MIT JOINT PROGRAM ON THE SCIENCE AND POLICY OF GLOBAL CHANGE

ENERGY & CLIMATE OUTLOOK

PERSPECTIVES FROM 2015

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Exploring Global Changes

The 2015 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 Systems 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 and planned policies, while recognizing that our projections of environmental change indicate that further policy measures are needed to stabilize atmospheric greenhouse gas concentrations. The scenario presented here is a description and not intended as 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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Program Co-Directors

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About the 2015 Outlook

New in this edition of the Outlook are estimates of the impacts of post-2020 proposals from major countries that were submitted by mid-August 2015 for the UN Conference of Parties (COP21) meeting in Paris in December 2015. Our 2014 Outlook assumed that the commitments regarding greenhouse gas emission reductions submitted to the UN following the meetings in Copenhagen in 2009 and Cancun in 2010 would be achieved and that the agreed emission levels or policies would remain in place through the end of the century, although formally those commitments did not extend beyond 2020. Several large emitting countries have submitted proposals for post-2020 mitigation targets as Intended Nationally Determined Contributions (INDCs) ahead of the COP21 negotiations. INDCs specify actions through 2030, and we assume these levels of commitment remain in place through the horizon of the study. Where possible, we included specific measures that countries would be likely to take to meet the emissions targets they have described. For other regions, we continue to represent Copenhagen–Cancun commitments for the horizon of our study.

We provide detailed global and regional projections for economic, energy, emissions, land use, ocean acidity, precipitation, and temperature change results. In our 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). We report greenhouse gas (GHG) emissions in carbon dioxide-equivalent (CO_2-eq) using Global Warming Potential indices (GWPs) to sum together the warming influence of different long-lived GHGs that have different lifetimes and radiative forcing effects.

Box 1.

Regional Classification Details

The IGSM modeling system used to generate the projections in this Outlook divides the global economy into 16 regions (**Figure 1**). These regions do not align exactly with the G20, which is the 20 largest economies of the world. The group we identify as the *Other G20* includes the Dynamic Asia region. It is comprised of Indonesia and South Korea (both G20 members), as well as Malaysia, Philippines, Singapore, Taiwan, and Thailand (nations that are not among the G20). Conversely, South Africa, Argentina, Saudi Arabia, and Turkey are G20 countries, but are part of other regions in our model, and are included in the *Rest of the World* grouping. EUR is the EU-27, plus Norway, Switzerland, Iceland, and Liechtenstein.

A full list of the countries included in each IGSM region is provided in the Appendix and supplementary projection tables available online at: http://globalchange.mit.edu/Outlook2015.

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

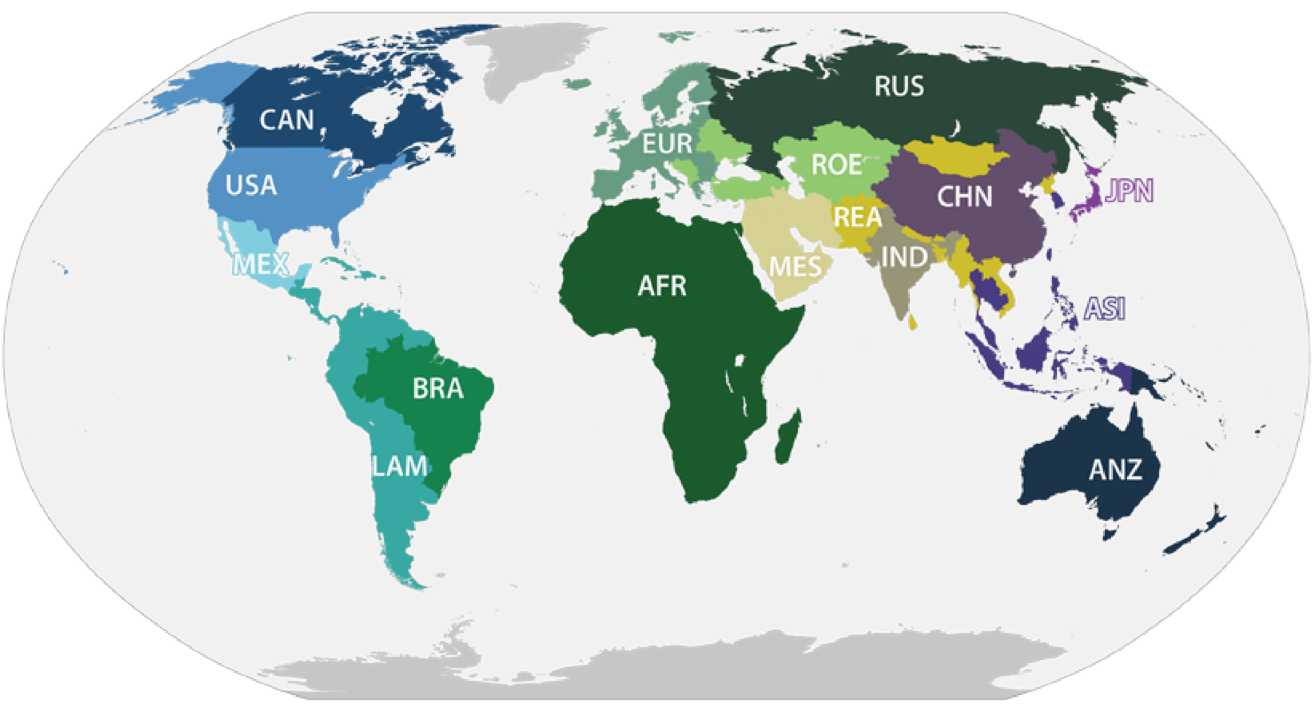


Figure 1. IGSM regions: Africa (AFR), Australia & New Zealand (ANZ), Dynamic Asia (ASI), Brazil (BRA), Canada (CAN), China (CHN), Europe/EU+ (EUR), India (IND), Japan (JPN), Other Latin America (LAM), Middle East (MES), Mexico (MEX), Other East Asia (REA), Other Eurasia (ROE), Russia (RUS), United States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

Key Findings

Changes in Energy and Emissions

With emissions stable and falling in *Developed* countries, on the assumption that the Paris pledges made at COP21 are met and retained in the post-2030 period, future emissions growth will come from the *Other G20* and developing countries.

- Growth in global emissions results in 64 gigatons (Gt) CO_2-eq emissions in 2050, rising to 78 Gt by 2100 (a 63% increase in emissions relative to 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 1/3 of total global GHG emissions by 2100, slightly down from the 35% in 2010.
- Emissions from electricity and transportation will together account for about 51% of global CO_2 emissions from fossil fuel use in 2050, decreasing slightly from the 56% in 2010.
- Energy from fossil fuels continues to account for about 75% of primary energy by 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.

- The global mean surface temperature increase is in the range of 1.9 to 2.6°C (central estimate 2.2°C) by mid-century relative to the pre-industrial level (1860–1880 mean), and 3.1 to 5.2°C (central estimate 3.7°C) by 2100.
- Global mean precipitation increase ranges from 3.9 to 5.3% by 2050 relative to the pre-industrial level, and 7.1 to 11.4% (central estimate 7.9%) by 2100.
- Thermal expansion and land glacier melting contribute 0.15 to 0.23 meters to sea level rise from the pre-industrial level by 2050, and 0.30 to 0.48 meters (central estimate 0.35 meters) by 2100. Melting of large ice sheets will contribute significantly to sea level rise, but our modeling system does not have the capability to project those effects.
- More carbon absorbed in the ocean leads to increasing acidity, with average pH dropping from 8.13 in the pre-industrial era to about 7.82 by 2100.

Impacts of Emissions Reduction Proposals for the 21st Conference of the Parties (COP21)

We have incorporated in our projections the post-2020 proposals of major countries that were submitted by mid-August 2015 for the COP21 meeting in Paris. In the language of the climate negotiations, these are Intended Nationally Determined Contributions (INDCs). Where there was indication of the form of the policies intended to achieve at least part of the planned GHG reductions, we have approximated the specific policies and measures. It is likely that other countries will ultimately make additional commitments, and many developing countries have made commitments conditional on outside funding; these commitments have not been included.

The proposed additional commitments that are not conditional on outside funding that have been made as of August 2015 will continue to bend the curve of emissions growth, but will not reverse it, as is needed to stabilize atmospheric concentrations.

- The 64 Gt CO_2-eq emissions level we estimate for 2050 is about 13 Gt less than our 2014 Outlook, in which only Copenhagen–Cancun pledges were considered.
- Assuming the proposed cuts are extended through 2100 but not deepened further, they result in about 0.2°C less warming by the end of the century compared with our estimates, under similar assumptions, for Copenhagen–Cancun. Other adjustments in our economic projections resulted in another 0.2°C reduction in warming (see **Box 2**).
- Under the proposed cuts, the emissions path far exceeds levels consistent with the 2°C goal often used as a target in climate negotiations as a level necessary to prevent dangerous climate change.
- If no policy beyond these proposed cuts is implemented, then by 2030 the world will be within about 5 years of hitting the cumulative emissions level that the Intergovernmental Panel on Climate Change (IPCC) Working Group I estimates as consistent with there being a 50% chance of holding the temperature increase to less than 2°C.
- With high climate sensitivity, the 2°C target may be exceeded in as little as 15 to 20 years from now. Even with low climate sensitivity, on this path, the 2°C target will be passed shortly after mid-century.

Box 2.

The COP21 Contribution to Avoided Warming

A natural question is: How much do the INDCs proposed ahead of the COP21 meeting further reduce warming, assuming our estimates reflect the agreement and its implementation? In principle, a simple comparison between the 2014 and 2015 Outlook results would answer that question. However, over that time our underlying economic projections have changed and we have recalibrated the climate component of the IGSM. The accompanying figure shows how each of these changes affected the projection of mean global surface temperature for central values of climate response. The black line labeled *Copenhagen (2014 Econ&Climate)* is the actual simulation from last year's Outlook.* The blue line labeled *Copenhagen (2015 Climate)* is the exact emission scenario from the 2014 Outlook, but with the new climate model calibration. Recalibration of the climate model results in 0.2°C more warming by the end of the century (mean for 2091–2110). The green line labeled *Copenhagen (2015 Econ&Climate)* represents the same Copenhagen policies as the 2014 Outlook, but with the most recent recalibration of both the economic and climate models. Notably, this lies almost exactly on the black line for the second half of the century, implying that the recalibration of the economic model contributed to less warming by 2100, which almost exactly offsets the additional warming due to the climate model recalibration. Finally, the red line is the 2015 Outlook projection with COP21 policies. The difference between the red and green lines is the additional contribution of COP21 policies, and that is about 0.2°C less warming by the end of the century.

* Note: To be consistent with the 2°C warming goal, the 2015 Outlook reports the global temperature relative to pre-industrial levels (1861–1880) whereas the 2014 outlook used 1901–1950 as the base. As can be seen from the chart, there was a small warming trend from 1900 to 1950. The difference between the 1901–1950 and 1861–1880 base period is 0.07°C of warming.

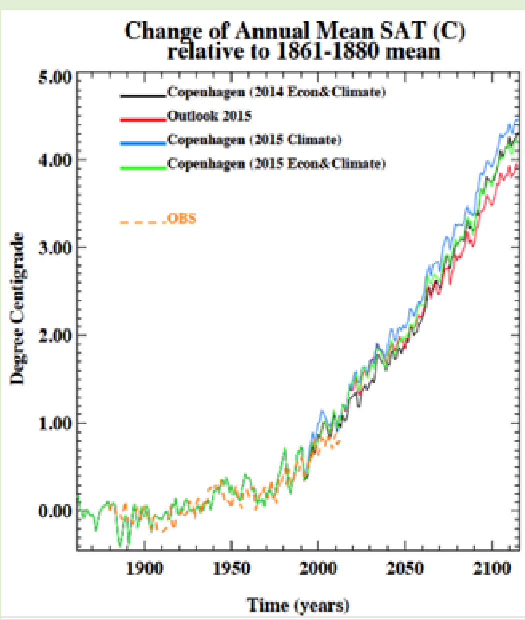


Figure 2. Change in temperature above pre-industrial (°C).

While conditional commitments of developing countries could contribute to greater reductions, the extent to which they do will depend on the nature of the funding. For example, Japan has proposed in its INDC that it expects to meet its commitment at least in part through a Joint Crediting Mechanism. One such existing approach is the Clean Development Mechanism, under which funding is provided to developing countries from developed countries to make emissions reductions that the developed country can then use as offsets against its commitments. Such joint crediting would allow, in this case, Japan to emit more than specified in its INDC, by amounts reduced in other countries. So while this would change the regional emissions and energy results we report, it would not change global emissions. Similarly, emissions trading among countries could be another form of Joint Crediting, but that would not reduce emissions further than the national commitments countries have made; it would only change where the reductions occurred.

The remaining report briefly describes the details behind these broad conclusions. **Box 3** details the major updates and changes in the 2015 Outlook. A principal product of our Outlook process is a set of detailed tables containing economic, energy, land use, and emissions results for each of 16 major countries or regions of the world.[1] We provide our detailed regional projections up to 2050, and also show global results through 2100, which are useful for providing the longer-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. While we do not attempt to assess what would be required to keep within the 2°C limit, dropping emissions from the 55 Gt CO_2-eq projected for 2030 to zero in 5 years would seem a near-impossible task, and so to stay within the 2°C limit would likely require revisiting commitments through 2030. Modeling exercises described in the IPCC's most recent report that do attempt to meet the 2°C target show greater reductions now and through 2030 than have so far been agreed in international negotiations. The report also considers scenarios that overshoot the emissions limit, taking advantage of the inertia in climate system to buy time to employ biomass energy with carbon capture and storage (CCS) (Clarke *et al.*, 2014). Biomass with carbon capture and storage can be a net sink for CO_2 as plants take carbon from the atmosphere when they grow, and at least some of this can be captured when the biomass is converted to liquids or electricity.

[1] Available at: http://globalchange.mit.edu/Outlook2015

Box 3.

Major Updates in the 2015 Outlook

Climate Policy Assumptions: The central Outlook scenario includes our assessment of a post-2020 international agreement on emissions mitigation that is likely achievable at COP21. In addition, diverse policy instruments are used to achieve emissions reductions—such as vehicle standards, renewable requirements, coal power generation restrictions, and carbon pricing—to reflect as closely as possible the policies that different countries appear likely to pursue. In the 2014 Outlook a simple cap on emissions was applied to meet agreed targets or to approximate the effect of agreed policies.

Economic Growth: Regional economic growth assumptions reflect the latest International Monetary Fund Outlook (IMF, 2015) 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 about 25% lower compared to the 2014 Outlook. In 2011-2015 the world economy is estimated to grow by 2.2% instead of 3% as projected before. After 2015, the most substantial changes are in China (where the average annual GDP growth rate in 2016-2020 is reduced from 6.8% to 6.1%) and India (where the average annual GDP growth rate through 2050 is increased from 4.97% to 5.11%).

Updated Land Use Conversion: New estimates of land-use conversion (see Gurgel *et al.*, 2015) resulted in updated patterns of land-use change and the resulting land-use emissions. In the 2014 Outlook, global land-use emissions were estimated at 3.2 Gt CO_2 in 2050 and 1.3 Gt CO_2 in 2100. Our new estimates are 1.2 Gt CO_2 in 2050 and 0.8 Gt CO_2 in 2100.

Updated Inventories for non-CO_2 GHGs and Air Pollutants: Historic data for 2005-2010 for inventories of methane were updated based on Kirschke *et al.* (2013) and for inventories of air pollutants based on the HTAP2.1 database (HTAP, 2013). The major changes are in a lower base year emissions of methane, NO_x, CO, VOC, and NH_3, and higher emissions of NO_x, while the base year emissions of SO_2 were unchanged.

Updated Policy Projections: Nuclear development in Japan and fuel efficiency in USA and Europe were updated based on our latest assessments.

Additional Reporting: Data on total GHG emissions in CO_2-equivalence and number of private vehicle per person have been included in the detailed regional tables available online.

The Changing World

Our 2015 Outlook relies on the same population forecasts as the 2014 Outlook (**Figure 3a**). 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 such as 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). The productivity improvements along with the availability of advanced energy supply technologies more than offset the effects of resource depletion, which may include diminished supplies of fossil fuels or limits on renewable resources such as arable land. In terms of contribution to GDP growth, labor is the single largest resource, so we can use labor productivity to target GDP growth, especially in the near term.

In particular, near-term growth in GDP has been adjusted to reflect the most recent International Monetary Fund Outlook (IMF, 2015). In general, GDP shows further recovery from the recession, but slightly slower than in the 2014 Outlook. The result is that the average annual GDP growth rate from 2010 to 2015 is 0.08% less compared to the 2014 Outlook, mostly attributed 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

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%

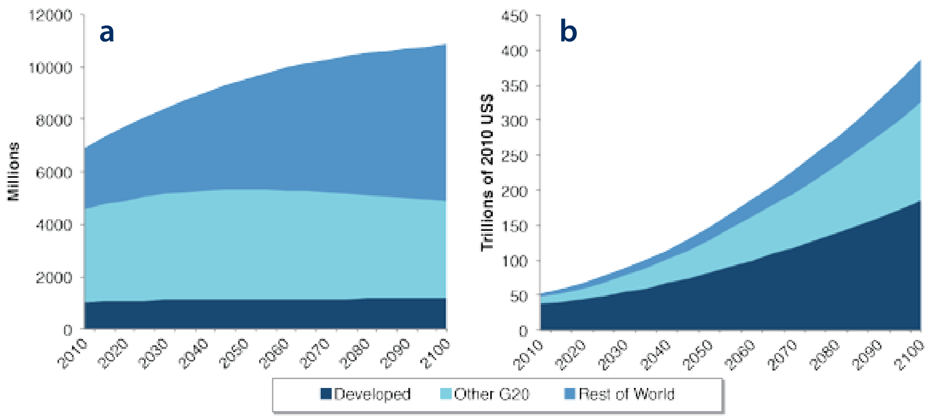


Figure 3. (a) World population and (b) World GDP.

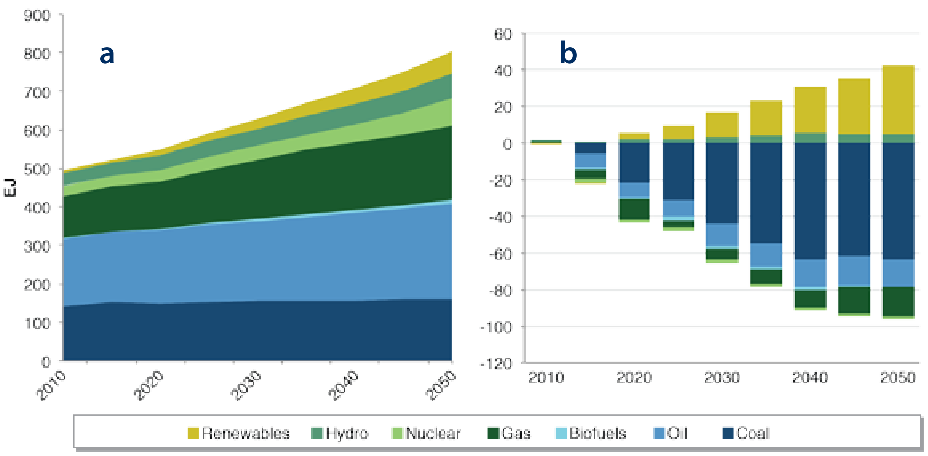


Figure 4. (a) Global primary energy use and (b) changes from the 2014 Outlook (exajoules).

growth for China and 0.15% increased growth for India through 2050. **Figure 3b** shows GDP projections. Even as we complete this report, the Chinese economy appears to be weakening further, with repercussions for other economies that have benefited from supplying energy, minerals, metals, and other inputs to meet the needs of China's economy, which had been expanding rapidly over the past two decades. That said, our projection for China has GDP growth slowing gradually from 7.2% in 2015 to 4.5% in 2030 and to 3.1% in 2050.

Note that we report 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, which would result in, for example, the *Other G20* and *Rest of the World* with a larger share of GDP initially. Since our projections have those regions growing more rapidly, global GDP would grow more rapidly. Such an adjustment can be made by applying purchasing power conversions to the GDP data we provide.

Based on our reporting in market exchange rates, global GDP is projected to grow 2.8 times between 2010 and 2050, and increase by another 2.6 times by 2100, corresponding to an average annual growth rate of 2.6% per year through 2050 before slowing to a rate of 2.2% through the remainder of the century. The rate through 2050 is about 0.04% lower than the 2014 Outlook projection because of adjustments, particularly in China and India. While this difference in the growth rate is small, it shaves over $3.1 trillion from global GDP 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**). GDP growth is relatively rapid in the *Rest of the World* group compared to the *Developed* countries, but most of that is offset by more rapid population growth, and so growth in GDP *per capita* in the two regions is quite similar.

We find that global energy use grows from about 500 exajoules (EJ) in 2010 to about 802 EJ by 2050 (**Figure 4a**). This is 55 EJ less in 2050 than the 857 EJ projected in the 2014 Outlook. The reduction in energy use is, in part, due to somewhat lower GDP growth, but mostly due to the proposed post-2020 policies of major countries that have been submitted ahead of COP21. As will be shown in subsequent figures, the reduction in energy use is almost entirely due to China, with most other regions showing little change or small increases in energy use from our 2014 projection. In the 2014 Outlook we had represented the Copenhagen–Cancun emissions commitments as being achieved via a broad cap on emissions in each region that had made a commitment. As imposed in our model, this cap creates a uniform shadow price on carbon within the region, and in terms of an actual policy is best interpreted as an economy-wide price through a cap-and-trade system or a carbon tax. In 2014, it seemed likely that few, if any, countries would achieve their target with a pure carbon-pricing policy. Even where carbon-pricing policies have or are being implemented, such as in Europe, China, and South Korea, they only cover a portion of emissions and have been combined with renewable energy targets, vehicle standards, or, in the case of China, nuclear power development targets. Other countries, notably the U.S., have no carbon pricing policy and instead are promulgating a mix of regulatory policies.

The picture for likely post-2020 policies is now becoming clearer. As of August 2015, most large emitters submitted their INDCs. The proposals are very heterogeneous. For example, China pledged to reduce its carbon intensity relative to 2005 by 40–45% by 2020 and by 60–65% by 2030. The European Union submitted a proposal for GHG reduction of 40% by 2030 relative to 1990 levels. The United States proposes a 26–28% reduction in GHG emissions by 2025 relative to 2005 levels. Japan's target is 26.4% reduction in 2030 relative to 2013 levels. Russia proposed a reduction of 25–30% relative to 1990 levels. Several countries (such as South

Box 4.

INDCs of Major Countries Submitted by Mid-August of 2015 for Consideration at COP21

Major countries submitting INDCs (Intended Nationally Determined Contributions) ahead of COP21 are listed below (column 1), along with the policies and measures we have represented in our projections. In Europe, the USA, China, and Japan we have attempted to approximate the effect of transportation (column 3) and electricity sector (column 4) measures the countries are pursuing. By themselves, these may not achieve the emissions reduction targets proposed in their INDC, so in addition we impose a cap on national emissions to meet the emissions target (column 2).

Region	Policies and Measures		
	Emissions cap	**Transport policies**	**Electricity policies**
USA	27% GHG reduction by 2025 onward relative to 2005	30 miles per gallon (mpg) for all private vehicles by 2030	No new coal-fired power plants without CCS after 2020; support to wind and solar power to triple production in 2030 relative to 2010
EUR	40% GHG reduction by 2030 onward relative to 1990	45 mpg for all private vehicles by 2030	No nuclear expansion; support to wind and solar power to triple production in 2030 relative to 2010
CHN	CO_2 peaks by 2030; coal consumption does not exceed 4.2 billion tons		No new coal-fired power plants without CCS after 2030; support to wind and solar power to quadruple production in 2030 relative to 2010, quadrupled 2015 nuclear production by 2030
JPN	24% GHG reduction by 2030 relative to 2010		Limited nuclear production in 2015 and gradual restart of nuclear reaching 2010 levels by 2050
RUS	27% GHG reduction by 2030 relative to 1990		
CAN	21% GHG reduction by 2020		
ANZ	13% GHG reduction by 2030 relative to 2010		
MEX	11% GHG reduction by 2030 relative to 2015		

Korea, Mexico and Ethiopia) stated their targets relative to their "business-as-usual" emissions. India and Brazil so far have not submitted their INDCs.

We represent the goals submitted by major emitting countries. Where there is indication of the nature of the policies that the countries are likely to pursue, we model a mix of measures to achieve reductions (see **Box 4**). The main measures we represent are targeted penetration of renewables, phase-out of coal power generation, policies regarding nuclear power, and the growing attention to new vehicle efficiency standards.

Overall, the effect of including these targeted technology/sector policies is to greatly accelerate renewable energy development (by 2050 it is more than triple our projection in the 2014 Outlook), and cause a greater reduction in coal use (on the order of 15–30% less than in our 2014 Outlook (see **Figure 4b**). Changes for oil and gas are more in line with the general reduction in energy use. Nuclear is nearly unchanged, but this reflects lower production in Japan, accounting for the only gradual reopening of nuclear capacity after Fukushima, offset by increasing nuclear in China as part of its efforts to reduce coal. Hydropower increases, mainly due to less coal power in China, which creates greater demand for hydro.

As in the 2014 Outlook, growth in energy use in our projection is led by the *Other G20* nations, which reach more than 400 EJ by 2050, which is 65 EJ less than our 2014 projection for this region (**Figure 5**). Net energy use is up somewhat in the *Developed* countries from the 2014 Outlook, reaching 212 EJ in 2015. Mostly this reflects an increase in renewables and a reduction in most other primary energy sources, led by oil use. The effect on coal use of representing a phase-out of coal plants in the *Developed* region was not much different than when we implemented a broad carbon constraint, so there is little difference from the 2014 projection for coal. The vehicle standards in this region do reduce oil use compared with the broad carbon constraint applied in the 2014 Outlook. At 180 EJ, the *Rest of the World* is nearly unchanged from the 2014 Outlook, in both the level of total primary energy use and the fuel mix, reflecting the fact that we have not represented specific new policies in these regions. Otherwise the economic projections are very similar to the 2014 Outlook projections. Together, primary energy use in the *Developed* and *Rest of the World* regions is less than the *Other G20*.

Given the growing dominance in energy consumption of the *Other G20* countries, we focus in on China, the largest single primary energy-consuming country in this region, and in the world. Our ability to focus on China benefits from our collaboration with Tsinghua University through our China Energy and Climate Project (http://globalchange.mit.edu/CECP/). Given the ongoing developments in energy, pollution, and climate policy in China over the past year, we have significantly revised our projection. We project primary energy use in China to nearly double from 2010 to about 200 EJ by 2050, which is about 70 EJ less than our projection in 2014 (**Figure 6**). This change reflects policies in China to stop growth in CO_2 emissions by 2030 and coal use by 2020, as well as measures to support renewables and aggressively increase nuclear. However, the explicit target for nuclear expansion did not change our projection for nuclear very much from the 2014 Outlook. As noted earlier, the significant reduction in coal use spurs some additional hydropower generation.

As 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 reduced energy use is growth in GDP. GDP includes the effect of both a larger and wealthier population. Actual projected energy use includes the effects of exogenous improvements in efficiency as well as efficiency and conservation spurred by price or policy changes, and structural change in the economy. Structural change can lead to an increase or decrease in energy intensity. The general observation is that at low incomes, structural change associated with growth may increase energy intensity, as infrastructure development is energy intensive. However, structural change in higher income countries tends to reduce energy intensity, as growth is disproportionately in high value-added

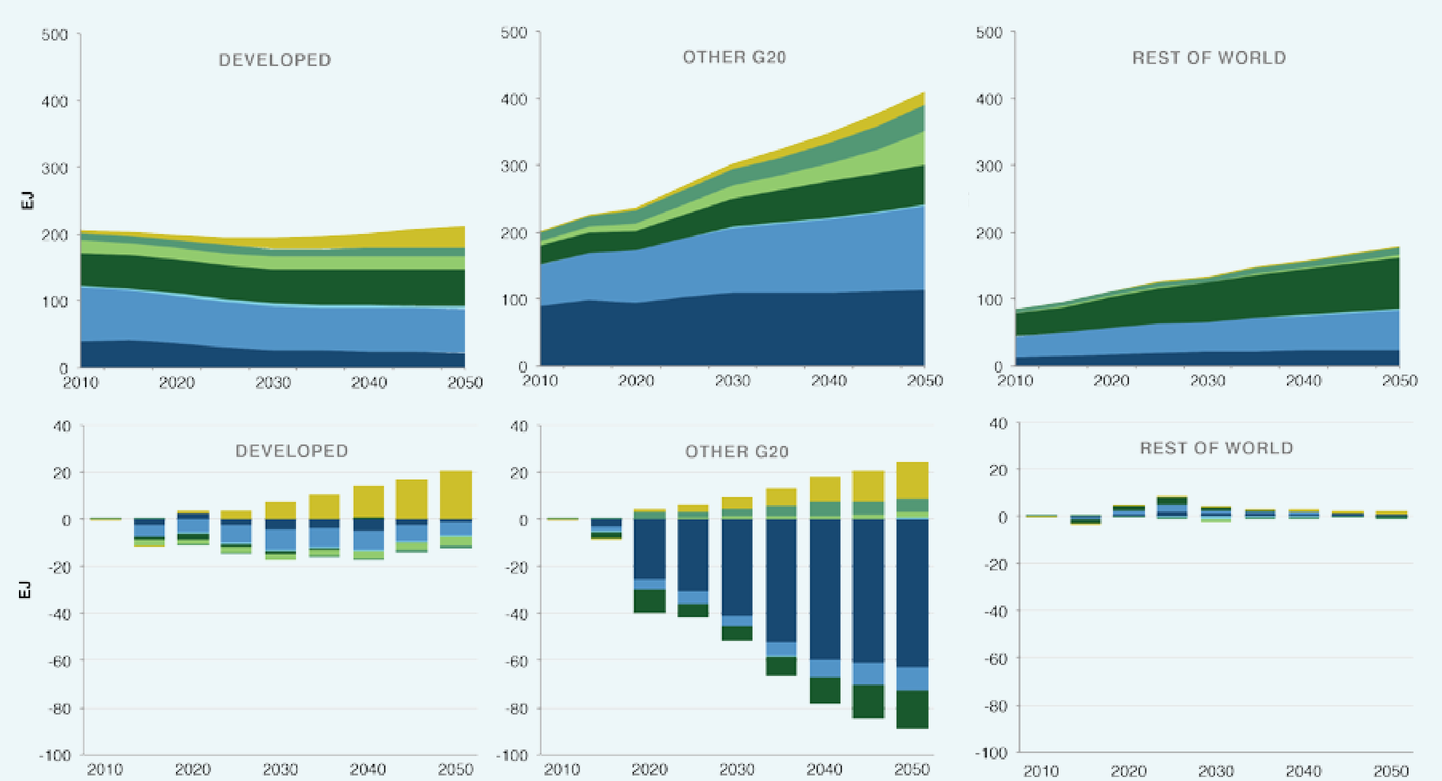


Figure 5. Primary energy use (top row) and changes from the 2014 Outlook (bottom row) by major group (exajoules).

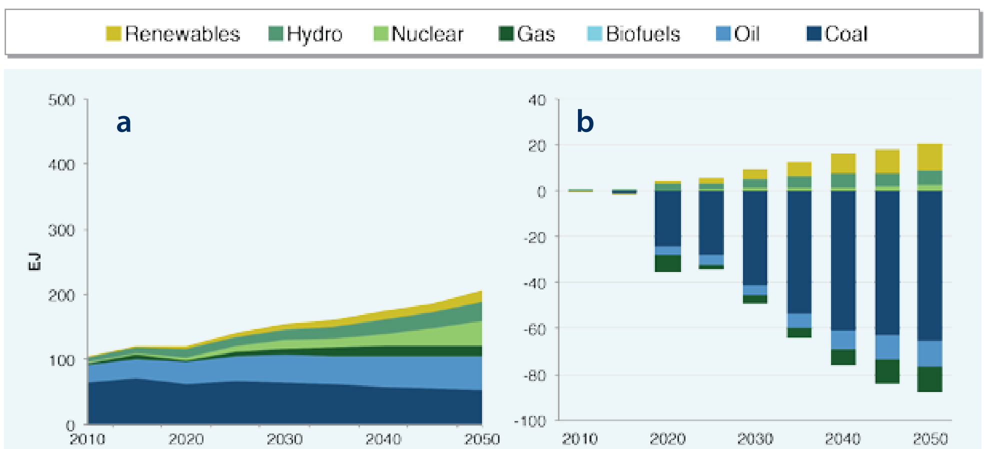


Figure 6. (a) Primary energy use in China and (b) changes from the 2014 Outlook (exajoules).

manufacturing and the service sectors, which are less energy-intensive. Energy price changes also have counteracting drivers. Depletion of high-grade resources is partly offset by advanced technologies that make more resources available as well as general improvements in economy-wide productivity.

Accounting for all of these factors, our projections show continued decreases in energy intensity of GDP (EJ of Energy use divided by GDP) across the world (**Figure 7**). 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. These results are, for most regions, nearly unchanged from our 2014 Outlook as GDP growth and total primary energy use have not changed much. The one exception is China, where proposed policies would significantly reduce energy use. As a result, China's energy intensity falls to one-third the level of 2010 by 2050. This is an improvement of about 2.5% annually, which is much more rapid than what other regions are projected to achieve or have seen historically. However, this likely corrects some of the huge build-up of energy-intensive production sectors that occurred over the past 10 to 15 years.

As with the 2014 Outlook, we focus on two sectors, transportation and electricity production, that together accounted for about 56% of CO_2 emissions and 57% find that total electricity production in 2050 is about 140 EJ (within 1 EJ of that in the 2014 Outlook), or a 91% increase from 2010 levels (**Figure 8**). While total electricity production is almost identical to what was reported in the previous Outlook, the source of generation shifts to more renewables at the expense of almost all other sources, especially coal. The largest percentage increase for 2010 to 2050 is from renewable generation (608%), followed by gas (118%), nuclear (113%) and hydropower (85%). As a result, the coal share of generation drops from 40% in 2010 to only about 25% in 2050.

Electricity generation currently contributes about 11.2 Gt of CO_2 (about 36% of total global CO_2 emissions). Given the projections, to about 13.2 Gt of CO_2 (about 31% of total global CO_2 emissions) by 2050. This represents an 18% increase in electricity emissions from 2010 to 2050. With total world generation increasing by 90%, the carbon intensity of generation is falling substantially.

All three large regions highlighted in the Outlook show growth in electricity use, with the *Rest of the World* nearly unchanged in total electricity use or fuel mix compared with the 2014 Outlook (**Figure 9**). The share of coal use in the *Developed* regions falls from about 33% in 2010 to 19% in 2050. This is less than the 23% share in 2050 we projected in the 2014 Outlook, but much of that share reduction is due to an increase in total generation, with most of that

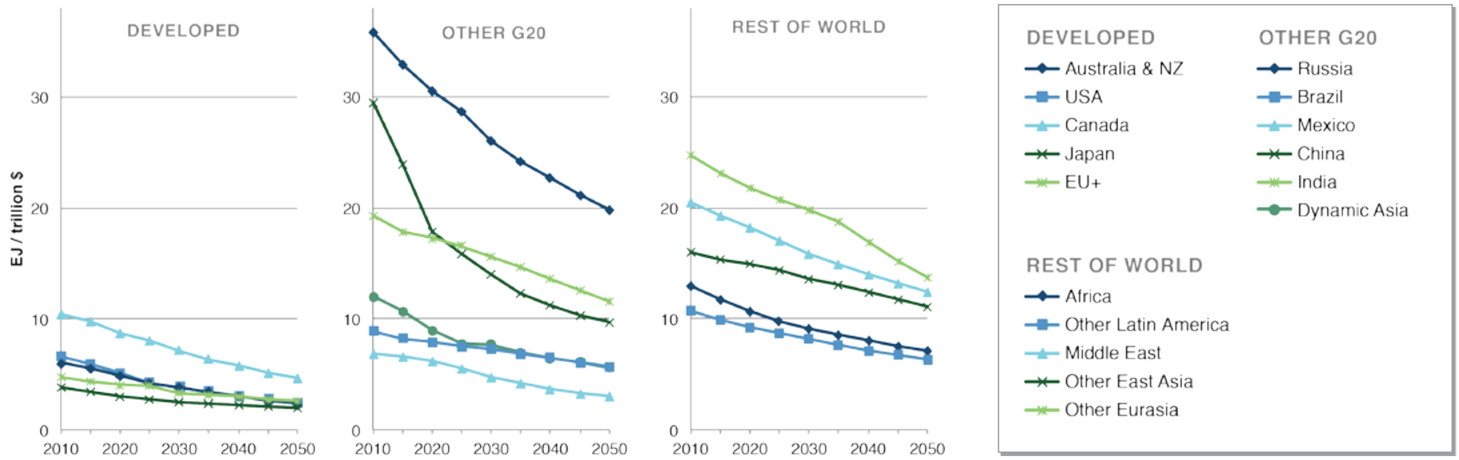


Figure 7. Energy intensity by region.

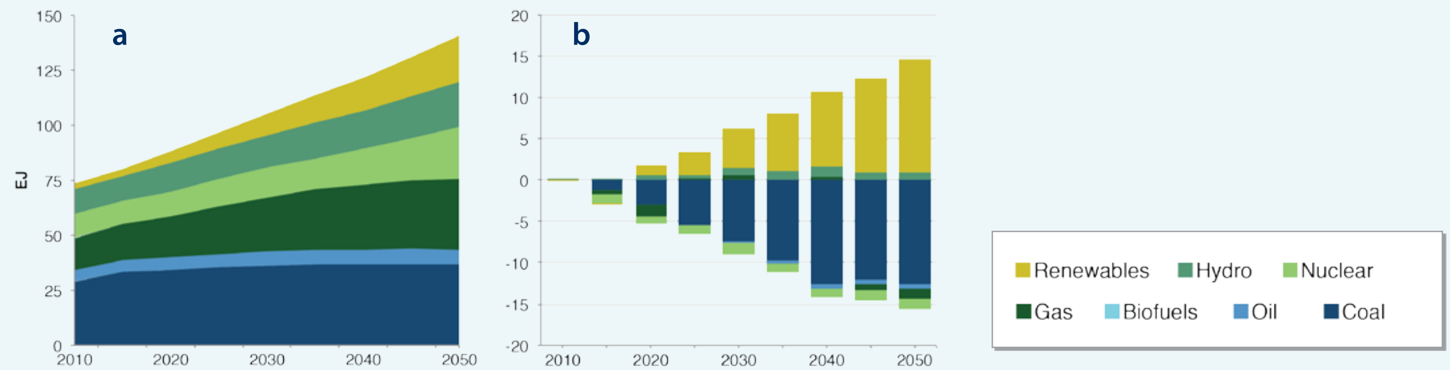


Figure 8. (a) World electricity production and (b) change from the 2014 Outlook (exajoules).

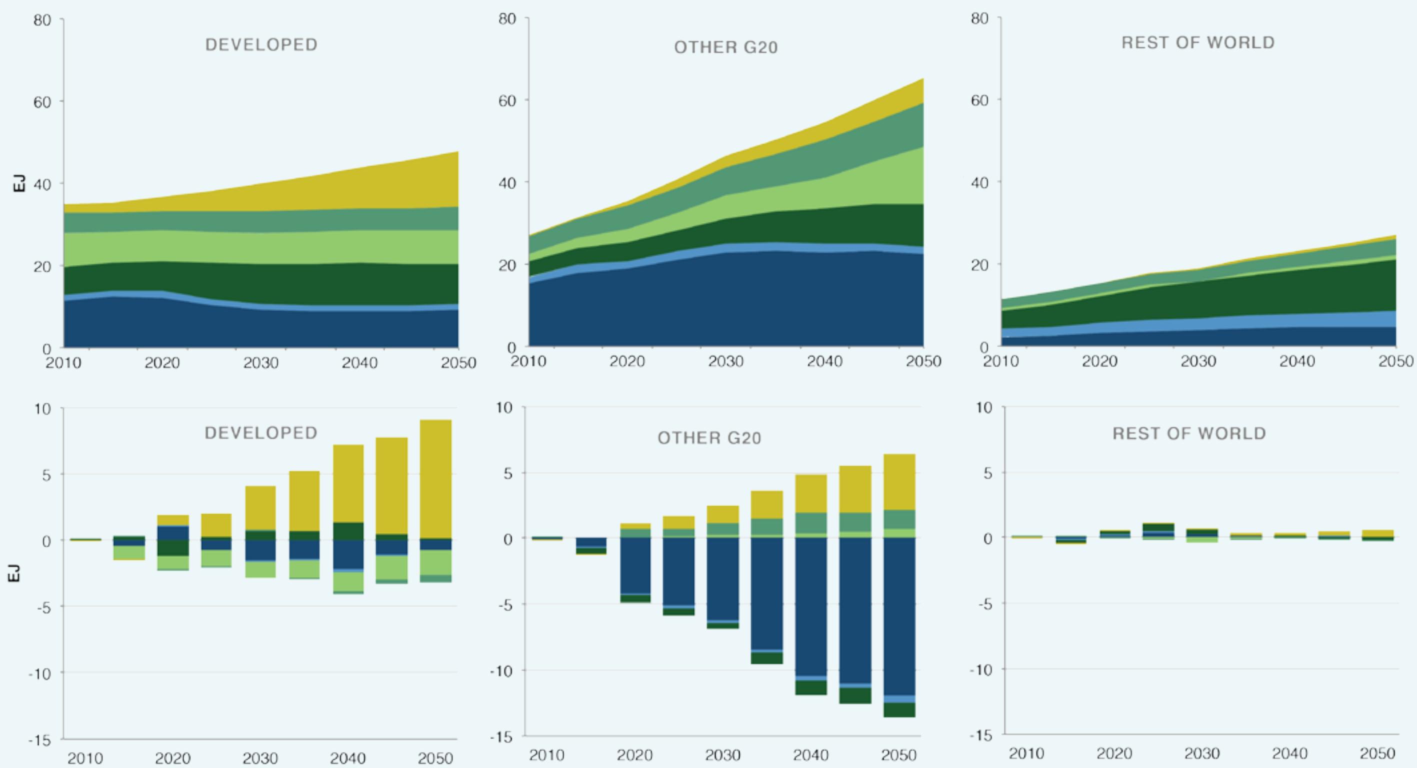


Figure 9. Electricity production (top row) and changes from the 2014 Outlook (bottom row) by major group (exajoules).

increase coming from renewables. We have seen in previous analyses that renewable requirements and similar sectoral policy such as vehicle fuel economy standards are not as effective at reducing emissions as, for example, a broad carbon pricing strategy. The share of coal falls from 56% to 34% by 2050 in the *Other G20*, far below the 47% we projected in the 2014 Outlook. Renewables expand the 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 7.5 and 2.6 times by 2050, to 21% and 17% of generation, respectively. These significant changes in fuel mix from the 2014 Outlook reflect the specific policies we believe are likely to be pursued in various of the *Developed* and *Other G20* economies to meet the emissions reductions proposed in INDCs submitted ahead of COP21. As in the 2014 Outlook, the share of natural gas used in electricity generation grows most rapidly in the *Rest of the World*, from 39% in 2010 to 46% by 2050.

Our 2015 projections continue to show rapid expansion of vehicle use especially in *Other G20* nations, with little change at the global level from our 2014 projections (**Figure 10**). For the *Other G20*, we project about 3.3 times more automobiles on the roadways in 2050 than in 2010. The increase is also substantial in the *Rest of the World*, rising over 2.7 times. Growth is particularly fast in the *Other G20* nations as increased income levels enable more widespread personal vehicle use. Meanwhile, vehicle use in *Developed* countries increases by only about 30% because population growth is slow or negative in some of the areas within this region and markets are near saturation. For the world as a whole, the vehicle stock almost doubles by 2050.

There is considerable variation in projected trends in vehicle ownership among the countries and sub-regions that make up the three large regions of our focus (**Figure 11**). Among the *Rest of the World*, vehicle growth is slow in Africa, where the rate of ownership is low, because incomes do not reach levels that support widespread vehicle ownership. It is higher in Other East Asia, where we project faster economic growth. The *Other G20* stands out, largely because the number of vehicles increases by nearly five times in China and somewhat more than five times in India. Other countries in this region show more modest increases in vehicle growth. There is also a mix among those countries that make up the *Developed* region. In the U.S., population grows by 30% and vehicle use by about 43%, and so the increase is largely due to the rise in population. In Europe (EU+), population is increasing by only 2% and vehicle use by

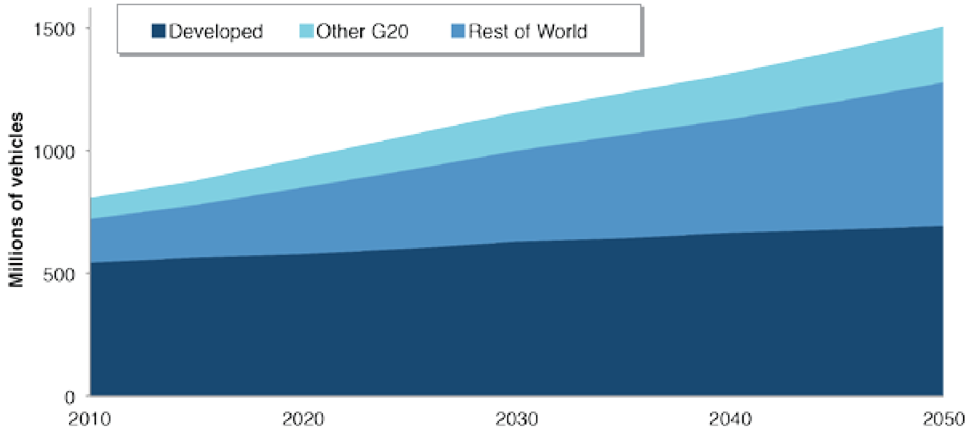


Figure 10. World private vehicle stock (millions of private cars and light trucks).

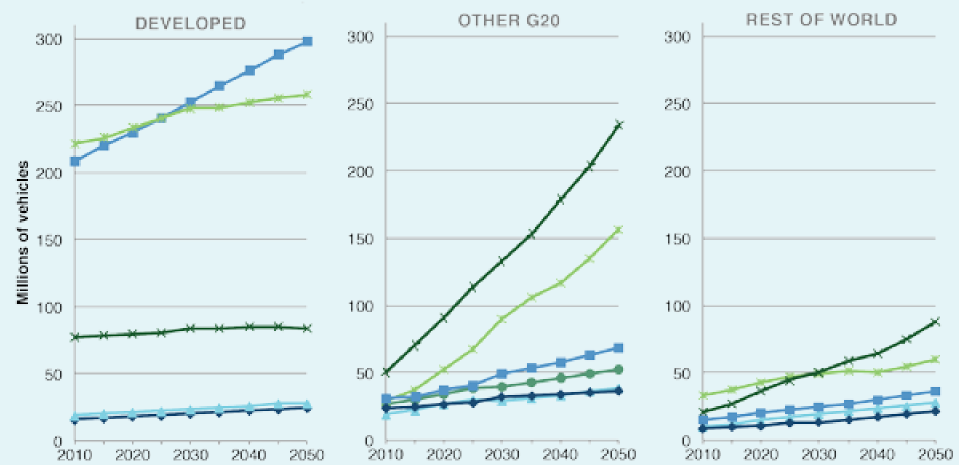


Figure 11. Regional private car and light truck stocks (millions of vehicles).

16%, reflecting the fact that Europe remains a diverse group of countries in terms of incomes and vehicle saturation.

For most regions there is little change in the number of vehicles on the road from the 2014 Outlook—a difference of +/- 1 million vehicles, with the exception of Europe, China, the U.S., and India. In China, we project 17 million fewer vehicles in 2050 than in our 2014 Outlook, a reduction of about 7%. In Europe, we project 11 million fewer vehicles, a reduction of about 4%, and in the U.S. a reduction of 4 million vehicles, or about 1.3%. India bucks this trend with 5 million more vehicles than projected in the 2014 Outlook, about 3.3% higher. The results for India primarily reflect slightly more rapid GDP growth. For Europe and the U.S., the tighter vehicle standards increase the cost of vehicles, and as a result, fewer are sold.

For China the story is more complex. While we have not applied any transport-specific policies in China, the strong constraint on coal use results in substitution toward other energy sources, including petroleum products. That increases the price of vehicle fuel, and is the apparent main source of reduced vehicle use. There is also a small income effect due to lower GDP as a result of the combination of all the new energy policies. But the GDP in China is only about 2% lower in 2050 compared to the 2014 Outlook, and so that alone is insufficient to result in a 7% reduction in vehicle use.

Currently, transportation worldwide contributes 6 Gt of CO_2 per year. Given these projections, emissions from transportation rise to 8.5 Gt of CO_2 by 2050. While this represents an increase of approximately 41% in transport emissions from 2010 to 2050, the emissions share from transport in 2010 and 2050 is about the same (around 20% of total CO_2 emissions). One possible lesson here is that even though electricity generation is a large share of emissions, and we often focus on vehicles (probably because vehicles are very visible and their numbers are growing rapidly), other energy uses and emissions are increasing as well. We project that the combined share of emissions from transportation and electricity generation is falling somewhat to 51% of total CO_2 emissions in 2050. While the temptation for policy is to focus on these visible sectors, that would miss substantial opportunities elsewhere and ultimately frustrate attempts to significantly reduce emissions in line with targets for the atmospheric stabilization of GHG concentrations.

As noted in the 2014 Outlook, we now have closer linkages among our economic projections of land use, terrestrial emissions of greenhouse gases, and impacts on climate. Modeling of land use in integrated assessment models has been a recent development. Projections aimed at getting best estimates of future land use often rely heavily on expert judgment instead of utilizing models that represent behavioral responses and detailed ecosystem processes. Such an approach can incorporate many different kinds of information and intelligence, but requires a broad range of expertise and evaluation. The value of endogenously representing different behavioral responses is that, once the model is developed, different "what if" scenarios can be easily explored. Otherwise, each new scenario requires a reassessment of expert judgment as to what the response would be to the new scenario—such as large-scale biomass development, a widely different economic growth path, or different climate scenario.

A recent model comparison (see Gurgel *et al.*, 2014) showed that many integrated assessment models projected substantial increases in cropland by 2050—by as much as several hundred million hectares. In contrast, the Food and Agriculture Organization (FAO) expects an increase of less than 100 million hectares over that period. That led us to investigate and ultimately revise parameters in the land-use component of our model (see Gurgel *et al.*, 2015). Now, in a business-as-usual projection, our cropland and overall land use is more in line with FAO projections, with considerably less cropland expansion and deforestation than in our 2014 Outlook.

Among the parameters important in determining future land requirements is productivity improvement, which in our modeling approach includes exogenous and price-driven improvements. Exogenous improvements are pure technology advances that allow more yield per hectare for a given level of other inputs, whereas price-driven improvements occur by substituting other inputs for land, which could involve, for example, more fertilizer, pest control, or irrigation. The improvement in productivity limits the need for increased cropland to feed a wealthier and larger population. But food demand itself responds, with a large literature of econometric estimates of food demand response to price and income.

With our revised formulation we project an increase of about 10% in cropland between 2010 and 2050, compared with a 50% increase in the 2014 Outlook, and a similar gradual trend through 2100 (**Figure 12**). Pastureland increases by 10% between 2010 and 2050. The cropland and pastureland increases are at the expense of all other land uses, which contract slightly by 2050. Natural forestland decreases by about 5%, and natural grassland by about 14% from their levels in 2010. The small exception is land devoted to biomass crops—it nearly doubles from 2010 levels by 2030 with increasing demand for biomass energy, but by 2050 declines back to levels projected in 2015 as productivity of biomass crops continues to rise. While the doubling between 2010 and 2030 would seem to be a concern, even at the 2030 level the amount of land devoted to biomass energy crops

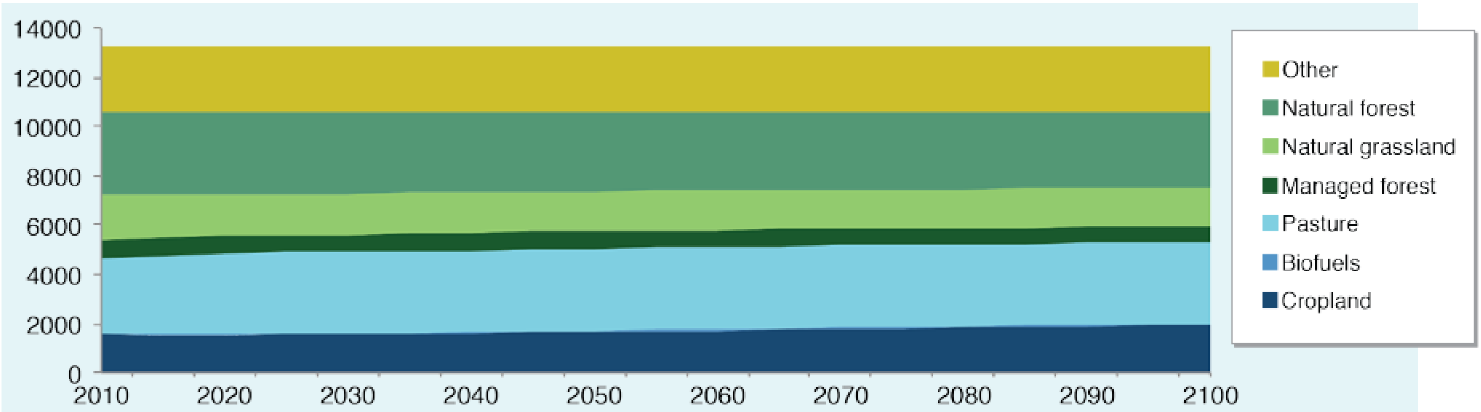


Figure 12. Global land use (megahectares).

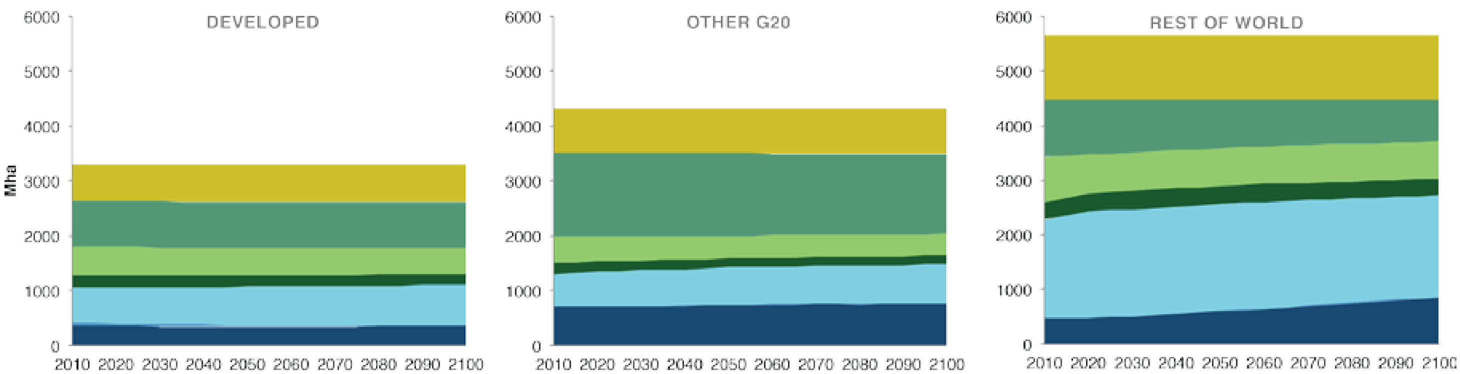


Figure 13. Land use by major group (megahectares).

is less than 4% of global cropland, a result underscored by the fact that in **Figure 12** the biofuel bar is barely visible.

Regionally, the patterns of change are similar to the 2014 Outlook, but with less overall change, the regional differences are less pronounced (**Figure 13**). Cropland expansion is largest in the *Rest of the World* region, increasing by about 125 million hectares by 2050. It increases by about 36 million hectares in the *Other G20* and declines by nearly 30 million hectares in the *Developed* region. The underlying reasons are related to income and population growth. The *Rest of the World* group includes some of the poorest countries, where a substantial share of increased income will continue to be devoted to food consumption, whereas even in the *Other G20*, the income driver of consumption begins to taper off by mid-century as smaller shares of additional income are devoted to food consumption.

Population growth is also expanding more rapidly in the *Rest of the World*, and these countries, in many cases, have substantial amounts of potential agricultural land, with 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 domestically produce a very large share of the food they consume. This preference for consumption of domestic products over imports is represented in the model structure. Hence, the regional expansion of population and income growth is a relatively good predictor of changes in cropland in the region.

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 78 Gt CO_2-equivalent. This includes CO_2 emissions from fossil fuel combustion, cement production, and land-use change; methane emissions from agriculture, waste, and fossil energy production; nitrous oxide from agricultural fertilizers; and fluorinated compounds (SF_6, HFCs, and PFCs). We sum emissions of different gases by converting to CO_2-eq using Global Warming Potential (GWP) indices (see **Box 5**). The projected 78 Gt is an increase of more than 60% from the level in 2010. By 2040, the total emissions are about 13 Gt less than our projection in the 2014 Outlook, a difference that remains nearly constant through the end of the century (**Figure 14**). Total fossil fuel CO_2 emissions reach 52 Gt by 2100, about a 70% increase 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 2/3). Of course that leaves almost 1/3 from other CO_2 sources and other gases. Compared to the 2014 Outlook, global CO_2 emissions in 2100 are about 15% lower. Emissions of CH_4, N_2O, PFC, HFC and SF_6 in 2100 are lower, by 15%, 6%, 9%, 2% and 6% respectively. The recalibrated land-use model results in significantly lower CO_2 emissions through about 2075. The other reductions are primarily due to policy changes.

To a large degree, changes in regional emissions (**Figure 15**) reflect the policy-induced changes in energy use and the fuel mix, and to a lesser extent the land-use change and agriculture projections. The projected emissions in *Developed* countries fall by about 25% by 2030 relative to 2010 with the incorporation of the INDCs of major emitting countries submitted ahead of COP21. The emissions remain roughly constant after that, reflecting our policy assumptions. In the *Other G20* nations, the Paris pledges result in slow growth in GHG emissions. However, unless emission reduction targets are extended and escalated, emissions are projected to increase substantially (by about 70% from 2010 to 2100) and the *Other G20* nations become the world's largest sources of emissions—contributing about 50% of global emissions by 2100 (up from 48% of the total in 2010). Meanwhile, 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.

Compared with the 2014 Outlook, all three broad regions have lower emissions. For the *Rest of the World* and India, this is largely driven by emissions from land-use change. India was a small net source of land-use emissions in early years in the 2014 Outlook and neutral or a small sink in later years. In the current Outlook, India is a significant land-use emissions sink over the entire period. While land-use emissions play some role in the deviation from the 2014 Outlook in the *Developed* region and China, most of the difference is due to the new post-2020 policies, and by far the largest change is lower emissions in China. By 2030, China's emissions are more than 4 Gt lower than we projected in the 2014 Outlook, and the difference increases to 8 Gt and more by 2050. In part, this reflects how we represented China's policies in the 2014 Outlook. At that time China had specified CO_2/GDP intensity improvements through 2030. With generally improving energy intensity in a base case without policy, and no further intensity goal, the intensity target became non-binding over time, and emissions were largely uncontrolled after 2050. Now, with more explicit policies with absolute goals, such as a peak in coal use and emissions, constraints remain binding indefinitely. While this large difference may, in part, be an artifact of our interpretation of China's policies, the fact that China has become much more specific in terms of the policies it is likely to pursue, with absolute rather than simple intensity targets, means that we can estimate their effect with greater certainty.

Given that substantial progress has been made in bending the curve of emissions growth, and even reversing it in the *Developed* region (if the proposed policies are implemented effectively), we may now have more hope that subsequent rounds of international negotiation after COP21 will lead to more policies with further reductions. Thus the extension of the forecast beyond 2025 or 2030 is not a prediction of what is most likely. Rather it is intended to indicate the need for continued effort, and a measure of the magnitude of effort needed. Assuming the *Developed* region, and China and *Other G20* countries will bring tighter targets in subsequent rounds of negotiations, we can imagine emissions from these groups of countries stabilizing and even beginning to decline by 2050. However, that leaves the *Rest of the World* countries with a growing and ever-larger share of emissions. While many of these countries are currently poor and the total emissions are relatively low, their emissions growth will have to be tackled eventually if stabilization goals are to be achieved.

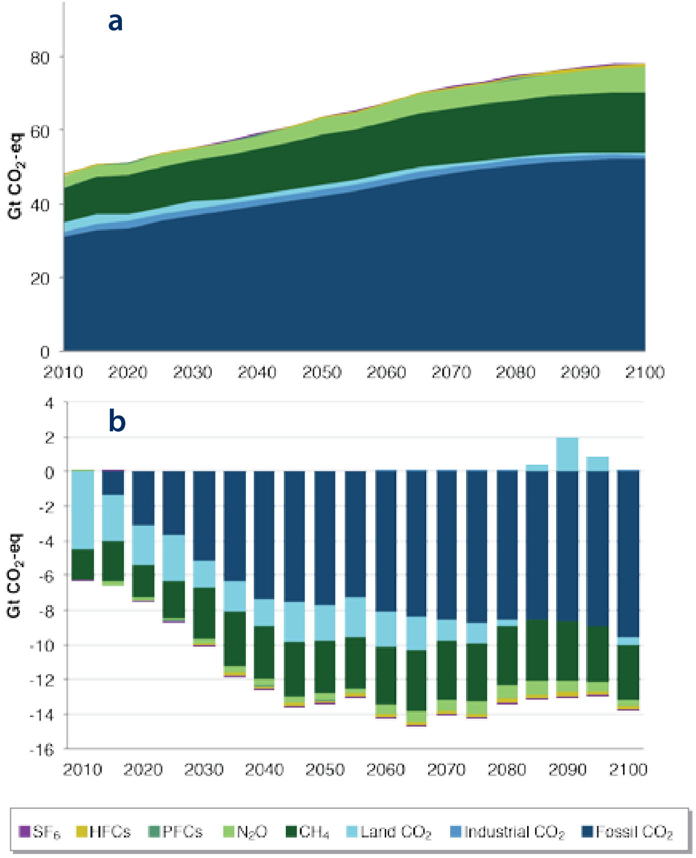


Figure 14. (a) Global greenhouse gas emissions and (b) change from the 2014 Outlook (gigatons CO_2-equivalent).

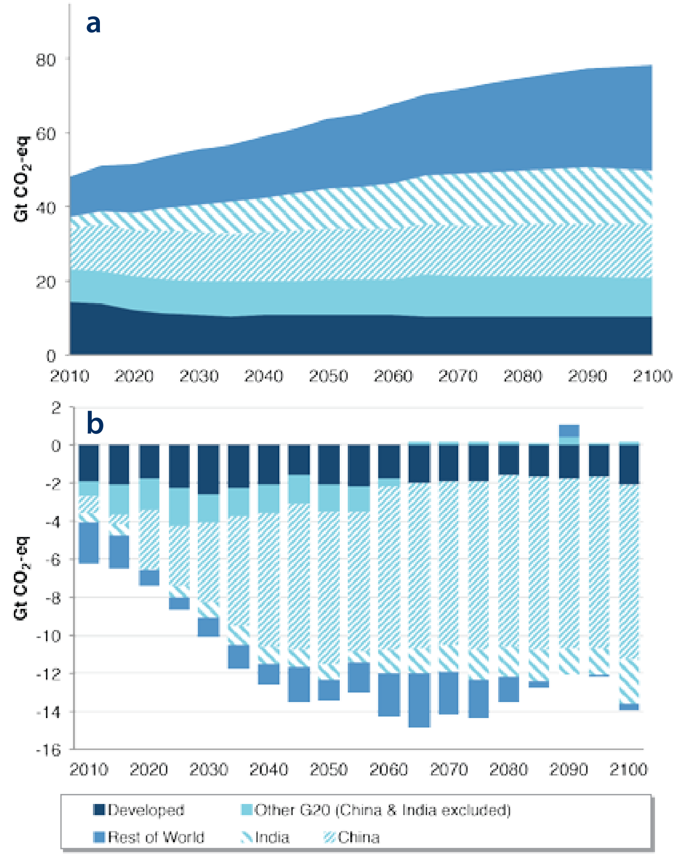


Figure 15. (a) GHG emissions by major group and (b) differences from the 2014 Outlook (gigatons CO_2-eq).

Box 5.

Comparing Greenhouse Gas Emissions and Concentrations

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 on the order of 200 years*, 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—policymakers 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 and include at times some of the indirect effects of the gas, 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 Fifth Assessment Report (AR5) estimates for 100-year GWPs, which are shown at right compared to the AR4 estimates.

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 IPPC 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.

In contrast, when summing concentrations of different gases in the atmosphere, the common approach is to combine their instantaneous radiative forcing and calculate the equivalent CO_2 concentration that would give the same total radiative forcing. This metric is intended to incorporate the relative importance of different gases in terms of the warming influence they contribute at any given time. We use this approach for summing concentrations of different gases as in **Figure 16**.

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

*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.

Greenhouse Gas Concentrations and Climate Implications

While there is good news of more progress in gradually slowing emissions growth, those numbers confront the reality of the cumulative nature of GHGs and the climate problem. Many analyses have focused on the target of 450 parts per million (ppm) as the limit for avoiding a temperature increase of more than 2°C above the pre-industrial average. Current GHG concentrations for Kyoto gases (**Figure 16**) are nearing 460 ppm CO_2-eq, and CO_2 concentrations are essentially at 400 ppm. We refer to Kyoto gases to denote those included in the emissions targets specified under the Kyoto Protocol. When all major GHGs, including chlorofluorocarbons (CFCs), are included, concentrations are currently nearing 490 ppm, as shown in **Figure 16** labeled CO_2-eq (IPCC). The use of 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 thousands of years due to their very long time lifetimes. In **Figure 16**, the seasonal cycle of CO_2 concentrations, due largely to the strong effect of northern hemisphere vegetation respiration, is smoothed to show the underlying trend (for details, see Huang *et al.* (2009), from which **Figure 16** is updated). The increase for all three time series has been nearly linear over the period, with CO_2 concentrations increasing by about 1.8 ppm/yr and all GHGs (CO_2-eq-IPCC) increasing at 3 ppm/yr. Note that here we use instantaneous radiative forcing to create CO_2-eq concentrations rather than GWPs because this calculation shows the contribution to warming at a point in time (see **Box 5**).

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 16**; and (2) 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, their concentrations would decrease almost immediately and their cooling effect would no longer mask a substantial amount of GHG-induced warming. Also, 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 while still seeing relatively small impacts on the global temperature.

The implication of our emissions projections are that CO_2 concentrations approach 710 ppm by 2100, which is 40 ppm less than our 2014 Outlook, but still with no sign of stabilizing (**Figure 17**). Also shown are CO_2 concentration pathways from the IPCC. These include the four Representative Concentration Pathways (RCP) scenarios (van Vuuren *et al.*, 2011) in dashed lines and the A1FI, A1B, A2 and B1 scenarios from the special report on emissions scenarios (SRES) (Nakicenovic *et al.*, 2000) in dotted lines. The smoothed Mauna Loa record through 2015 (as shown in **Figure 16**) is also plotted, although it is indistinguishable from the other scenarios, which lie atop it. The 2015 Outlook scenario lies between the SRES A1B and the RCP6.0 scenarios.

Carbon dioxide and long-lived greenhouse gases are not the only contributors to radiative forcing. Also important are ozone (O_3) and aerosols. Aerosols include black carbon (BC), which absorbs radiation and contributes to warming, as well as sulfate aerosols, which are reflective and hence have a cooling effect that partially offsets the warming influence of other aerosols and GHGs (**Figure 18**). Combining all of these, our 2015 Outlook scenario reaches nearly 7 W/m^2 by 2100 from 2.5 W/m^2 in 2010.

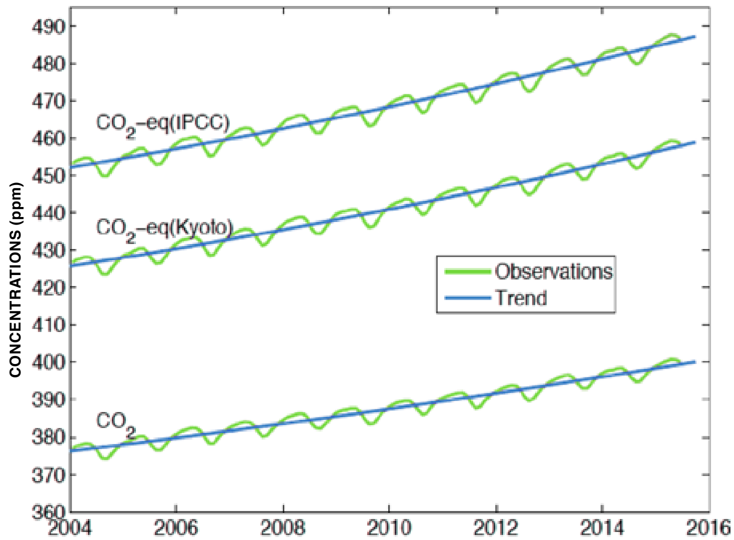


Figure 16. Current greenhouse gas (GHG) concentrations (ppm).

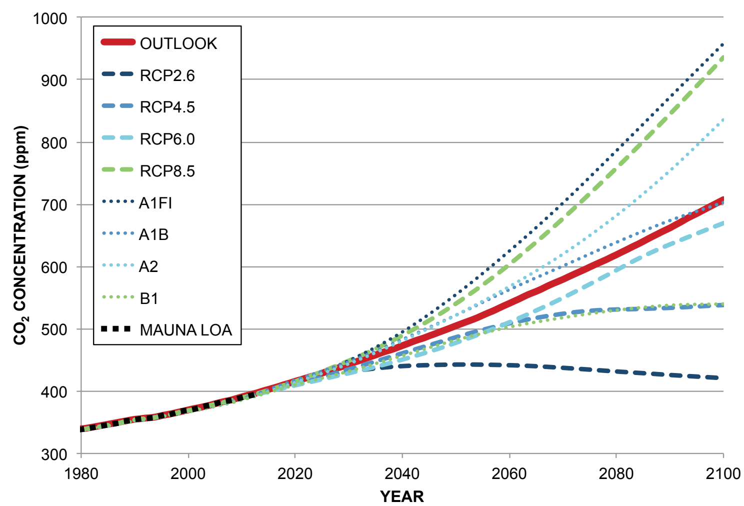


Figure 17. Projected CO_2 concentrations (ppm).

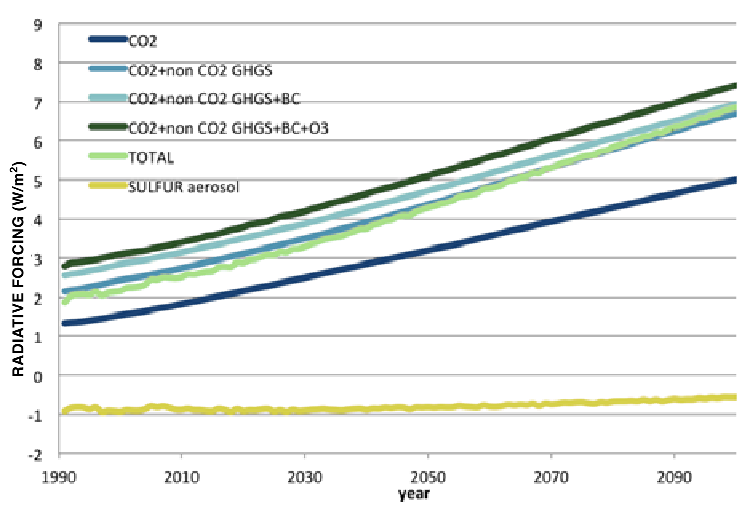


Figure 18. Projected greenhouse gas (GHG) radiative forcing (W/m^2).

The effect of sulfate aerosols, which today have a cooling effect of nearly 1 W/m^2, is to offset almost 30% of the warming from other substances, which is approximately the contribution of either the long-lived non-CO_2 gases or the combined effects of black carbon and ozone. In our projection, the aerosol cooling slowly falls to a little more than 0.5 W/m^2. This reflects reductions in coal use because of the climate policies we represent and a gradual lowering of the conventional pollutant emissions per unit of fuel burned, reflecting our assumption regarding efforts to control these conventional pollutants. That is also the reason that ozone and black carbon, together, contribute nearly a constant 1 W/m^2 over the whole period. With the sulfate aerosol concentration declining somewhat over time, the rate of increase in total radiative forcing is somewhat faster as the full warming effect of the other gases is slowly "unmasked".

There remains considerable uncertainty in the climate response to a given amount of radiative forcing. To incorporate the uncertainty in converting radiative forcing to a temperature increase, we developed three climate scenarios that account for the uncertainty in the Earth system's response to changes in aerosols and GHG concentrations. The climate response of the MIT IGSM-CAM to a given emissions level is essentially controlled by three climate parameters: the climate sensitivity, the ocean heat uptake rate, and the strength of aerosol forcing (Monier *et al.*, 2013). We use a single central value for the rate of ocean heat uptake (Forest *et al.*, 2008). We choose three values of climate sensitivity (CS) that correspond to the 5th percentile (CS=2.0°C), median (CS=2.5°C), and 95th percentile (CS=4.5°C) of the probability density function that were jointly estimated with the ocean heat uptake rate. The lower and upper bounds of climate sensitivity agree well with the conclusions of the IPCC's Fifth Assessment Report, which finds that the climate sensitivity is likely to lie in the 1.5–4.5°C range (IPCC, 2013). The value of the net aerosol forcing is then chosen with the objective of providing agreement with the observed 20th century climate change. The values for the net aerosol forcing are -0.25 W/m^2, -0.55W/m^2 and -0.85 W/m^2, corresponding to the CS=2.0°C, CS=2.5°C, CS=4.5°C values, respectively.

Using these three sets of climate parameters, the Earth's global mean temperature (**Figure 19**) is projected to increase by 1.9 to 2.6°C (central estimate 2.2°C) by mid-century relative to the pre-industrial level (1860–1880 mean), and 3.1 to 5.2°C (central estimate 3.7°C) 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.

The global precipitation anomaly increases from 0.05 mm/day in 2010 to a range of 0.2 to 0.32 mm/day in 2100. The precipitation changes represent increases of 3.9 to 5.3% by 2050 relative to the pre-industrial level, and 7.1 to 11.4% (central estimate 7.9%) 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

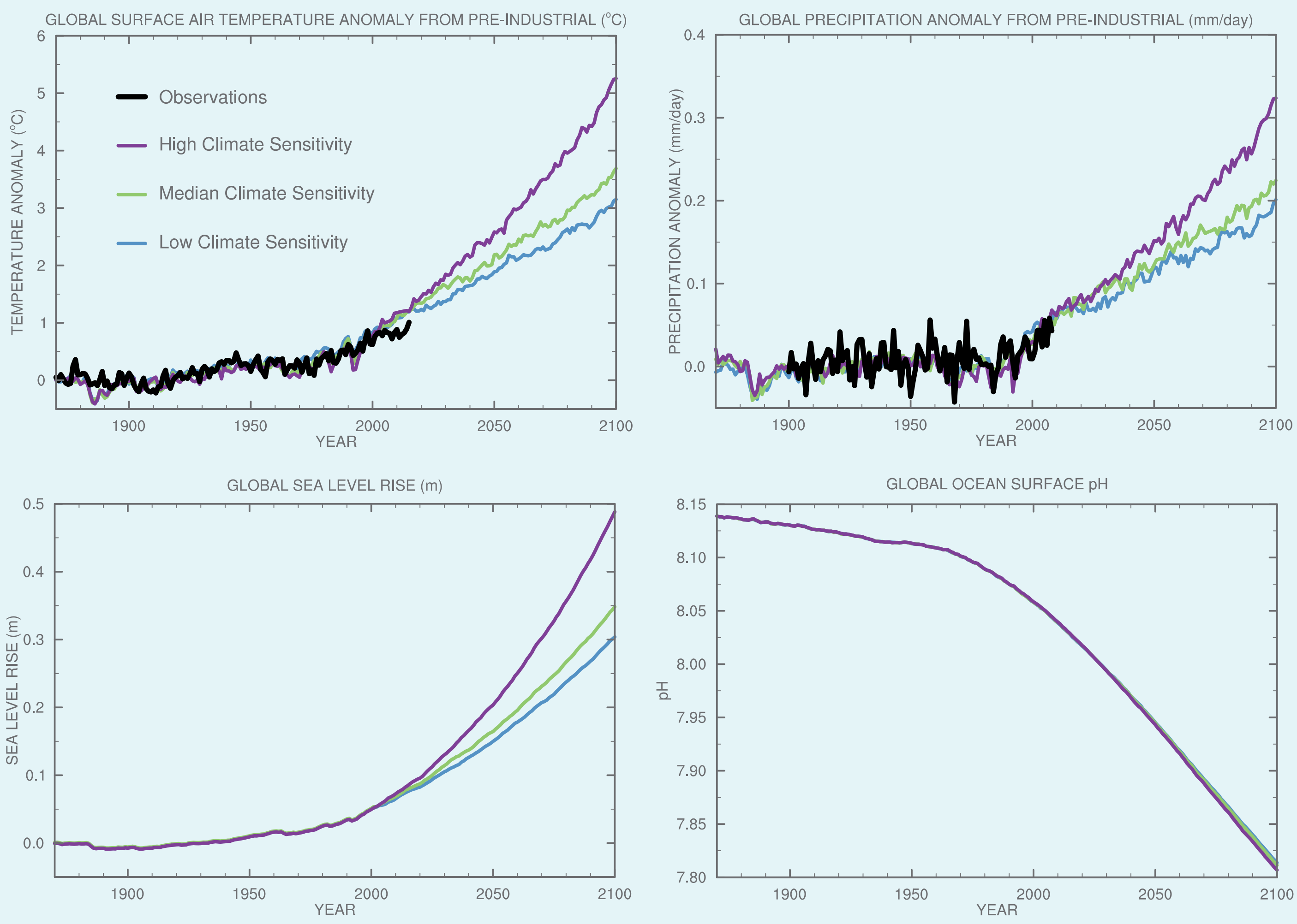


Figure 19. Global mean temperature and precipitation changes from the 1860–1880 mean and sea level rise and ocean surface acidity.

changing, the increase in precipitation does not necessarily mean that vegetation and water resources are less stressed everywhere.

Relative to pre-industrial levels, thermal expansion of seawater and melting of land glaciers contribute 0.15–0.23 meters to sea level rise by 2050, and 0.3–0.48 meters (central estimate 0.35 meters) by 2100. Melting of large ice sheets will contribute to sea level rise, but our modeling system does not have the capability to project those effects. Both thermal expansion and glacier melting, and even more so, ice sheet melting, have very strong inertia effects. The full impact of warming, at any given time, on sea level rise 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). Combining a halt to all emissions with more aggressive interventions, 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 planting or biomass energy with CCS—would require a massive change in energy infrastructure. 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 the 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 the simulations over historical period; and 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 the 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, the polar regions display the largest warming, as do the land areas. By 2100, in the high climate sensitivity scenario, some regions show warming as large as 12°C compared to pre-industrial levels (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.

The 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, Europe, North Africa and central Asia, where there is little change, or, in some cases, decreases. There is also little increase or even substantial decreases 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 a rise 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, whereas in other regions that are currently relatively dry, the same mm/day anomaly is a large proportional change. Areas that are receiving little increase, no increase, or a decrease may also suffer much greater drought conditions than the precipitation change alone would indicate. That is 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

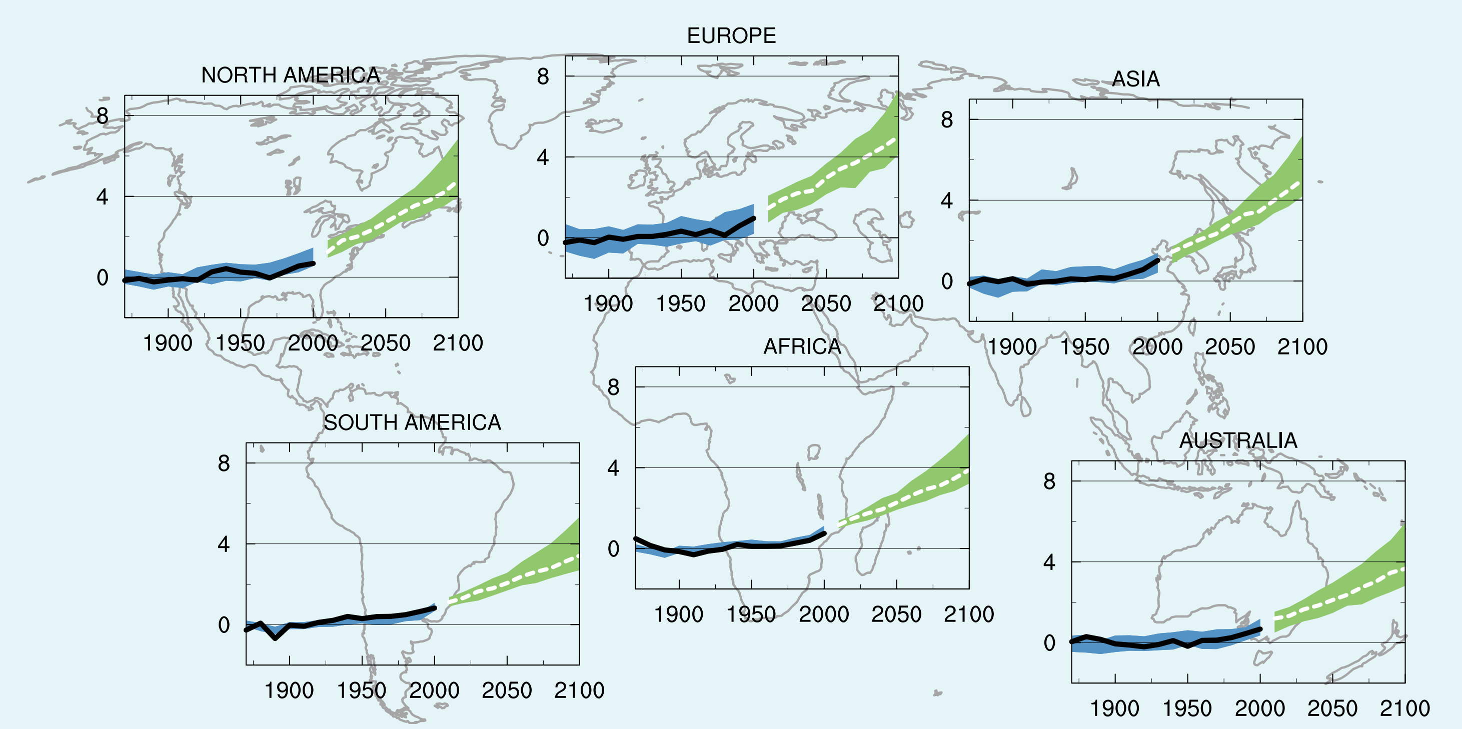


Figure 20. Regional temperature change (°C).

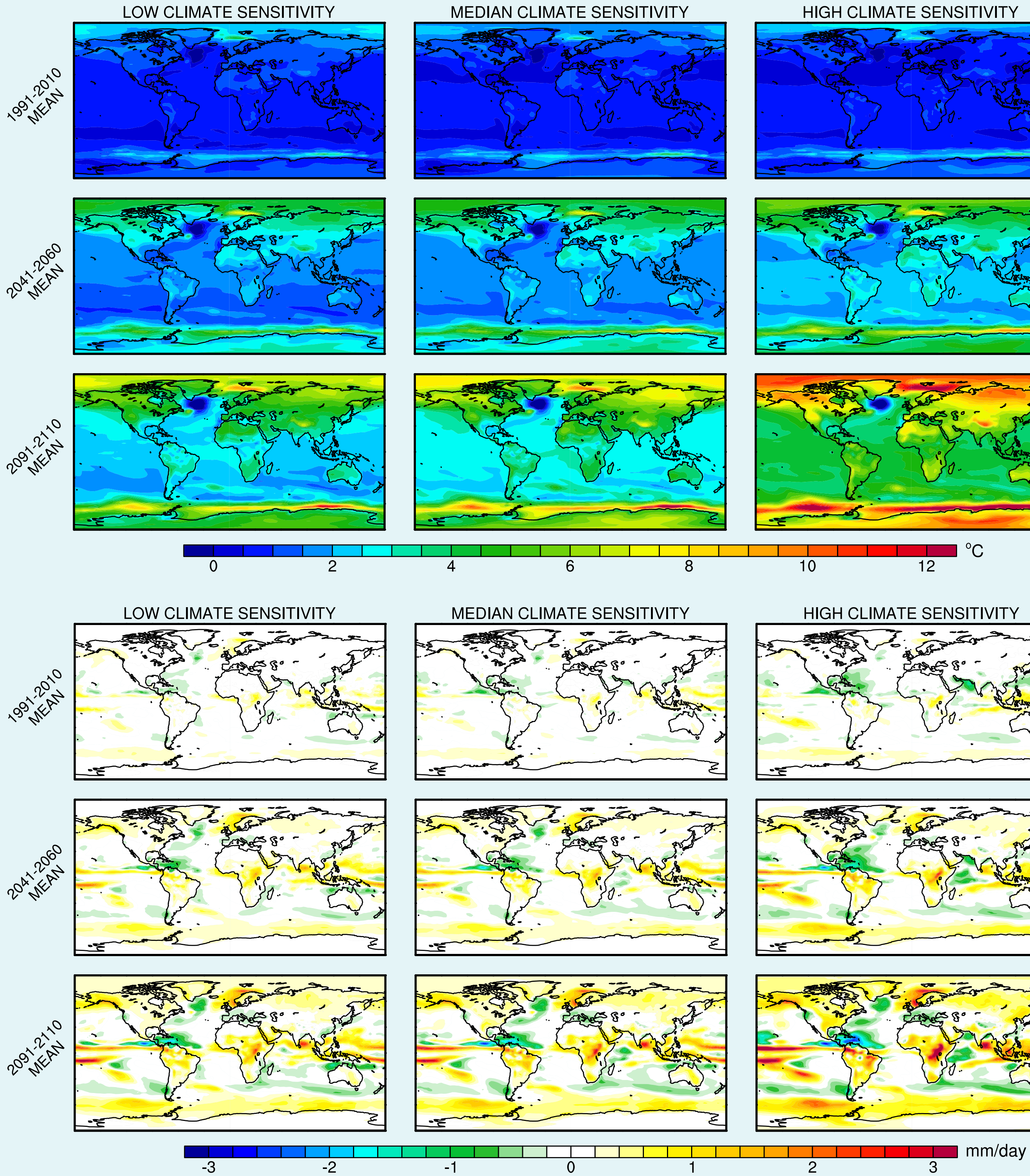


Figure 21. Mean surface temperature (top panels) and precipitation (bottom panels) anomalies for the periods 1991–2010, 2041–2060 and 2091–2110 from 1901–1950 means.

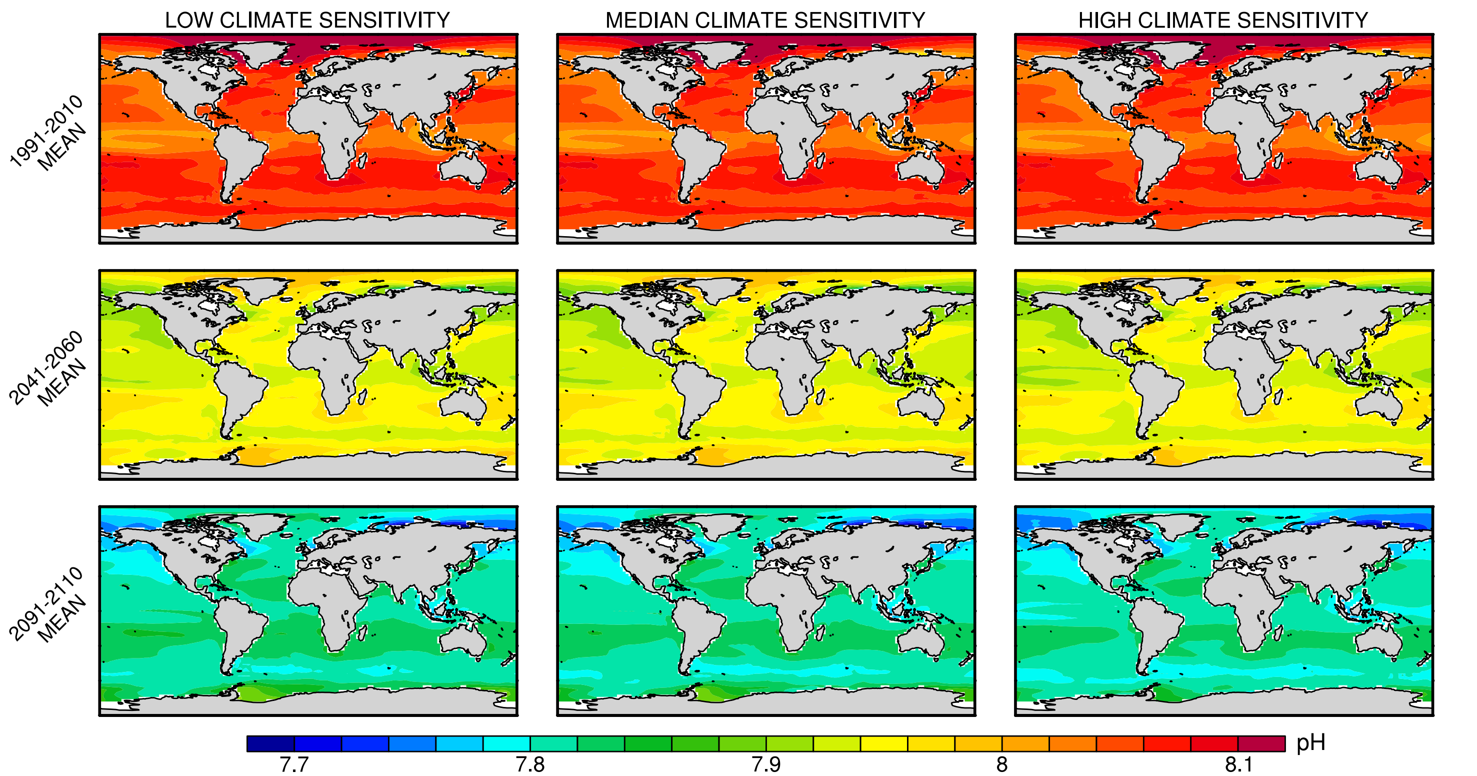


Figure 22. Ocean surface level pH for the periods 1991–2010, 2041–2060 and 2091–2110.

more acidic. The oceans serve as significant carbon 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 in the amount 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.

As highlighted in the summary of major findings and **Box 2**, the additional mitigation by major emitting countries (based on the INDCs proposed ahead of the COP21) have lowered our estimate of future warming by about 0.2°C. Recalibration of the climate model and our economic model over the past year have had offsetting effects, with the climate recalibration adding 0.2°C by 2100, and the recalibration of the economic model lowering the 2100 temperature by the same amount. By accurately separating recalibration and the impacts of policy, we can see the contribution of additional measures proposed in the INDCs, assuming those policies are implemented and maintained through the end of the century. It seems likely that countries that are proposing measures through 2025 or 2030 will not only maintain them beyond that time, but strengthen them further, and that countries currently doing little to control emissions will begin to do something. However, it will remain a great challenge to keep within the 2°C target the international community has set for itself. On the emissions path we project here, by 2030 we are within about 5 years of pushing past the cumulative emissions level the IPCC has estimated is consistent with a 50% chance of remaining below 2°C.

Many poorer countries have proposed to reduce emissions if there are financial incentives to do so. If these contributions can become a part of the COP21 agreement, that may offer more leeway to keep below the temperature target. A caution, however, is that in some cases the financing of these reductions is proposed as part of a Joint Crediting Mechanism, of which the Clean Development Mechanism (CDM) or international emissions trading would be examples. Such mechanisms could significantly lower the cost of achieving a reduction. However, if they are not associated with a further tightening of the targets of countries that are financing the reductions and crediting them toward their commitment, they will result in no further global emissions reduction. In that case, the reductions that the crediting country pledges will occur outside of that country, allowing the crediting country to have higher emissions. So these additional potential reductions depend both on the availability and nature of how they are financed.

The other uncertainty in the COP21 agreement is the period of time to which it would apply. Some countries proposed reductions through 2025, others through 2030. Unless the COP21 agreement is much stronger than we estimate from the initial INDCs, it seems preferable to choose 2025 as the endpoint. That will make clear the need to come back with deeper cuts sooner, rather than negotiate an agreement through 2030 that locks the world into a path that is ever less consistent with its stated goal.

Preparing for Tomorrow Today

This Outlook provides a view into the future as we project it in 2015. It is not a most-likely projection, especially beyond the 2025 to 2030 horizon, because we make no effort to estimate what additional actions countries will propose in future international negotiations. Given at least the stated intentions of most countries of the need to stabilize concentrations, it is clear that Paris is an important waypoint for negotiations, but is unlikely to be the endpoint.

References

Outlook References:

Clarke L., K. Jiang, K. Akimoto, M. Babiker, G. Blanford, K. Fisher-Vanden, J.-C. Hourcade, V. Krey, E. Kriegler, A. Löschel, D. McCollum, S. Paltsev, S. Rose, P. R. Shukla, M. Tavoni, B. C. C. van der Zwaan, and D.P. van Vuuren, 2014: Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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).

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

Gurgel, A., P. Havlik, E. Heyhoe, D. Mason d'Croz, A. Popp, R. Sands, A. Tabeau, D. van der Mensbrugghej, M. von Lampe, M. Wise, E. Blanc, T. Hasegawa, A. Kavallari, H. Valin, 2014: Land-use change trajectories up to 2050: insights from a global agro-economic model comparison. Agricultural Economics, 45(1): 85–101.

Gurgel, A., Y-H. Chen, S. Paltsev and J. Reilly, 2015. CGE models: linking natural resources to the CGE framework. Chapter 3 in T. Bryant and A. Dinar (eds.) Global Economic and Computable General Equilibrium Models Of Society, Environment and Resources, Volume 3 In The WSPC Set on Globalization, Society and Environment, in press.

HTAP, 2013, Hemispheric Transport Air Pollution version 2 dataset, Joint Research Centre, European Commission (http://edgar.jrc.ec.europa.eu/htap_v2/index.php?SECURE=123).

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 Program on the Science and Policy of Global Change *Report 174* (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt174.pdf).

IMF [International Monetary Fund Outlook], 2015: World Economic and Financial Surveys: World Economic Outlook Database, Washington, D.C., USA (http://www.imf.org/external/pubs/ft/weo/2015/01/weodata/download.aspx).

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.

Kirschke S., et al, 2013: Three decades of global methane sources and sinks, Nature Geoscience, 6: 813–823.

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

Paltsev, S., J. Reilly and A. Sokolov, 2013: What GHG Concentration Targets are Reachable in this Century? MIT Joint Program on the Science and Policy of Global Change *Report 247*, (http://globalchange.mit.edu/research/publications/2460).

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.

Publications describing the basic structure of the IGSM:

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, doi:10.1073/pnas.1107470109 (http://globalchange.mit.edu/files/document/MITJPSPGC_Reprint_12-12.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).

Applications of the IGSM are described in the Joint Program reports and peer-reviewed research available on our website: http://globalchange.mit.edu/research/publications

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 at http://globalchange.mit.edu/Outlook2015

MIT Joint Program Energy and Climate Outlook 2015

Projection Data Tables

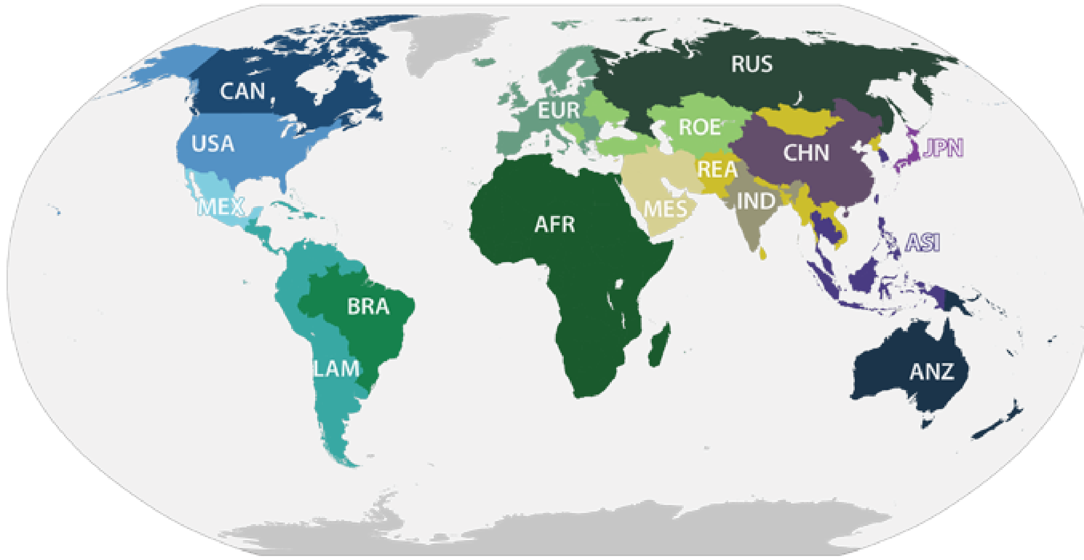
Region: World

	Units	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators										
GDP	(bil 2010 $)	52,840	59,080	67,955	78,051	89,861	102,035	115,431	130,662	148,148
Consumption	(bil 2010 $)	32,363	36,192	41,882	47,931	55,057	62,288	70,323	79,549	90,143
GDP growth	(% / yr)	1.9%	2.3%	2.8%	2.8%	2.9%	2.6%	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 $)	7,640	8,066	8,806	9,656	10,666	11,670	12,771	14,037	15,511
GHG Emissions										
CO_2 – fossil	(Mt CO_2)	30,944	33,071	33,416	35,354	36,868	38,311	39,417	40,614	42,090
CO_2 – industrial	(Mt CO_2)	1,564	1,894	2,050	2,032	1,739	1,542	1,628	1,687	1,720
CH_4	(Mt)	335.00	359.80	369.30	396.00	405.90	427.00	446.00	466.10	492.10
N_2O	(Mt)	11.62	11.67	12.02	12.53	12.75	13.61	14.46	15.36	16.40
PFCs	(kt CF_4)	14.62	7.93	5.57	5.64	5.38	5.76	5.97	6.06	6.35
SF_6	(kt)	6.38	5.11	5.21	5.72	6.43	6.59	7.29	7.83	8.36
HFCs	(kt HFC-134a)	349	224	187	167	166	188	219	248	281
Total GHG net of Land Use	(Mt CO_2e)	45,668	48,598	49,394	52,184	53,752	55,856	57,861	59,969	62,541
CO_2 – land use change	*(Mt CO_2)*	*2,560*	*2,580*	*1,972*	*1,841*	*2,125*	*1,317*	*1,369*	*1,286*	*1,218*
Primary Energy Use	**(EJ)**									
Coal		140.5	153.6	148.5	152.9	156.5	156.7	155.2	157.8	159.5
Oil		175.9	182.6	189.3	200.0	208.4	218.2	227.9	237.0	249.2
Biofuels		2.3	2.9	3.9	4.5	5.9	6.8	7.1	8.0	8.3
Gas		109.0	118.0	124.4	139.7	152.2	165.5	176.3	182.7	191.4
Nuclear		27.6	27.3	30.7	34.6	40.0	41.3	48.7	58.8	73.2
Hydro		31.3	32.9	37.6	39.6	43.3	48.8	52.5	57.7	63.6
Renewables		7.5	8.7	14.1	20.3	27.2	34.3	41.4	48.8	56.7
Electricity Production	**(TWh)**									
Coal		8,090	9,289	9,522	9,788	10,001	10,129	10,038	10,168	10,034
Oil		1,391	1,577	1,690	1,780	1,829	1,853	1,886	1,936	1,974
Gas		4,120	4,528	5,089	6,086	6,799	7,634	8,380	8,717	9,058
Nuclear		3,018	2,873	3,151	3,452	3,859	4,002	4,573	5,354	6,450
Hydro		3,104	3,235	3,594	3,765	4,111	4,545	4,844	5,283	5,778
Renewables		815	926	1,462	2,096	2,807	3,512	4,226	4,975	5,784
Household Transportation										
Number of vehicles	(millions)	808	884	978	1,069	1,163	1,239	1,316	1,410	1,514
Vehicle miles traveled	(trillions)	6.67	7.48	8.50	9.50	10.59	11.50	12.41	13.48	14.70
Miles per gallon	(mpg)	22.80	24.50	25.20	26.40	27.20	27.70	28.00	28.10	28.10
Vehicles per person		*0.12*	*0.12*	*0.13*	*0.13*	*0.14*	*0.14*	*0.15*	*0.15*	*0.16*
Land Use	**(Mha)**									
Cropland		1,552.2	1,543.8	1,538.6	1,559.7	1,576.1	1,613.1	1,628.5	1,651.9	1,676.4
Biofuels		38.6	45.8	53.3	53.8	54.8	48.8	45.3	44.0	41.2
Pasture		3,035.4	3,146.7	3,247.7	3,269.9	3,270.8	3,279.3	3,294.4	3,306.0	3,326.6
Managed forest		727.7	724.8	720.8	721.4	713.8	706.3	703.4	698.6	691.6
Natural grassland		1,870.5	1,779.6	1,692.6	1,662.4	1,659.4	1,642.3	1,633.5	1,621.3	1,601.2
Natural forest		3,380.7	3,363.2	3,339.6	3,313.4	3,290.0	3,264.7	3,240.5	3,215.5	3,193.0
Other		2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6	2,659.6
Air Pollutant Emissions	**(Tg)**									
SO_2		103.03	103.85	101.25	100.97	99.28	95.92	91.82	88.93	86.15
NO_x		119.82	132.18	143.64	158.89	174.19	187.37	199.20	213.07	228.24
Ammonia		48.30	54.46	61.59	67.02	70.38	75.89	80.86	86.00	91.15
Volatile organic compounds		110.17	119.40	132.20	147.79	162.86	175.98	187.47	198.65	212.11
Black carbon		5.52	5.45	5.59	5.77	5.87	5.90	5.69	5.51	5.35
Organic particulates		12.56	12.60	13.55	14.15	14.65	14.96	14.43	14.02	13.65
Carbon monoxide		549.39	613.33	700.31	806.51	913.59	1,016.57	1,114.38	1,215.07	1,324.01

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/Outlook2015



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
Azerbaijan	ROE
Bahamas	LAM
Bahrain	MES
Bangladesh	REA
Barbados	LAM
Belarus	ROE
Belgium	EUR
Belize	LAM
Benin	AFR
Bermuda	LAM
Bhutan	REA
Bolivia	LAM
Bosnia and Herzegovina	ROE
Botswana	AFR
Brazil	BRA
Brunei	REA
Bulgaria	EUR
Burkina Faso	AFR
Burundi	AFR
Cambodia	REA
Cameroon	AFR
Canada	CAN
Cape Verde	AFR
Cayman Islands	LAM
Central African Republic	AFR
Chad	AFR
Chile	LAM
China	CHN
Côte d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo	AFR

Country	Region
Congo, Dem. Rep. (Zaire)	AFR
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
India	IND
Indonesia	ASI
Iran	MES
Iraq	MES
Ireland	EUR
Israel	MES
Italy	EUR
Jamaica	LAM
Japan	JPN
Jordan	MES
Kazakhstan	ROE
Kenya	AFR
Kiribati	ANZ
Korea	ASI
Korea, Dem. Ppl. Rep.	REA
Kuwait	MES
Kyrgyzstan	ROE
Laos	REA
Latvia	EUR
Lebanon	MES
Lesotho	AFR
Liberia	AFR
Liechtenstein	EUR
Lithuania	EUR
Luxembourg	EUR
Libya	AFR
Macau	REA
Macedonia	ROE
Madagascar	AFR
Malawi	AFR
Malaysia	ASI
Maldives	REA
Mali	AFR
Malta	EUR
Marshall Islands	ANZ
Martinique	LAM
Mauritania	AFR
Mauritius	AFR
Mayotte	AFR
Mexico	MEX
Micronesia	ANZ
Moldova	ROE
Monaco	ROE
Mongolia	REA
Montserrat	LAM

Country	Region
Morocco	AFR
Mozambique	AFR
Myanmar	REA
Namibia	AFR
Nauru	ANZ
Nepal	REA
Netherlands	EUR
Netherlands Antilles	LAM
New Caledonia	ANZ
New Zealand	ANZ
Nicaragua	LAM
Niger	AFR
Nigeria	AFR
Niue	ANZ
Norfolk Islands	ANZ
Northern Mariana Islands	ANZ
Norway	EUR
Oman	MES
Pakistan	REA
Palestine	MES
Panama	LAM
Papua New Guinea	ANZ
Paraguay	LAM
Peru	LAM
Philippines	ASI
Poland	EUR
Portugal	EUR
Puerto Rico	LAM
Qatar	MES
Réunion	AFR
Romania	EUR
Russian Federation	RUS
Rwanda	AFR
Saint Helena	AFR
Saint Kitts and Nevis	LAM
Saint Lucia	LAM
Saint Pierre and Miquelon	LAM
Saint Vincent & Grenadines	LAM
Samoa	ANZ
San Marino	ROE
São Tomé and Príncipe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychelles	AFR

Country	Region
Sierra Leone	AFR
Singapore	ASI
Slovakia	EUR
Slovenia	EUR
Solomon Islands	ANZ
Somalia	AFR
South African Republic	AFR
Spain	EUR
Sri Lanka	REA
Sudan	AFR
Suriname	LAM
Swaziland	AFR
Sweden	EUR
Switzerland	EUR
Syria	MES
Taiwan	ASI
Tajikistan	ROE
Tanzania	AFR
Thailand	ASI
Timor-Leste	REA
Togo	AFR
Tokelau	ANZ
Tonga	ANZ
Trinidad and Tobago	LAM
Tunisia	AFR
Turkey	ROE
Turkmenistan	ROE
Turks and Caicos Islands	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
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