use, emissions, and other variables to 2050. Similar tables for 16 regions of the world are available in the Excel file online at: http://globalchange.mit.edu/Outlook2014

MIT Joint Program Energy and Climate Outlook 2014 — Projection Data Tables

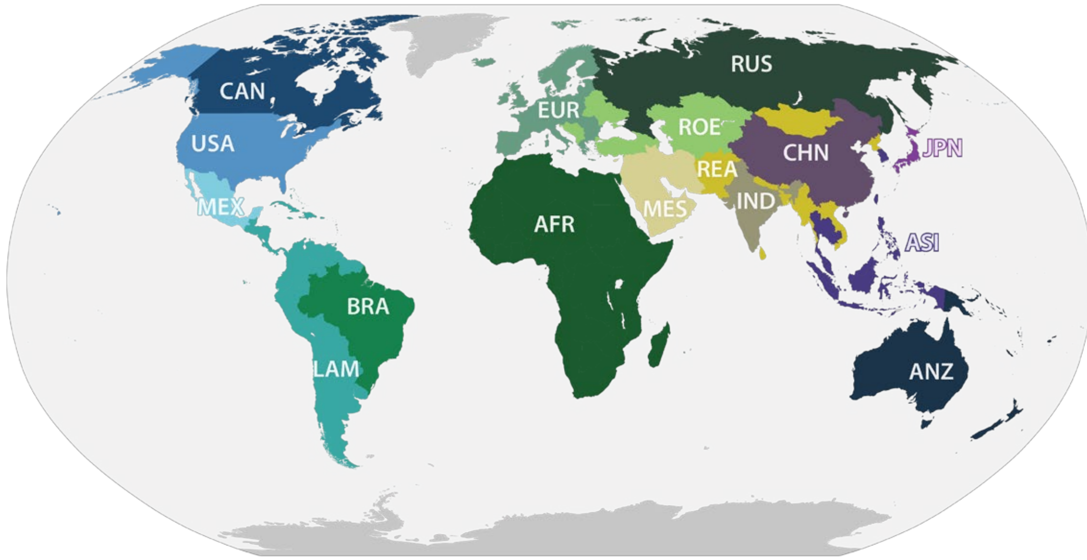
Region: World

	Units	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators										
GDP	(bil 2010 $)	52,872	61,277	69,977	79,790	91,078	103,861	117,708	133,286	151,085
Consumption	(bil 2010 $)	32,363	37,833	43,051	48,928	55,637	63,438	71,788	81,304	92,189
GDP growth	(% / yr)	1.9	3.0	2.7	2.7	2.7	2.7	2.5	2.5	2.5
Population	(millions)	6,916.2	7,324.8	7,716.8	8,083.4	8,424.9	8,743.4	9,038.7	9,308.4	9,550.9
GDP per capita	(2010 $)	7,645	8,366	9,068	9,871	10,811	11,879	13,023	14,319	15,819
GHG Emissions										
CO_2 – fossil	(Mt CO_2)	30,895	34,226	36,482	39,016	41,908	44,687	46,845	48,295	49,938
CO_2 – industrial	(Mt CO_2)	1564	1922	2102	2040	1728	1536	1624	1685	1720
CO_2 – land use change	(Mt CO_2)	7017	5273	4257	4516	3693	3086	2939	3608	3217
CH_4	(Mt)	400.6	441.6	440.9	470.9	503.0	532.7	551.0	572.6	601.3
N_2O	(Mt)	11.54	12.59	12.77	12.92	13.48	14.78	15.71	16.69	17.81
PFCs	(kt CF_4)	14.62	7.02	6.86	7.02	7.56	8.11	8.30	8.13	8.26
SF_6	(kt)	6.38	5.11	5.66	6.25	6.92	7.63	8.19	8.81	9.42
HFCs	(kt HFC-134a)	349	210	200	225	265	304	345	372	403
Primary Energy Use	**(EJ)**									
Coal		140.6	158.4	170.9	184.9	200.4	212.0	220.2	221.5	224.2
Oil		175.6	189.8	196.7	209.2	219.8	231.2	242.6	252.8	264.4
Biofuels		3.0	4.3	5.5	6.8	7.8	8.1	8.5	8.7	8.5
Gas		108.9	123.0	135.1	142.7	157.6	173.8	185.4	197.1	207.6
Nuclear		27.6	29.4	32.3	36.5	41.9	42.9	50.2	60.4	74.6
Hydro		31.2	32.8	35.0	37.4	39.5	44.0	46.9	52.6	58.8
Renewables		7.6	9.2	10.9	12.7	13.8	15.0	16.4	17.6	18.9
Electricity Production	**(TWh)**									
Coal		8,098	9,551	10,355	11,329	12,111	12,913	13,632	13,657	13,646
Oil		1,392	1,594	1,660	1,792	1,894	1,950	2,054	2,079	2,142
Gas		4,119	4,661	5,482	5,950	6,595	7,602	8,118	8,807	9,284
Nuclear		3,017	3,146	3,386	3,729	4,172	4,289	4,865	5,674	6,775
Hydro		3,101	3,226	3,426	3,632	3,823	4,193	4,448	4,949	5,481
Renewables		826	974	1,132	1,309	1,421	1,544	1,682	1,818	1,956
Household Transportation										
Number of vehicles	(millions)	808	906	998	1088	1175	1263	1344	1441	1543
Vehicle miles traveled	(trillions)	6.67	7.67	8.69	9.71	10.68	11.66	12.62	13.73	14.93
Miles per gallon	(mpg)	22.7	23.1	23.8	24.0	24.5	24.9	25.3	25.6	25.8
Land Use	**(Mha)**									
Cropland		1864.6	2018.6	2103.5	2226.2	2346.3	2481.9	2580.6	2686.7	2778.3
Biofuels		47.4	61.0	74.1	78.1	85.2	74.7	70.9	81.7	74.5
Pasture		3002.2	3072.3	3064.7	3041.8	3002.3	2980.0	2965.6	2932.3	2915.0
Managed forest		681.4	665.2	657.4	646.9	636.0	621.5	612.7	603.2	596.0
Natural grassland		1637.5	1455.0	1418.7	1377.0	1353.2	1318.0	1298.5	1276.4	1267.2
Natural forest		3370.5	3328.5	3279.7	3224.8	3170.8	3116.4	3062.9	3009.8	2958.3
Other		2659.6	2659.6	2659.6	2659.6	2659.6	2659.6	2659.6	2659.6	2659.6
Air Pollutant Emissions	**(Tg)**									
SO_2		102.88	106.32	108.23	108.50	107.62	106.23	103.19	98.89	95.36
NO_x		102.07	115.66	129.37	143.34	156.92	171.13	183.65	195.07	208.04
Ammonia		60.55	70.53	78.16	83.66	86.76	94.08	100.12	106.31	112.51
Volatile organic compounds		133.48	149.04	162.79	179.34	197.91	215.03	230.61	246.32	263.37
Black carbon		7.16	7.34	7.35	7.52	7.75	7.99	7.89	7.83	7.75
Organic particulates		33.96	35.77	35.85	37.41	39.06	41.20	41.04	41.26	41.26
Carbon monoxide		712.09	809.03	916.54	1033.93	1156.17	1293.57	1424.94	1562.60	1705.54

IGSM regions:

AFR	Africa
ANZ	Australia & New Zealand
ASI	Dynamic Asia
BRA	Brazil
CAN	Canada
CHN	China
EUR	Europe (EU+)
IND	India
JPN	Japan
LAM	Other Latin America
MES	Middle East
MEX	Mexico
REA	Other East Asia
ROE	Other Eurasia
RUS	Russia
USA	United States

Regional data tables available at: http://globalchange.mit.edu/Outlook2014



Country	Region
Afghanistan	REA
Albania	ROE
Algeria	AFR
American Samoa	ANZ
Andorra	ROE
Angola	AFR
Anguilla	LAM
Antigua & Barbuda	LAM
Argentina	LAM
Armenia	ROE
Aruba	LAM
Australia	ANZ
Austria	EUR
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Belize	LAM
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Bolivia	LAM
Bosnia and Herzegovina	ROE
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Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
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Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR

Country	Region
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Cook Islands	ANZ
Costa Rica	LAM
Croatia	ROE
Cuba	LAM
Cyprus	EUR
Czech Republic	EUR
Denmark	EUR
Djibouti	AFR
Dominica	LAM
Dominican Republic	LAM
Ecuador	LAM
Egypt	AFR
El Salvador	LAM
Equatorial Guinea	AFR
Eritrea	AFR
Estonia	EUR
Ethiopia	AFR
Falkland Islands	LAM
Faroe Islands	ROE
Fiji	ANZ
Finland	EUR
France	EUR
French Guiana	LAM
French Polynesia	ANZ
Gabon	AFR
Gambia	AFR
Georgia	ROE
Germany	EUR
Ghana	AFR
Gibraltar	ROE
Greece	EUR
Greenland	LAM
Grenada	LAM
Guadeloupe	LAM
Guam	ANZ
Guatemala	LAM
Guinea	AFR
Guinea-Bissau	AFR
Guyana	LAM
Haiti	LAM
Honduras	LAM
Hong Kong	CHN
Hungary	EUR
Iceland	EUR

Country	Region
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Indonesia	ASI
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
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Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
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Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
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Montserrat	LAM

Country	Region
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Mozambique	AFR
Myanmar	REA
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Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
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Oman	MES
Pakistan	REA
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Papua New Guinea	ANZ
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Peru	LAM
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