MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT JOINT PROGRAM ON THE SCIENCE AND POLICY of GLOBAL CHANGE

2013 Energy and Climate 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.

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

For more information, please contact:

The Joint Program on the Science and Policy of Global Change
Massachusetts Institute of Technology
77 Massachusetts Avenue
Building E19, Room 411
Cambridge MA 02139-4307 (USA)

Phone: (617) 253-7492
Fax: (617) 253-9845
E-mail: globalchange@mit.edu
Website: http://globalchange.mit.edu/

Confronting Energy and Climate Challenges

Climate change is one of the forces of global change that will shape how the world feeds, shelters, transports, and otherwise attends to a population projected to exceed 10 billion people by 2100. The 2013 Energy and Climate Outlook provides an integrated assessment of how human activities, given our current development path, are interacting with complex Earth systems and ultimately affecting the natural resources on which we depend. It uses a projection modeling system developed by MIT's Joint Program on the Science and Policy of Global Change, the Integrated Global Systems Model (IGSM) framework, to determine the associated energy, climate, atmosphere, ocean, and land-use implications. As in the 2012 edition of the Outlook[1], we provide a projection, not a prediction, as the future will be determined by actions taken over the next decades that are intended to stabilize our relationship with the planet.

In the 2013 Outlook we expand the presentation of our climate projections by providing regional results for temperature, precipitation and ocean acidity. This Outlook updates energy, policy, and other estimates based on developments over the past year. It includes new data on regional economic growth, population, natural gas usage, renewables, and policies (see **Box 1** for a discussion of major updates relative to the 2012 Outlook). These changes result in cumulative total CO_2 emissions that are 12% lower by the end of the century compared to the 2012 Outlook. The median forecast for temperature change is 3.8 °C by 2100, which is lower by 0.5 °C compared to the 2012 Outlook.

As in the 2012 Outlook, we incorporate the emissions targets currently proposed by the international community to address the challenges of climate change. The United Nations Framework Convention on Climate Change (UNFCCC) reached an accord in 2009 for the so-called Copenhagen pledges (UN, 2009), which were further specified in the Cancun agreements (UN, 2010). These agreements mainly provide targets for 2020. The Outlook assumes that there will be no additional policy changes after the nations achieve their targets in 2020, with the exception of the EU where targets proposed in the EU Emissions Trading Scheme (EU, 2013) continue beyond 2020 (the cap on emissions from power stations and other fixed installation is reduced by 1.74% every year).

By some estimates, achieving these 2020 targets may be difficult for many countries. However, most countries recognize that the 2020 targets are only a first step toward stabilizing greenhouse gas (GHG) concentrations in the atmosphere and limiting global warming to levels that will avoid dangerous consequences. In fact, the agreements express a longer-term objective of keeping the average global temperature rise below 2 °C relative to the preindustrial level.

Currently, the international community is preparing new targets based on the Durban Platform that would expand efforts to reduce greenhouse gas emissions in the post-2020 period. The Durban platform calls for agreement on these measures to be developed by 2015. At this point, the nature of those measures or the time period over which they would apply has not yet been determined. Hence we do not speculate on additional reductions after 2020.

Box 1. Major Updates in the 2013 Outlook

Updates to Model Inputs:

- **Population Data:** New UN population data (the 2012 Revision replaces the 2010 Revision) is incorporated into the model. Compared to the previous projections, the global population is higher by nearly 370 million in 2050 and by 700 million in 2100. The largest increases are in China, India, and Southeast Asia.
- **Economic Growth:** Regional economic growth assumptions reflect the latest International Monetary Fund Outlook (IMF, 2013) through 2015 and our own long-term projections. Compared to the 2012 Outlook, the most substantial changes are in China, Europe, and Russia where GDP growth is slightly lower (reductions in annual GDP growth are around 0.1–0.2%).
- **Natural Gas Availability:** Increased estimates of shale gas resources and domestic policies in China to promote natural gas are represented. Global natural gas consumption is 8% higher in 2050 than in the 2012 Outlook. Natural gas usage in China more than triples in 2050 compared to the 2012 Outlook.
- **Renewable Electricity:** Policies supporting renewables in the USA and EU are updated. By 2050 renewable electricity in the USA and EU increases by 35% and 11%, respectively, compared to the 2012 Outlook. Global electricity from renewables in 2050 is about 13% higher than in the 2012 Outlook.
- **Emission Policies in China and EU:** China's policy is now only applied to CO_2 emissions. In the EU, the emissions trading scheme (ETS) is extended beyond 2020, reducing the cap on power stations and other fixed installations by 1.74% every year.

Additional Outlook Reporting:

- Electricity mix
- Results for temperature, precipitation and ocean pH changes at a spatial level
- Radiative forcing
- Temperature change is reported relative to the 1901–1950 mean instead of relative to the year 2000

---

[1] Available at: http://globalchange.mit.edu/research/publications/other/outlook

Our objective is to show how far the current 2020 pledges take us, and what is at risk if we fail to push beyond these emissions reduction goals.

A principal product of this Outlook is a set of detailed tables containing economic, energy, land use, and emissions results for each of the 16 major countries or regions of the world (**http://globalchange.mit.edu/Outlook2013**). In this summary, we report results for three broad 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—see **Box 2**); and the rest of the world. We base our results on the UN's recent "2012 Revision" of population projections (UN, 2013) showing that the global population will reach 10.8 billion people by the end of the century. Though we provide our detailed regional projections up to 2050, we also show global results through 2100, which are needed to project the long-term climate implications.

Broad conclusions have not substantially changed from the 2012 Outlook. The major findings are as follows:

- The Copenhagen–Cancun pledges will nearly stabilize emissions in developed countries, but global emissions will continue to grow rapidly (total global GHG emissions in 2100 will be almost 95% higher than 2010 emissions).
- Most emissions growth will occur outside the developed countries, with growth concentrated in other G20 nations and the rest of the world (total GHG emissions from those regions combined grow by almost 150% from 2010 to 2100).
- While further cuts in developed countries would be useful, such cuts will have less impact on global emissions over time because, given Copenhagen–Cancun pledges, by 2100 emissions from developed countries are only about 13% of global GHG emissions.
- While emissions from fossil fuels are sizeable, other greenhouse gas emissions are also important (accounting for about $^{1}/_{3}$ of total global GHG emissions by 2100) and cannot be ignored if more stringent stabilization and temperature goals are to be achieved. Reductions in these emissions are often the most cost effective. If policies to reduce them fail, a major opportunity to limit climate change may be missed.
- The transition to alternative energy has begun in developed countries and China, but the Copenhagen–Cancun pledges do not provide enough incentive to create the transformation needed in the energy system—such as wide-scale adoption of renewables, carbon capture and storage, or alternative propulsion systems in vehicles. In particular, by 2050 renewables compose only 5% of the global electricity mix.
- Population growth will drive increased electricity production as well as growing emissions. Global electricity production increases by about 85% from 2010 to 2050 and CO_2 emissions from electricity grow by 46%. Electricity's share of total global CO_2 emissions slightly decreases from about 36% in 2010 to 33% in 2050.
- Population and income growth will fuel a significant increase in the vehicle fleet and cause CO_2 and other pollutant emissions to increase, especially in developing regions (the global vehicle fleet doubles by 2050, and among other G20 countries the fleet grows by about 3.6 times. Emissions from transport grow by about 60% from 2010 to 2050, and remain about 20% of total global CO_2 emissions).
- Global change will accelerate with changes in global and regional temperatures, precipitation, land use, sea level rise, and ocean acidification (temperature is projected to increase by 3.5–6.5 °C by 2100 relative to the 1901–1950 mean, the global precipitation anomaly increases from 0.02 mm/day in 2010 to a range of 0.25–0.42 mm/day in 2100, global sea level rise due to thermal expansion increases from 0.1 m in 2010 to a range of 0.4–0.62 m in 2100[2], and ocean acidity changes from pH 8.05 in 2010 to about pH 7.85 in 2100).

As difficult as the progress made in Copenhagen and Cancun was to achieve, far more effort is needed to limit greenhouse gas concentrations to levels that avoid dangerous climatic consequences. While the amount of temperature increase and associated greenhouse gas concentrations that are generally considered to be "dangerous" remain open to much debate and uncertainty, the risk of warming projected here is well above those generally considered dangerous.

The Changing World

Over the next century, a growing population will spur changes throughout the world. According to the latest UN estimates (UN, 2013), the world's population is projected to surge past 9.6 billion by 2050 and reach 10.8 billion by the end of the century if trends in fertility

---

[2] Thermal expansion includes only sea level rise due to warming of the oceans. Melting of land glaciers and large ice sheets will contribute significantly to sea–level rise but we do not have the capability in our modeling system to project these effects.

rates continue to decline at expected levels. The UN projections show that much of the growth will happen in developing regions like the Middle East, Africa, and Latin America **(Figure 1)**.

We project that labor, land, and energy productivity across the world will continue to grow and will be a source of continued growth in gross domestic product (GDP), even taking into consideration the impact of resource depletion and higher energy costs on the global economy **(Figure 2)**. Global GDP is projected to grow 7.5 times between 2010 and 2100, corresponding to an average annual growth rate of 2.3%. While per capita income will grow in all regions, this income growth is projected to be more rapid in developing regions.

As global population increases, energy needs will likewise increase. Additionally, with higher incomes, more people will be able to afford necessities and conveniences that will require energy. In our projections, global energy use almost doubles by 2050 **(Figure 3)**. This growth 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, in part because of the assumption that these countries will meet their Copenhagen–Cancun pledges. The most substantial growth in energy use is projected to occur in the other G20 nations **(Figure 4)**. These countries currently use slightly less energy than the developed world, but by 2050 they are projected to use more energy than the entire world uses today—close to 500 exajoules (EJ). Growth in the rest of the world is also projected to be substantial, with their energy use in 2050 approaching what is used today in the developed world. While total energy use by 2050 is almost the same as in the 2012 Outlook, there is a shift in the type of energy used: there is slightly less coal (3% less in 2050 relative to the 2012 Outlook), oil (3% less), and biofuels (2% less), but more

Box 2: The Regional Classification Used in this Outlook

The IGSM modeling system used to generate the projections in this Outlook divides the global economy into 16 regions (see a map in the Appendix). 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, the 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.

Note that a full list of the countries included in each IGSM region is provided in the Appendix and supplementary projection tables are available online at: ***http://globalchange.mit.edu/Outlook2013****. For the reporting in this Outlook the regions are further aggregated into 3 broad groups: Developed, Other G20, and Rest of the World.*

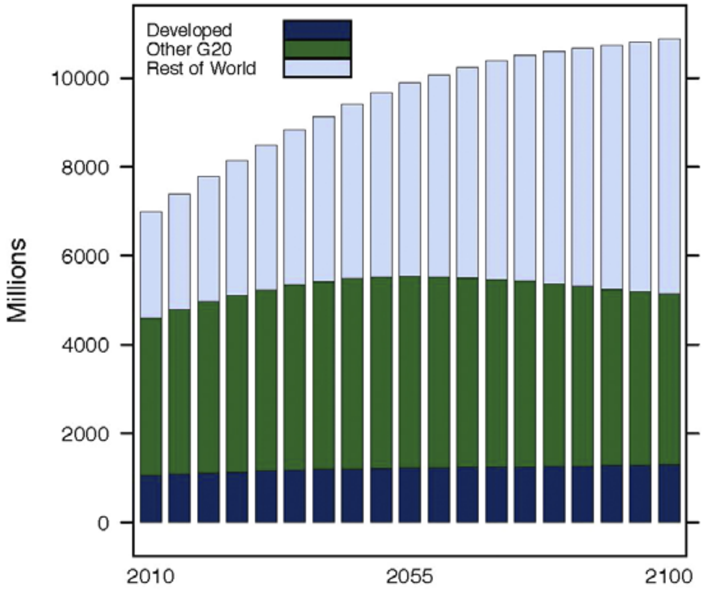


Figure 1. World Population.

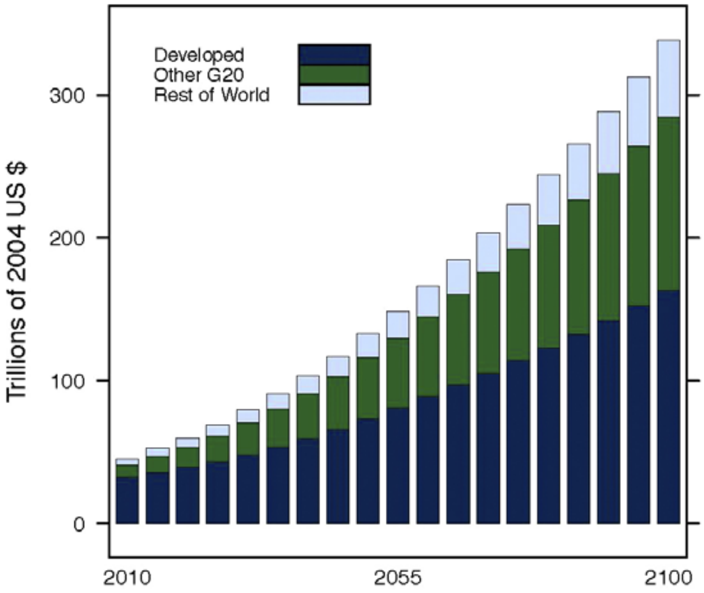


Figure 2. World GDP.

renewables (13% more), natural gas (8% more) and hydro (2% more). Of particular note is that by 2050 natural gas usage in China has more than tripled compared to the 2012 Outlook.

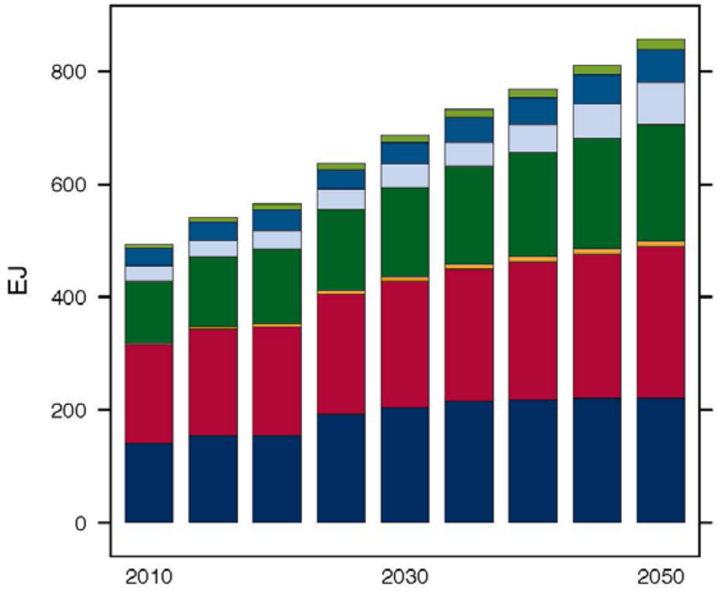


Figure 3. Global Energy Use (exajoules).

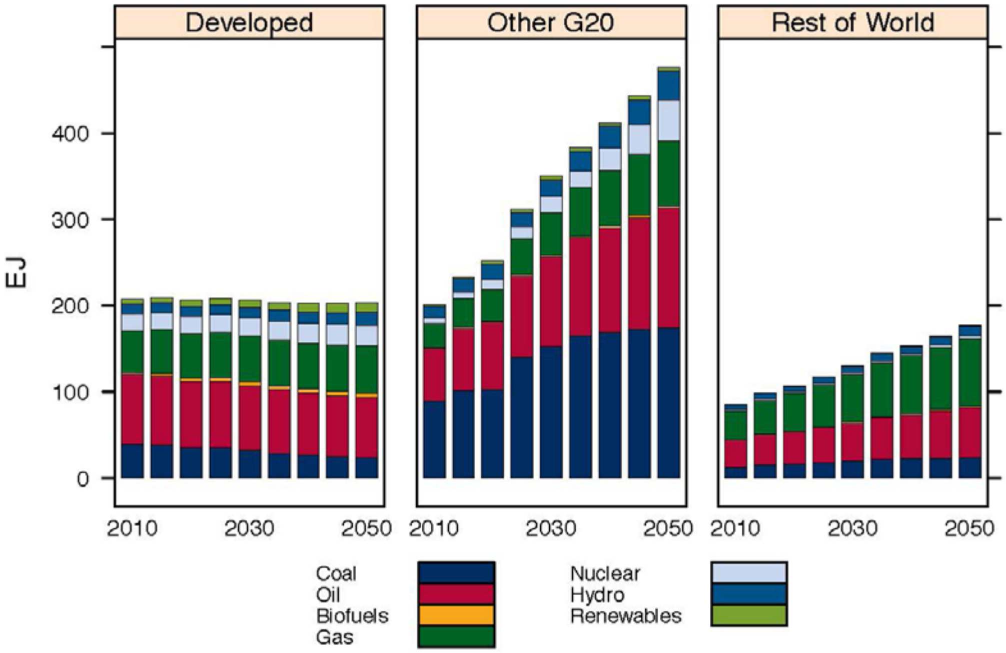


Figure 4. Energy Use by Major Group (exajoules).

Over the next 50 years, even with the Copenhagen–Cancun pledges, the majority (>80%) of the world's energy is projected to continue to come from the same sources that are currently utilized: coal, oil, and natural gas. Coal use levels off with time, and oil and natural gas use increases. Meanwhile, nuclear and hydropower use increases mostly in developing nations. However, without substantial mandates for other renewable energy sources, nuclear, or carbon capture and storage (or more widespread and tighter climate policies), the share of these resources in our primary energy supply mix is not projected to increase substantially. The continued large share of fossil energy reflects their abundance and relatively low cost compared to alternatives. The total coal resources are estimated to be around 180,000 EJ, while cumulative global coal use is only about 8,000 EJ up to 2050 and about 20,000 EJ up to 2100. For oil, resources total about 35,000 EJ, while cumulative oil use is about 9,000 EJ up to 2050 and about 25,000 EJ up to 2100. For natural gas, resources total about 29,000 EJ, while cumulative gas use is about 6,600 EJ up to 2050 and about 20,000 EJ up to 2100. As a result, fossil fuels, particularly coal, are still a major energy source by the end of the century.

While energy consumption is projected to increase over time, energy intensity (i.e. energy use per unit of GDP) generally decreases across the world **(Figure 5)**, with a reduction of about 40% across the globe from 2010 to 2050. 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.

Two important sectors affecting energy use and emissions are electricity and transportation. A growing population means increasing electricity demand **(Figure 6)**. Over the next 50 years, even with the Copenhagen–Cancun pledges, nearly 60% of global electricity generation is from coal and natural gas. Coal generation levels off with time and natural gas generation increases, mostly in developing nations. Nuclear and hydropower generation increases also occur mostly in developing nations, particularly China. Significant renewable generation increases take place in the USA and Europe by 2050, though the total renewable share remains small **(Figure 7)**.

Total electricity production by 2050 is about 150 EJ (1.6% lower than in the 2012 Outlook), reflecting about an 85% increase from 2010 levels. Of particular note is that by 2050 natural gas electricity usage in China has more than tripled compared to the 2012 Outlook.

Also, as a result of the EU-ETS policy representation, the EU uses 13% less electricity than in the 2012 Outlook (and almost half as much coal generation). There is also a significant increase in renewable (35%) and natural gas (15%) generation by 2050 in the USA compared to the last Outlook.

Electricity generation currently contributes about 11.2 Gt of CO_2 (about 36% of total global CO_2 emissions). Given the projections, emissions from power generation rise to about 16.4 Gt of CO_2 (about 33% of total global CO_2 emissions) by 2050. This represents a 46% increase in electricity emissions from 2010 to 2050.

As the world's population grows, motorized vehicle use is also projected to increase **(Figure 8)**. Similar to the 2012 Outlook, vehicle use expands, especially in other G20 nations—including China and India—where populations and incomes are growing rapidly. About 3.6 times more automobiles are projected to be on the roadways in other G20 countries by 2050 than at the present time. Meanwhile, a slight growth in vehicle use in developed countries is projected, and vehicle use in the rest of the world rises moderately to more than double present-day levels by 2050. Growth is particularly slow in Africa because income is not reaching levels that support widespread vehicle ownership **(Figure 9)**. For the world as a whole, the vehicle stock doubles by 2050.

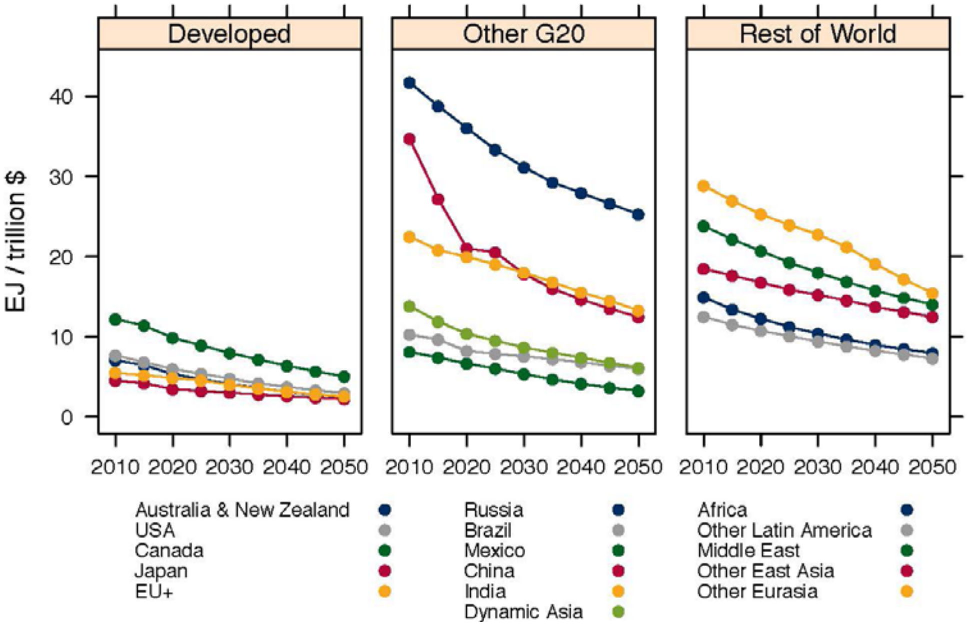


Figure 5. Energy Intensity by Region.

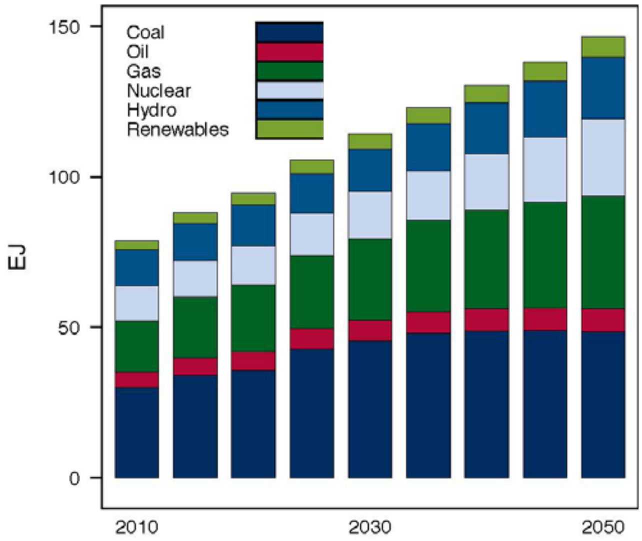


Figure 6. World Electricity Production (exajoules).

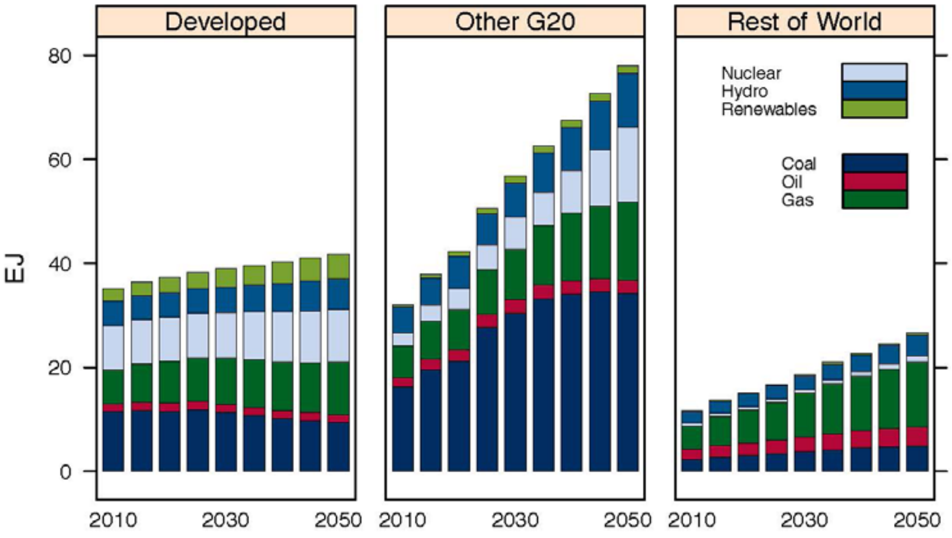


Figure 7. Electricity Production by Major Group (exajoules).

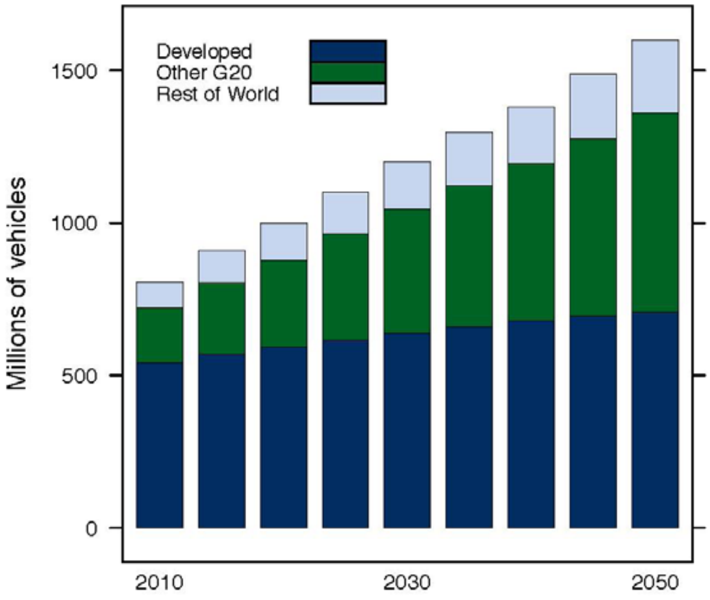


Figure 8. World Private Vehicle Stock (millions of private cars and light trucks).

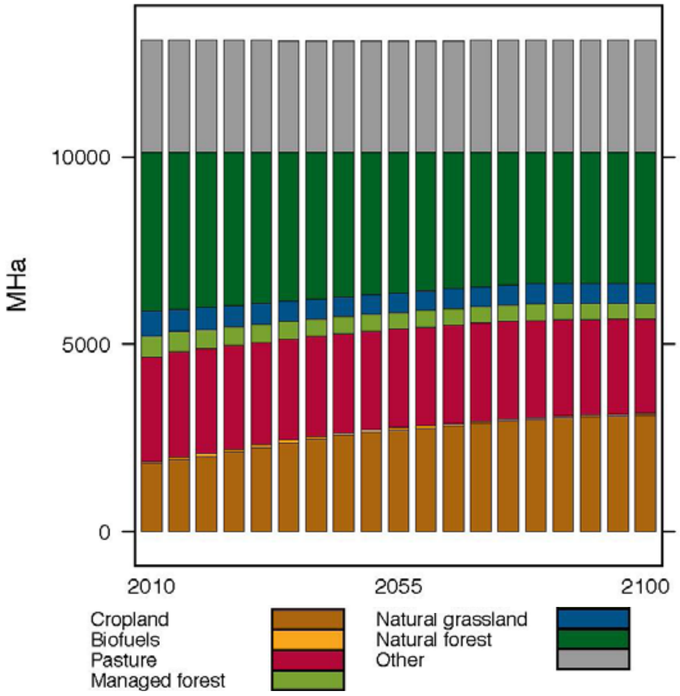


Figure 10. Global Land Use (megahectares).

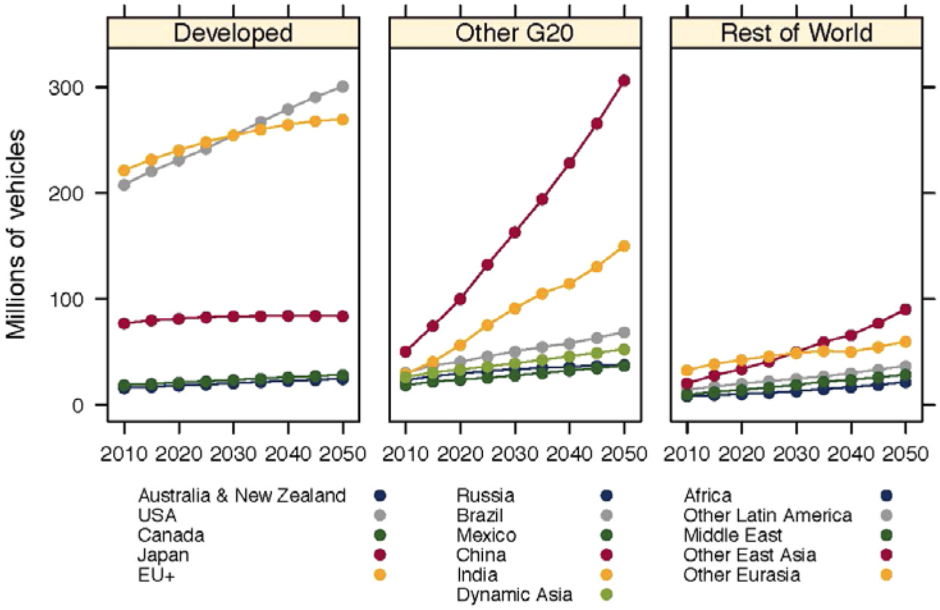


Figure 9. Vehicle Stock by Major Group.

Currently, transport contributes 6 Gt of CO$_2$. Given the projections, emissions from transport rise to 9.6 Gt of CO$_2$ by 2050. While this represents about a 60% increase 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).

To support the increasing global population, we project increasing cropland **(Figure 10)**. Most land conversion to agricultural usage (and other land-use changes over the next century) is projected to occur in the less developed regions. For example, Africa and Latin America currently have significant amounts of natural forest and grassland that could be used for crops **(Figure 11)**. Currently the share of land used for biofuel production is small (less than 1% of the total land or about 3% of cropland). However, if biofuels take a large share of energy demand, the impacts could be larger, and hence have a more significant impact on food prices.

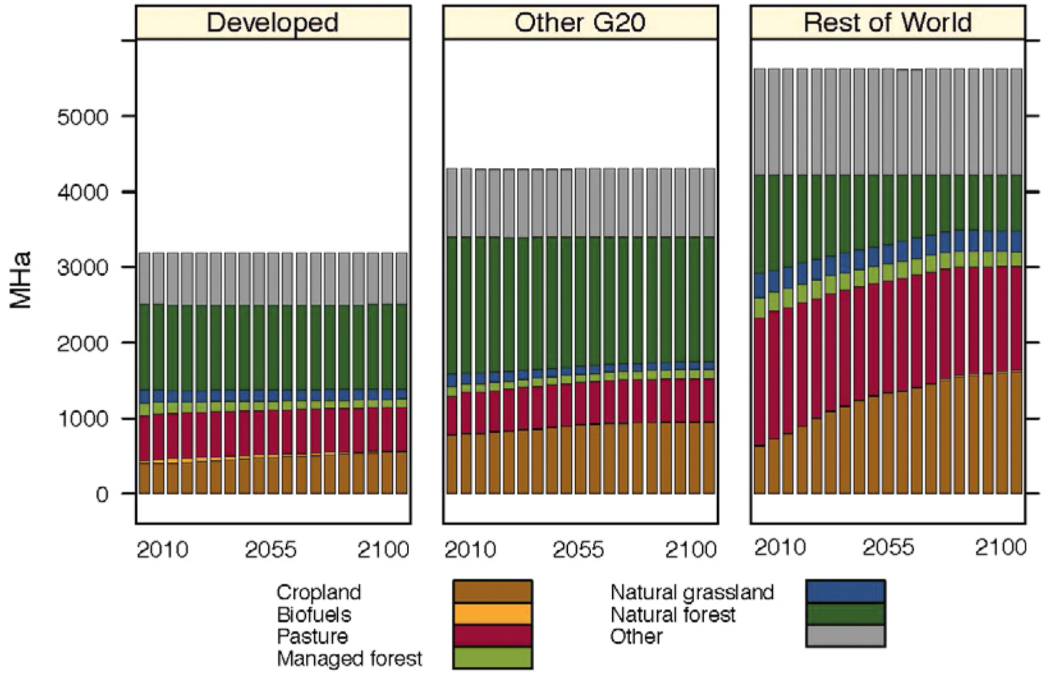


Figure 11. Land Use by Major Group (mega hectares).

GHG Emissions and the Warming Planet

Expanding economic activity results in the growth of most sources of long-lived greenhouse gases **(Figure 12)**. Total GHG emissions in 2100 are projected to reach 90 gigatons (Gt) CO_2-equivalent, which is almost 95% higher than in 2010. Total fossil fuel CO_2 emissions reach over 60 Gt by 2100, almost 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 two-thirds %). The projected increases are primarily attributed to energy use, emissions from agriculture activities (more nitrogen fertilizer use and nitrous oxide (N_2O) emissions, increased livestock production and associated methane (CH_4) emissions), energy production and CH_4 emissions (e.g., from natural gas production and distribution), and other industrial activities especially in areas without greenhouse gas emission limits. Compared to the 2012 Outlook, cumulative global CO_2 emissions over the century are about 12% lower (for input changes driving this result, see Box 1). Cumulative CH_4, N_2O, and HFC emissions are lower, by 18%, 13% and 14% respectively. Cumulative PFC emissions, on the other hand, are 22% higher.

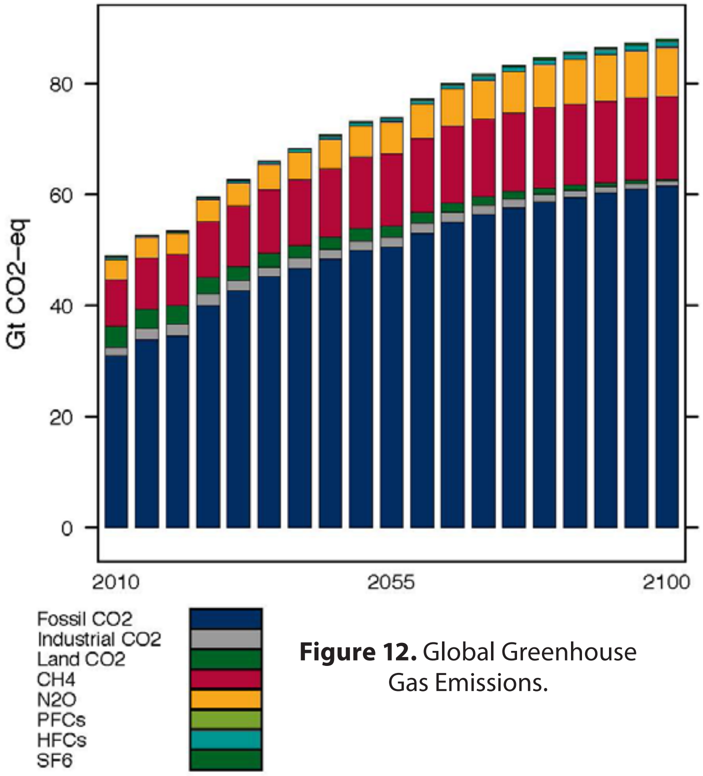


Figure 12. Global Greenhouse Gas Emissions.

Differentiating emissions by region **(Figure 13)**, the projected emissions in developed countries decrease slightly (about 10%) in the near term because of the Copenhagen–Cancun pledges, 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 increase substantially (by about 130% over the century) and the G20 nations become the world's largest sources of emissions—contributing about 55% of global emissions by 2100 (up from 47% 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 rest of the world are projected to nearly triple by 2100.

Our projections for 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 are still projected to increase (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. Therefore, emissions reduction efforts in developed countries are projected to have less of an impact on lowering global emissions over time.

To meet temperature and GHG concentrations goals discussed broadly amongst nations, global emissions need to peak very soon, if not immediately. Current GHG concentrations for Kyoto gases **(Figure 14)** already exceed 450 parts per million (ppm), while CO_2 concentrations approach 400 ppm. The seasonal cycle of concentrations, due largely to strong effects of northern hemisphere vegetation of CO_2, is smoothed to show the underlying trend (for details, see Huang et al. [2009], from which Figure 14 is updated).

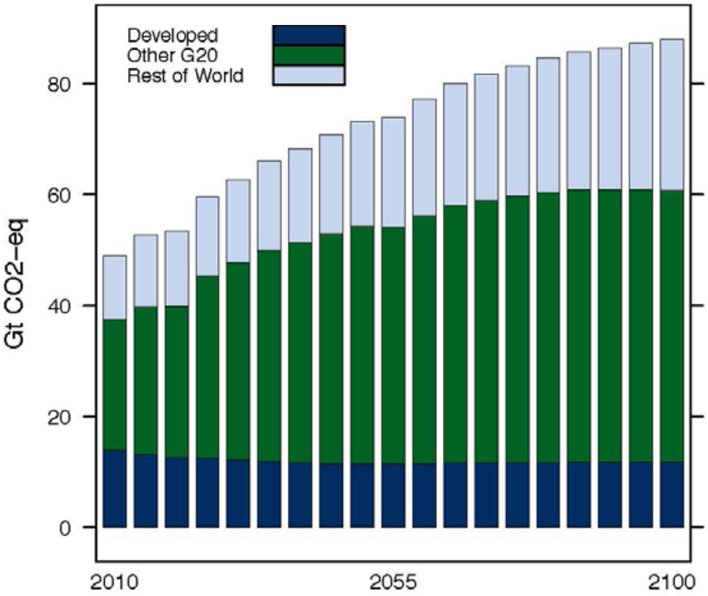


Figure 13. GHG Emissions by Major Group.

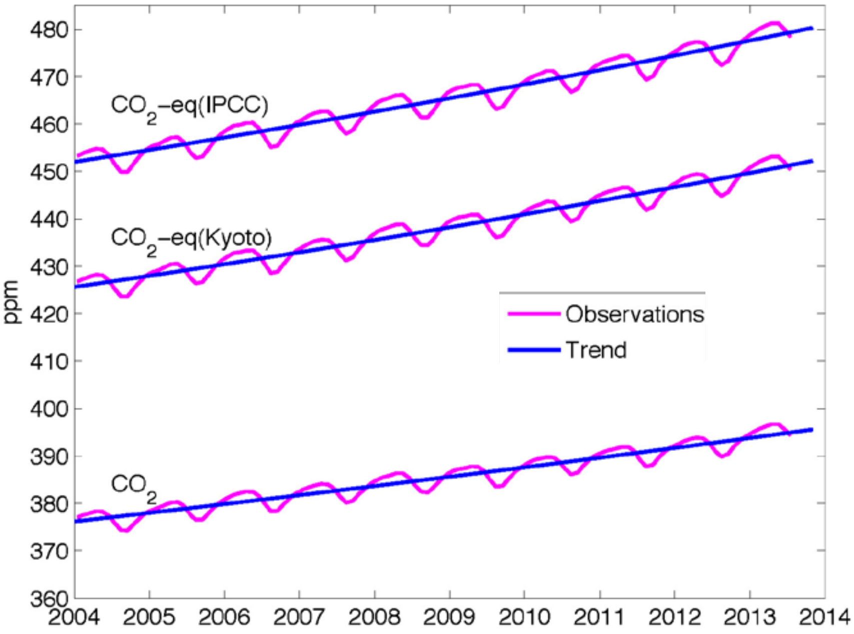


Figure 14. Current Greenhouse Gas Concentrations.

Our projections **(Figure 15)** show that CO_2 concentrations approach 750 ppm by 2100 and continue to rise. 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 report on emissions scenarios (SRES) (Nakicenovic et al., 2000) in dotted lines, and CO_2 concentrations observed at Mauna Loa until 2012. These scenarios are often used by the Intergovernmental Panel on Climate Change (IPCC) and we provide them for a comparison with the policy scenario represented in this Outlook. The 2013 Outlook scenario lies between the SRES scenarios A2 and A1B, and between the RCP scenarios RCP 6.0 and RCP 8.5. Compared to the 2012 Outlook, CO_2 concentrations in 2100 are 8% lower.

In terms of the GHG radiative forcing **(Figure 16)**, the Outlook scenario reaches 7.3 W/m^2 from about 3 W/m^2 in 2010. Different RCP scenarios are approaching 8.5, 6.0, 4.5, and 2.9 W/m^2 by 2100. SRES scenarios are reaching 8.6 (A1FI), 8 (A1B), 6.2 (A2), and 4.5 W/m^2 (B1) by 2100. For this Outlook we use the IPCC's approach to the radiative forcing calculation.

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 (airborne particles) and greenhouse gases 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 5th percentile (CS=2.0 °C), median (CS=2.5 °C), and 95th 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 Fourth Intergovernmental Panel on Climate Change (IPCC) assessment report (AR4) that finds that the climate sensitivity is likely to lie in the range 2.0 °C to 4.5 °C (Meehl et al., 2007a). The value of the net aerosol forcing is then chosen with the objective to provide the best agreement with the observed 20th century climate change. The values for the net aerosol forcing are -0.25 W/m2, -0.55 W/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. For each set of climate parameters, a five-member ensemble is run with different representation of natural variability, represented by different 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 the 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 17)** is projected to increase from about 1 °C in 2010 to 3.5 to 6.5 °C by 2100 relative to the mean temperature in 1901–1950 (which is a base level close to the preindustrial). Blue, green, and red lines in Figure 17 represent, respectively, the low, median, and high climate sensitivity scenarios. The bold solid lines represent the mean of the 5 model runs with different initial conditions, while the thin lines represent each of the runs. Under the median climate sensitivity scenario, temperature increases by 4.4 °C by 2100. In the 2012 Outlook, the temperature increase in the median sensitivity scenario was reported relative to the year 2000 and it was 4.3 °C. We have changed our reporting to be relative to the 1901–1950 mean. Comparing the new result to the year 2000 leads to a temperature increase of 3.8 °C, which is 0.5 °C lower than in the 2012 Outlook. This reflects the lower cumulative emissions in this 2013 Outlook.

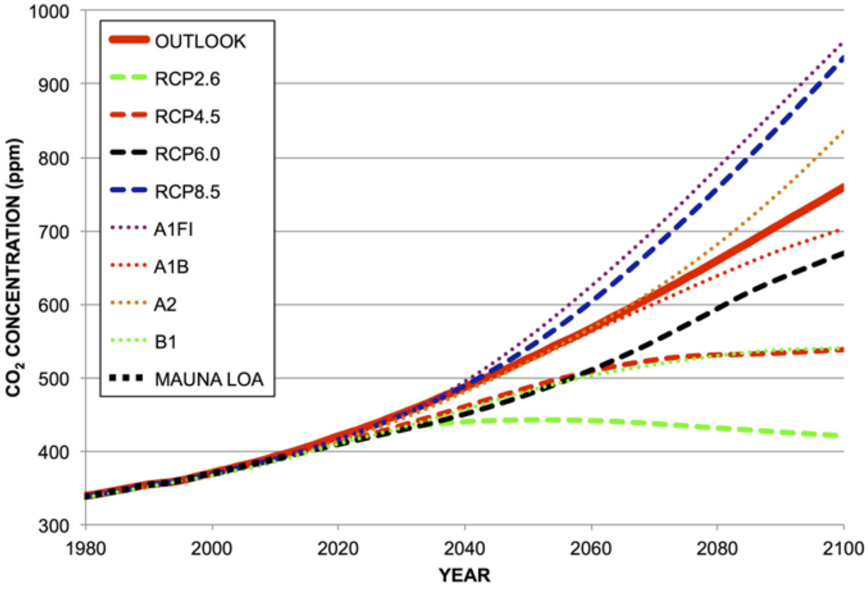


Figure 15. Projected CO_2 Concentrations (parts per million).

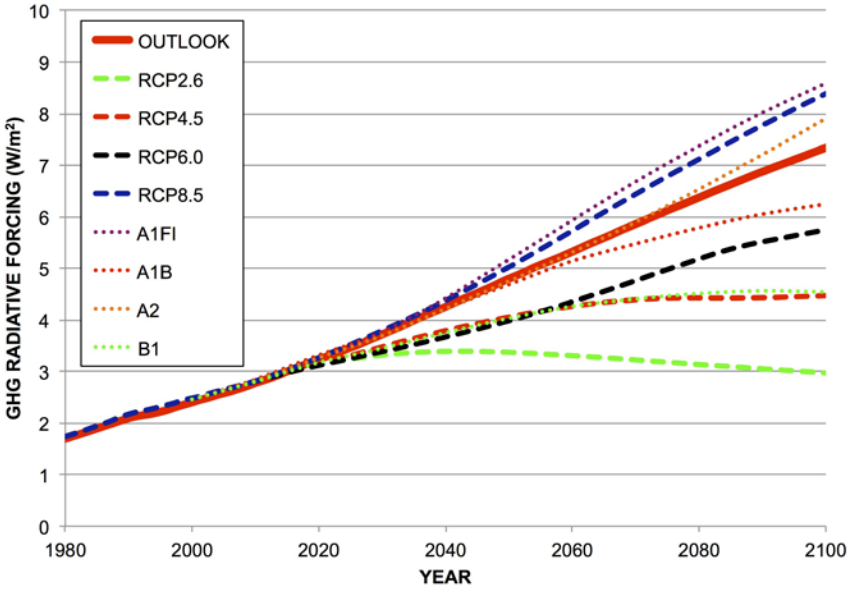


Figure 16. Projected Greenhouse Gas Radiative Forcing (watts per square meter).

Figure 17 also shows an increase in global precipitation anomaly (from 0.02 mm/day in 2010 to a range of 0.25–0.42 mm/day in 2100), an increase in global sea level rise due to thermal expansion from 0.1 m in 2010 to a range of 0.4–0.62 m in 2100, and a change in ocean acidity from pH 8.05 in 2010 to about pH 7.85 in 2100.

The time series of temperature changes from the 1901–1950 mean for each continent are shown in **Figure 18** with the yellow bands representing the range over all

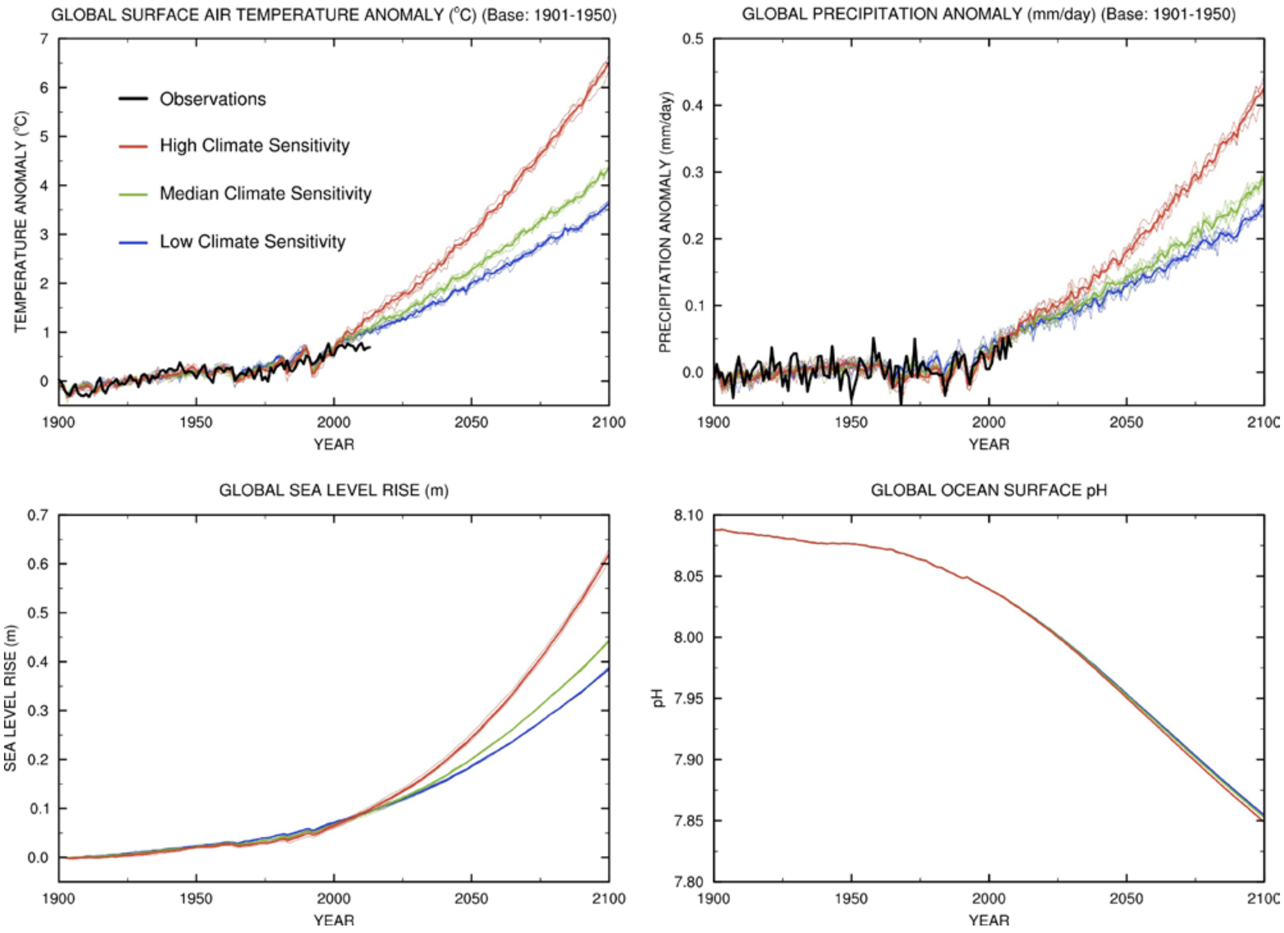


Figure 17. Global mean temperature and precipitation changes from the 1901–1950 mean and sea level rise and ocean surface acidity.

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 of the figure) 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).

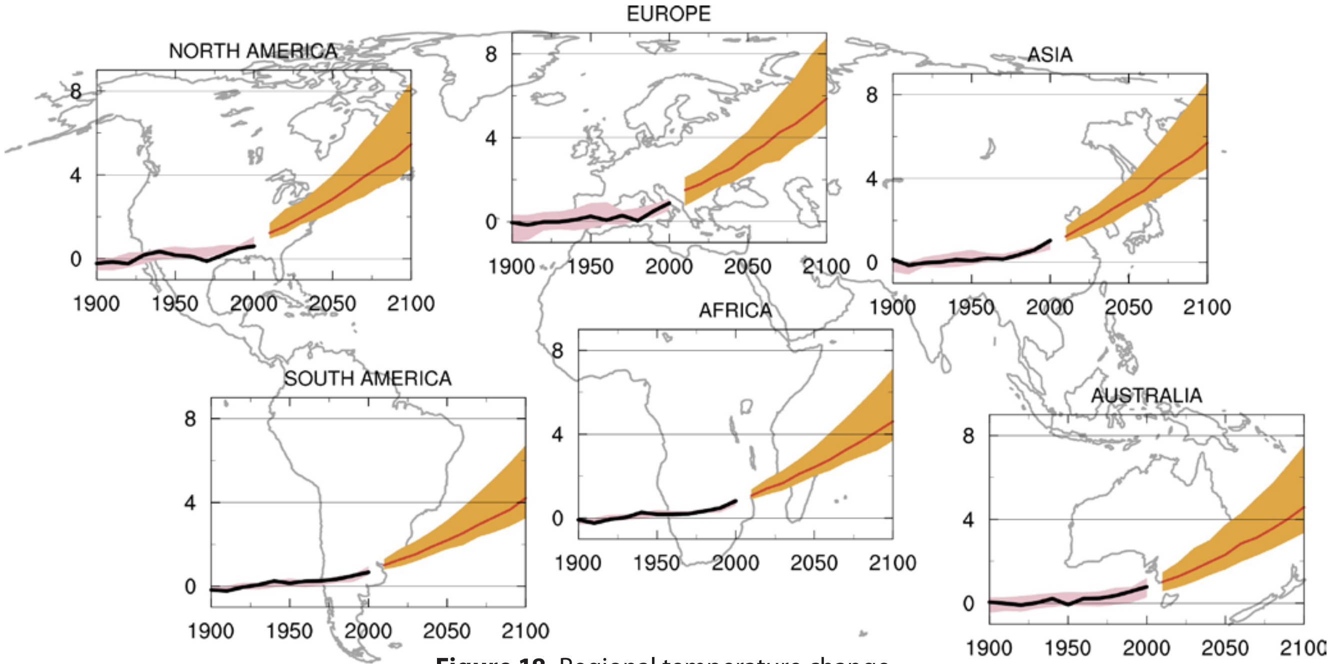


Figure 18. Regional temperature change.

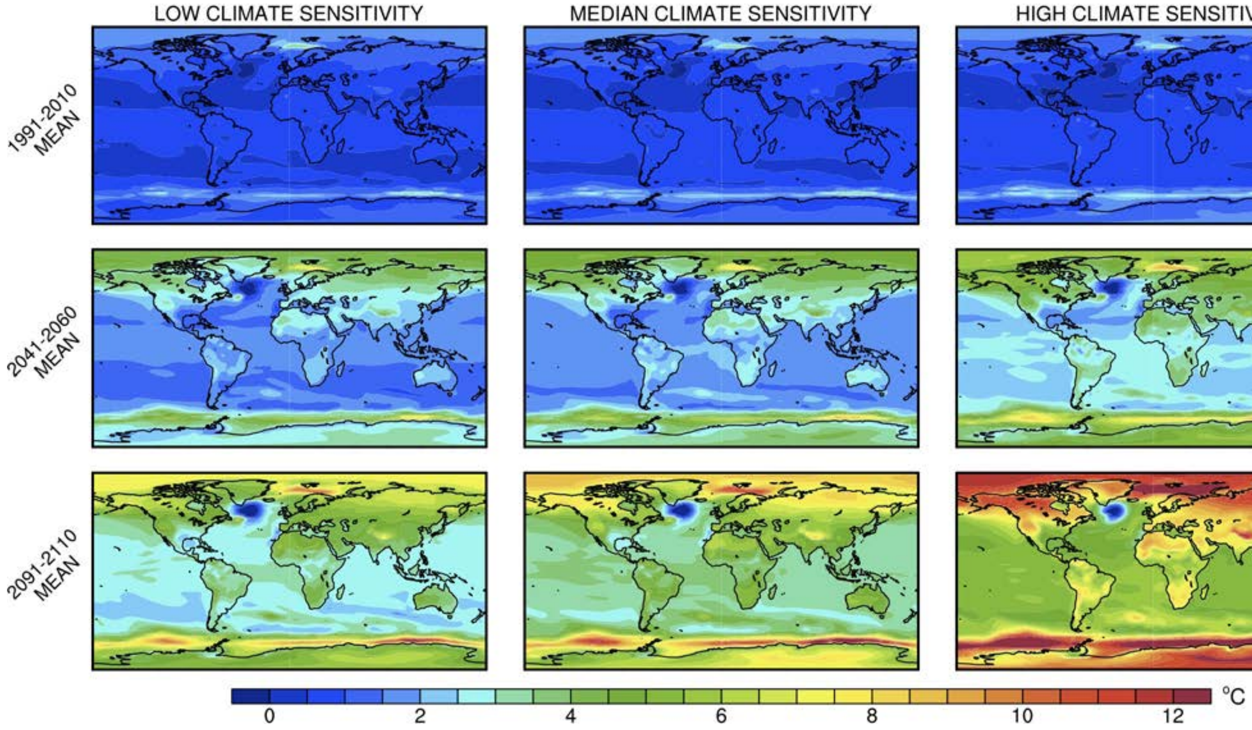


Figure 19. Mean surface temperature.

climate sensitivity scenarios and initial conditions for the projections over the 21st century, red lines showing the mean of the model runs with five different initial conditions for the median climate sensitivity, pink bands showing the range of the simulations over historical period, and black lines showing the 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.

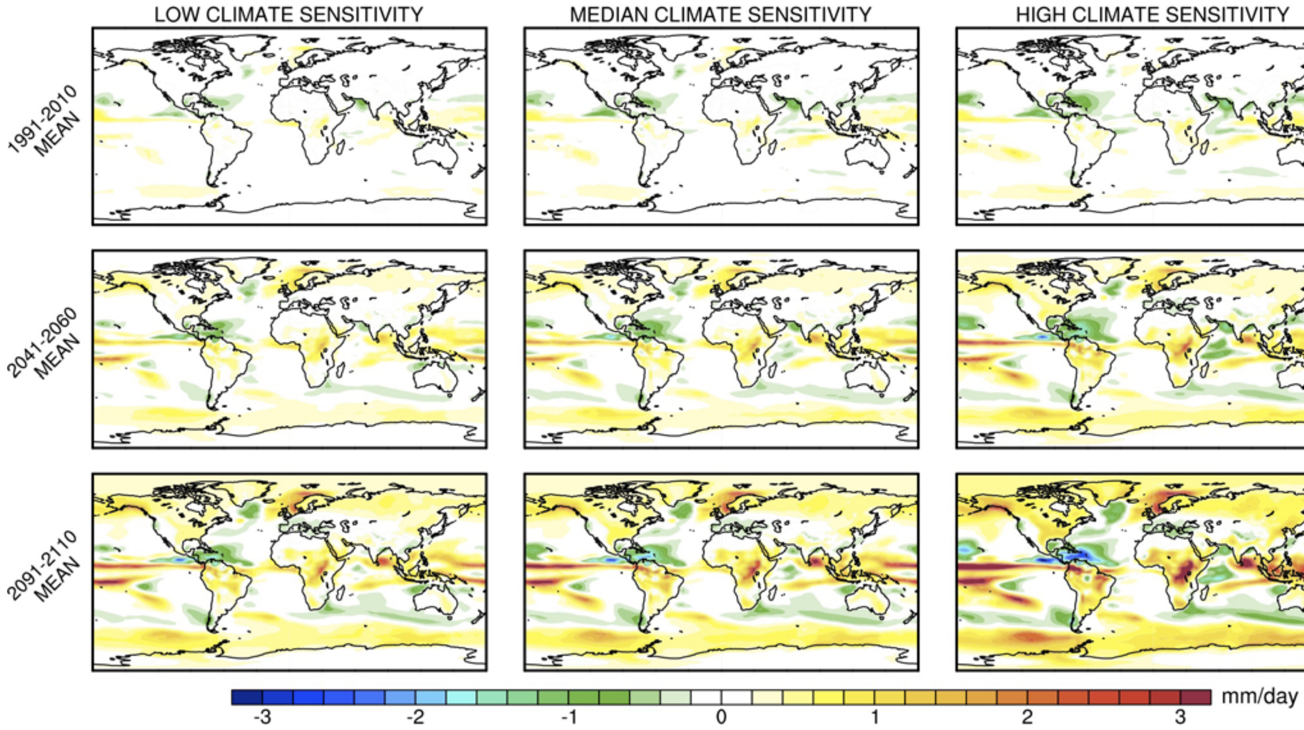


Figure 20. Precipitation anomaly.

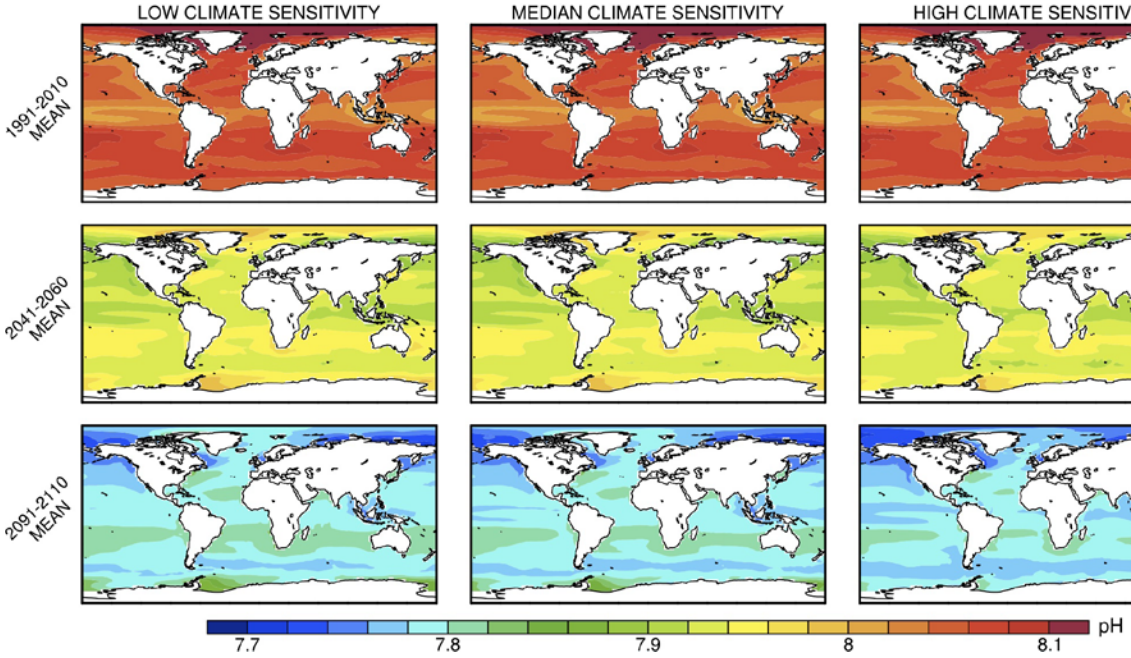


Figure 21. Ocean surface level pH.

Spatial results for the projected temperature changes from the 1901–1950 mean are presented in **Figure 19** for the three climate sensitivity scenarios for the periods 1991–2010, 2041–2060 and 2091–2110. Generally, 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 preindustrial (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.

Projections of precipitation changes from the 1901–1950 mean for the three climate sensitivity scenarios for the periods 1991–2010, 2041–2060, and 2091–2110 are shown in **Figure 20**. The patterns of change vary by location, with most of the land areas projected to become wetter and a few regions projected to become drier, mainly over the ocean in the Tropics. Because the increase in precipitation would likely be accompanied by an increase in extreme precipitation events, including floods, it could have very damaging consequences.

As atmospheric CO_2 concentrations increase, oceans become more acidic from the increasing levels of CO_2 in the ocean. This acidity 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 in **Figure 21** for the periods 1991–2010, 2041–2060, and 2091–2110. By 2100 most locations are projected to reach the levels of pH 7.7–7.8, regardless of the value of climate sensitivity, because the increasing levels of CO_2 are controlled by the emissions scenario. As a result, ocean acidification is quite insensitive to the uncertainty in the climate system's response to a given emissions scenario. The reduced pH would strongly affect marine organisms like corals and mollusks, as pH 7.7 is considered to be a level at which corals are likely to cease to exist.

Preparing for Tomorrow Today

This Outlook provides a window into the future as we view it in 2013. While the world has made progress, much more effort is needed to avoid dangerous climate change and its potential damaging impacts. From this research effort, it is clear that the Copenhagen–Cancun pledges do not take us very far toward 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.

References

Basic structure of the IGSM is described in the following publications:

Monier E., J. Scott, A. Sokolov, C. Forest, and A. Schlosser. 2013: An Integrated Assessment Framework for Uncertainty Studies in Global and Regional Climate Change: The IGSM-CAM (version 1.0). *Geosci. Model Dev. Discuss.*, 6, 2213–2248, doi:10.5194/gmdd-6-2213-2013.

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*, August, 72p. (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.

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*, July, 40p. (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 at: http://globalchange.mit.edu/research/publications

Additional References for the Outlook:

Balmaseda, M.A., K.E. Trenberth, and E. Källén, 2013: Distinctive climate signals in reanalysis of global ocean heat content. *Geophys. Res. Lett.*, 40: 1754–1759, doi:10.1002/grl.50382.

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.

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 174*, June, 10p. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt174.pdf).

IMF [International Monetary Fund], 2013: *World Economic Outlook*. Washington, DC.

Meehl, G., T. Stocker, W. Collins, P. Friedlingstein, A. Gaye, J. Gregory, A. Kitoh, R. Knutti, J. Murphy, A. Noda, S. Raper, I. Watterson, A. Weaver, and Z.-C. Zhao, 2007: *Global Climate Projections*, Chap. 8, pp. 747–845, 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.

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.

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/Outlook2013

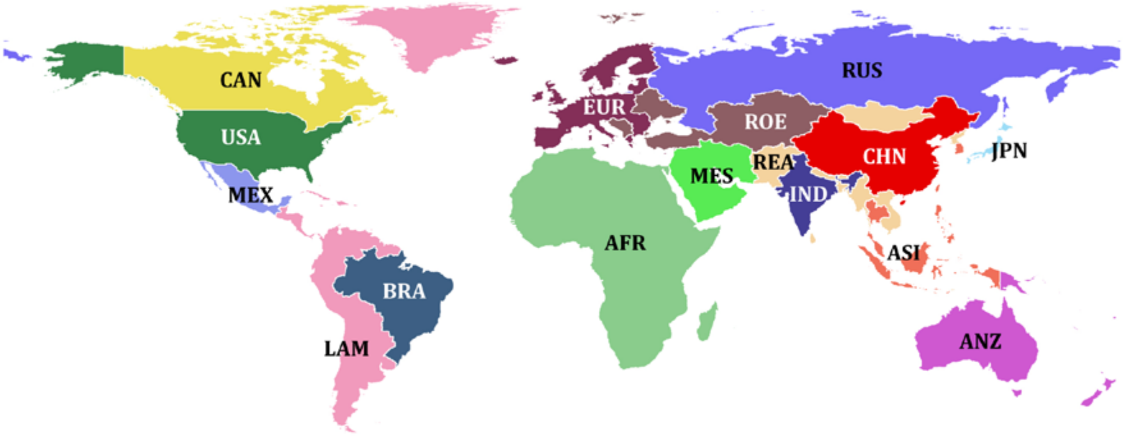
MIT Joint Program Energy and Climate Outlook 2013 **Projection Data Tables**

Region: **World**

	Units	2010	2015	2020	2025	2030	2035	2040	2045	2050
Economic Indicators										
GDP	(bil 2004 $)	45,230	52,550	59,986	69,025	79,546	91,057	103,165	116,949	132,732
Consumption	(bil 2004 $)	27,704	32,467	36,922	42,234	48,453	55,426	62,706	71,114	80,745
GDP growth	(% / yr)	1.9	3.0	2.7	2.8	2.9	2.7	2.5	2.5	2.6
Population	(millions)	6,987.7	7,392.7	7,783.5	8,145.9	8,494.7	8,831.4	9,136.9	9,417.0	9,673.6
GDP per capita	(2004 $)	6,473	7,108	7,707	8,474	9,364	10,311	11,291	12,419	13,721
GHG Emissions										
CO2 -- fossil	(Mt CO2)	30,918	33,816	34,540	39,992	42,604	45,247	46,781	48,399	49,917
CO2 -- industrial	(Mt CO2)	1562	1985	2140	2151	1844	1623	1705	1758	1775
CO2 -- land use change	(Mt CO2)	3826	3576	3324	2973	2621	2493	2365	2239	2112
CH4	(Mt)	398.3	437.6	437.2	476.4	515.0	546.2	562.4	586.1	614.0
N2O	(Mt)	11.41	12.15	12.39	12.75	13.58	14.88	15.84	16.94	18.09
PFCs	(kt CF4)	14.61	6.90	6.85	7.22	8.08	8.74	9.01	9.01	9.28
SF6	(kt)	6.37	5.07	5.42	6.40	7.18	7.98	8.53	9.21	10.07
HFCs	(kt HFC-134a)	349	189	209	225	267	306	348	385	420
Primary Energy Use	(EJ)									
Coal		140.3	154.2	153.8	192.6	204.5	215.2	218.1	220.7	221.4
Oil		175.8	188.8	193.2	211.8	223.8	235.1	244.5	255.6	267.8
Biofuels		2.3	4.2	5.7	6.7	7.9	8.2	8.5	8.7	9.1
Gas		109.0	123.7	132.7	144.4	158.2	173.6	185.3	196.7	208.1
Nuclear		27.6	29.4	32.5	35.5	41.5	42.8	50.3	60.5	74.6
Hydro		31.3	32.2	36.6	35.1	38.4	43.4	47.0	52.8	58.7
Renewables		7.6	9.0	10.7	12.0	13.3	14.4	15.6	16.6	17.5
Electricity Production	(TWh)									
Coal		8,326	9,446	9,925	11,903	12,607	13,325	13,521	13,577	13,454
Oil		1,442	1,623	1,700	1,872	1,967	2,025	2,058	2,114	2,161
Gas		4,761	5,660	6,171	6,747	7,465	8,420	9,149	9,756	10,405
Nuclear		3,201	3,362	3,626	3,877	4,390	4,566	5,195	6,018	7,135
Hydro		3,301	3,388	3,744	3,659	3,936	4,364	4,683	5,188	5,701
Renewables		825	966	1,122	1,253	1,381	1,500	1,633	1,744	1,849
Household Transportation										
Number of vehicles	(millions)	808	910	1000	1103	1202	1296	1382	1488	1600
Vehicle miles traveled	(trillions)	6.67	7.71	8.72	9.90	11.01	12.11	13.12	14.34	15.67
Miles per gallon	(mpg)	22.8	23.2	23.8	24.0	24.4	24.8	25.2	25.5	25.7
Land Use	(Mha)									
Cropland		1808.5	1927.5	2002.9	2120.4	2236.7	2366.1	2462.8	2564.6	2659.1
Biofuels		43.2	59.8	75.3	77.2	83.9	72.3	67.4	62.8	58.6
Pasture		2800.4	2821.8	2798.1	2764.7	2727.8	2701.1	2679.9	2655.1	2631.1
Managed forest		563.3	522.7	509.1	496.6	483.0	469.0	460.6	449.4	441.9
Natural grassland		666.5	596.5	595.0	577.0	560.5	541.2	534.8	529.0	524.1
Natural forest		4243.7	4194.4	4139.9	4082.3	4024.8	3965.9	3908.7	3852.9	3798.5
Other		2997.0	2997.0	2997.0	2997.0	2997.0	2997.0	2997.0	2997.0	2997.0
Air Pollutant Emissions	(Tg)									
SO2		102.68	106.26	104.19	112.98	113.72	113.58	110.10	106.88	102.79
NOx		101.50	114.61	124.53	146.79	162.51	178.76	191.63	205.44	218.71
Ammonia		59.83	70.39	77.07	83.79	89.90	98.46	104.72	111.39	118.24
Volatile organic compounds		132.32	146.92	158.48	181.12	199.75	218.36	234.07	251.22	269.34
Black carbon		7.16	7.39	7.23	7.71	7.96	8.26	8.21	8.20	8.19
Organic particulates		34.00	35.98	35.83	37.92	39.88	42.41	42.54	43.09	43.59
Carbon monoxide		695.43	780.19	884.14	1021.25	1160.95	1310.02	1452.47	1601.57	1762.65

16 regions:

AFR	Africa
ANZ	Australia and 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	USA



Regional data tables are available at: http://globalchange.mit.edu/Outlook2013

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 Herzogovina	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
Coe d'Ivoire	AFR
Colombia	LAM
Comoros	AFR
Congo`	AFR
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
Egypt	AFR
El Salvador	LAM
Equador	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
Giblartar	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
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
Lybia	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
Monserrat	LAM
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
Reunion	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 & the Grenadines	LAM
Samoa	ANZ
San Marino	ROE
Sao Tome and Principe	AFR
Saudi Arabia	MES
Senegal	AFR
Serbia and Montenegro	ROE
Seychells	AFR
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	LAM
Tuvalu	ANZ
Uganda	AFR
Ukraine	ROE
United Arab Emirates	MES
United Kingdom	EUR
United States	USA
Uruguay	LAM
Uzbekistan	ROE
Vanuatu	ANZ
Venezuela	LAM
Vietnam	REA
Virgin Islands, British	LAM
Virgin Islands, U.S	LAM
Wallis and Futuna	ANZ
Yemen	MES
Zambia	AFR
Zimbabwe	AFR

Acknowledgements

Contributors: Sergey Paltsev, Erwan Monier, Jennifer Morris, Henry Chen, Andrei Sokolov, Jin Huang, Stephanie Dutkiewicz, Jeffery Scott, Audrey Resutek, Allison Gold Roberts, Anne Slinn, and John Reilly.

The work of the MIT Joint Program on the Science and Policy of Global Change is funded by an international partnership of government, industry, and foundation sponsors, and by private donations. The consortium provides the long-term substantial commitment needed to support our dedicated and specialized staff, and to realize a coordinated integrated research effort.

MIT Joint Program Sponsors

The work of the Joint Program is funded by an international partnership of government, industry, and foundation sponsors, and by private donations. Our sponsor consortium provides the long-term substantial commitment needed to support our dedicated and specialized staff, and to realize a coordinated integrated research effort.

Alstom Power (USA)
American Electric Power (USA)
BP (UK)
Cargill (USA)
Caterpillar (USA)
Centro Mario Molina (Mexico)
Chevron (USA)
CLP Holdings (Hong Kong)
ConocoPhillips (USA)
Deutsche Asset Management (USA)
Dow Chemical (USA)
Duke Energy (USA)
Electric Power Research Institute (USA)
Electricité de France (France)
Eni (Italy)
Exelon (USA)
ExxonMobil (USA)
GDF SUEZ (France/Belgium)
J-Power (Japan)
Lockheed Martin (USA)
Murphy Oil (USA)
Norwegian Ministry of Petroleum and Energy (Norway)
Oglethorpe Power Corporation (USA)
Petrobras-Petroleo Brasilerio S.A. (Brazil)
RWE Power (Germany)
Shell International Petroleum (Netherlands/UK)
Southern Company (USA)
Statoil (Norway)
Suncor Energy (Canada)
Tokyo Electric Power Company (Japan)
Total (France)
Toyota Motor North America (USA)
Vetlesen Foundation (USA)
U.S. Department of Agriculture [USDA]
U.S. Department of Energy [DOE]
U.S. Department of Transportation [DOT]
U.S. Environmental Protection Agency [EPA]
U.S. Federal Aviation Administration [FAA]
U.S. National Aeronautics and Space Administration [NASA]
U.S. National Science Foundation [NSF]

2013 Joint Program Reports *(as of November 2013)*

Report 253: An Analogue Approach to Identify Extreme Precipitation Events: Evaluation and Application to CMIP5 Climate Models in the United States

Report 252: Synergy between Pollution and Carbon Emissions Control: Comparing China and the U.S.

Report 251: Regulatory Control of Vehicle and Power Plant Emissions: How Effective and at What Cost?

Report 250: The Association of Large-Scale Climate Variability and Teleconnections on Wind Energy Resource over Europe and its Intermittency

Report 249: Limited Sectoral Trading between the EU ETS and China

Report 248: The Energy and Economic Impacts of Expanding International Emissions Trading

Report 247: What GHG Concentration Targets are Reachable in this Century?

Report 246: Probabilistic Projections of 21st Century Climate Change over Northern Eurasia

Report 245: Climate Change Impacts on Extreme Events in the United States: An Uncertainty Analysis

Report 244: A Framework for Modeling Uncertainty in Regional Climate Change

Report 243: Integrated Economic and Climate Projections for Impact Assessment

Report 242: The Energy and CO2 Emissions Impact of Renewable Energy Development in China

Report 241: Consumption-Based Adjustment of China's Emissions-Intensity Targets: An Analysis of its Potential Economic Effects

Report 240: Protection of Coastal Infrastructure under Rising Flood Risk

Report 239: Analysis of U.S. Water Resources under Climate Change

These and previous reports are available online open-access at ***http://globalchange.mit.edu/research/publications/reports***

Science & Policy Working Together

The Joint Program on the Science and Policy of Global Change is MIT's response to the research, analysis and communication challenges of climate change. The Program combines scientific research with policy analysis to provide an independent, integrative assessment of the impacts of global change and how best to respond.

The Program is made up of a team of close-working specialists from a wide range of disciplines. It combines the efforts and expertise of two complementary MIT research centers – the ***Center for Global Change Science (CGCS)*** and the ***Center for Energy and Environmental Policy Research (CEEPR)*** – and collaborates with other MIT departments, leading research institutions, and nonprofit organizations worldwide.

Co-directors:

Professor Ronald G. Prinn
TEPCO Professor of Atmospheric Science
Director, Center for Global Change Science

Dr. John M. Reilly
Senior Lecturer, Sloan School of Management

MIT Joint Program on the
Science and Policy of Global Change
77 Massachusetts Avenue, E19-411
Cambridge, MA 02139 USA

E-mail: globalchange@mit.edu
Phone: (+1) 617.253.7492
Fax: (+1) 617.253.9845

For inquiries, permission to reproduce material, or
to subscribe to future newsletters, please email:
globalchange@mit.edu