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An emission pathway for stabilization at 6 Wm^{-2} radiative forcing

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Abstract Representative Concentration Pathway 6.0 (RCP6) is a pathway that describes trends in long-term, global emissions of greenhouse gases (GHGs), short-lived species, and land-use/land-cover change leading to a stabilisation of radiative forcing at 6.0 Watts per square meter (Wm^{-2}) in the year 2100 without exceeding that value in prior years. Simulated with the Asia-Pacific Integrated Model (AIM), GHG emissions of RCP6 peak around 2060 and then decline through the rest of the century. The energy intensity improvement rates changes from 0.9% per year to 1.5% per year around 2060. Emissions are assumed to be reduced cost-effectively in any period through a global market for emissions permits. The exchange of CO_2 between the atmosphere and terrestrial ecosystem through photosynthesis and respiration are estimated with the ecosystem model. The regional emissions, except CO_2 and N_2O, are downscaled to facilitate transfer to climate models.

1 Introduction

Representative Concentration Pathway 6.0 (RCP6) is a scenario of long-term, global emissions of greenhouse gases (GHGs), short-lived species, and land-use/land-cover change which stabilizes radiative forcing at 6.0 Wm^{-2} in the year 2100 without exceeding

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that value in prior years. The defining characteristics of this scenario are enumerated in Moss et al. (2008, 2010). The RCP6 scenario is quantified by using a model framework which is mainly developed and maintained at the National Institute for Environmental Studies (NIES) and Japan Agency for Marine-Earth Science and Technology. Taken together this set of models is referred to as the Asia-Pacific Integrated Model (AIM).

RCP6 is a climate-policy intervention scenario. That is, without explicit policies designed to reduce emissions, radiative forcing would exceed 6.0 Wm^{-2} in the year 2100. However, the degree of GHG emissions mitigation required over the period 2010 to 2060 is small, particularly compared to RCP4.5 and RCP2.6, but also compared to emissions mitigation requirement subsequent to 2060 in RCP6 (Van Vuuren et al., 2011). The IPCC Fourth Assessment Report classified stabilization scenarios into six categories as shown in Table 1. RCP6 scenario falls into the border between the fifth category and the sixth category. Its global mean long-term, steady-state equilibrium temperature could be expected to rise 4.9° centigrade, assuming a climate sensitivity[1] of 3.0 and its CO_2 equivalent concentration could be 855 ppm (Metz et al. 2007).

AIM is a system of inter-related component models developed by an interdisciplinary team of researchers at NIES and Kyoto University (Kainuma et al. 2002). The AIM was developed for assessing climate mitigation options and climate change impacts and has contributed to numerous analyses and assessments including the evaluation of national climate policies in Japan and the quantification of the A1B scenario in the Special Report on Emissions Scenarios (SRES) (Nakicenovic and Swart 2000).

The process flow diagram describing the relationship amongst the models used is presented in Fig. 1. The RCP6 scenario was developed in a series of steps. First, a reference scenario was constructed. The reference scenario was then constrained so as to stabilize radiative forcing at 6.0 Wm^{-2} in 2100, without exceeding that level in earlier years. Both scenarios are described in detail later in this paper.

The time path of emissions was calculated using AIM/Impact [Policy], a dynamic optimization model coupled with a simple climate model (Hijioka et al. 2008). That global GHG emissions pathway was then introduced as a constraint to AIM/CGE [Global] (Matsumoto and Masui 2010, and Masui 2011), to calculate regional and sectoral GHG emissions and emissions of short-lived species such as SO_x. AIM/CGE [Global] is a 24-region, dynamics-recursive, computable general equilibrium model. In addition to energy and economic variables, AIM/CGE [Global] also calculates agricultural production and prices.

Aggregate production reported by AIM/CGE [Global] was downscaled using the land use downscaling model. Grid-based land use is imputed by the vegetation model developed by Ito and Oikawa (2002) and the resulting pattern of land-use GHG emissions are then fed back to the AIM/CGE [Global] for reconciliation.

The regional GHG emissions, except CO_2 and N_2O, are downscaled using the emission downscale model.

The AIM system produces estimates of the global emissions of the following species: carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), other Kyoto gases, namely, hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6). The AIM system produces regionally disaggregated emissions of the following chemically-active species: carbon monoxide (CO), nitrogen oxides (NOx), non-methane volatile organic compounds (NMVOCs), and ammonia (NH_3), and aerosols such as sulfur dioxide

[1] Climate sensitivity is the number of degrees that the global average temperature could be expected to rise, relative to pre-industrial climate, if the concentration of CO_2 were to double and remain at that level indefinitely.

Table 1 Properties of emissions pathways for alternative ranges of CO_2 and CO2-eq stabilization targets in the IPCC fourth Assessment Report (Metz et al. 2007) and RCP

Class	Anthropogenic addition to radiative forcing at stabilization (Wm^{-2})	Multi-gas concentration level (ppmv CO_2-eq)	Stabilization level for CO_2 only, consistent with multi-gas level (ppmv CO_2)	Number of scenario studies	Global mean temperature C increase above pre-industrial at equilibrium, using best estimate of climate sensitivity	Likely range of global mean temperature C increase above pre-industrial at equilibrium	Peaking year for CO_2 emissions	Change in global emissions in 2050 (% of 2000 emissions)	RCP
I	2.5–3.0	445–490	350–400	6	2.0–2.4	1.4–3.6	2000–2015	−85 to −50	RCP2.6
II	3.0–3.5	490–535	400–440	18	2.4–2.8	1.6–4.2	2000–2020	−60 to −30	
III	3.5–4.0	535–590	440–485	21	2.8–3.2	1.9–4.9	2010–2030	−30 to +5	
IV	4.0–5.0	590–710	485–570	118	3.2–4.0	2.2–6.1	2020–2060	+10 to +60	RCP4.5
V	5.0–6.0	710–855	570–660	9	4.0–4.9	2.7–7.3	2050–2080	+25 to +85	RCP6
VI	6.0–7.5	855–1130	660–790	5	4.9–6.1	3.2–8.5	2060–2090	+90 to +140	

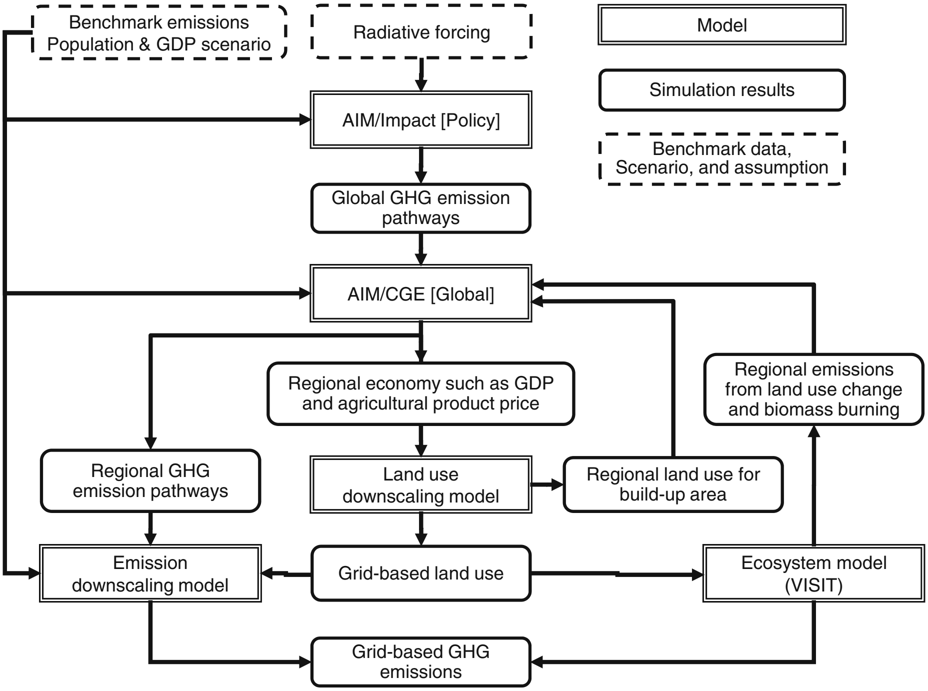


Fig. 1 Structure of the AIM Model components used to develop RCP6

(SO_2), black carbon (BC) and organic carbon (OC). The chemically-active species are downscaled and assigned to grid cells disaggregated at 0.5° by 0.5° resolution.

2 Model description

2.1 AIM/Impact [Policy]

The AIM/Impact [Policy] model is an aggregate, global dynamic optimization model coupled with a simple climate model (Hijioka et al. 2008). The model maximizes discounted total utility, which in turn is a function of consumption. AIM/Impact [Policy] aggregates global economic activities into one homogeneous final product, which can be either consumed to produce utility by the household sector or allocated to investment (savings). Investments can be used by the model to increase the capital stock and therefore produce more consumer goods in the future. The benchmark year for the AIM/Impact [Policy] model is 1990, which runs up to 2300. Nested constant elasticity of substitution (CES) production functions have been used to produce the final product. The top nest consists of energy and value added, with energy disaggregated into electricity and non-electricity, and value added disaggregated into capital and labor. Emissions are a by-product of energy use and aggregate production. Emissions are translated into atmospheric composition and radiative forcing by a simple aggregate representation of the atmosphere and carbon cycle. The model is run to maximize discounted total global utility derived from final consumption subject to a limit on radiative forcing of 6 Wm^{-2}. The resulting emissions trajectory is the optimal pathways for RCP 6.0. The optimal emissions path is then used as a constraint in the AIM/CGE [Global] model.

2.2 AIM/CGE [Global]

The AIM/CGE [Global] is a multi-regional and multi-sector, dynamics-recursive, computable general equilibrium (CGE) model (Masui 2011, and Matsumoto and Masui 2010). Each sector in the economy is represented by a nested constant elasticity of substitution (CES) production function. The time period of AIM/CGE [Global] is 2001 to 2100. AIM/CGE [Global] is disaggregated into 24 geographical regions each producing 21 types of economic goods and services (Table 2). In AIM/CGE [Global] electric power can be generated using thermal, hydro and nuclear, as well as renewable energy options including biomass (bio-ethanol and bio-gas) and solar. Future thermal power plants, including integrated gasification combined cycle (IGCC) are assumed to be available both

Table 2 Definition of region and commodity used in AIM/CGE [Global]

Region[a]		Commodity	
JPN	Japan (OECD90)	AGR	Agriculture
CHN	China (Asia)	LVK	Livestock
KOR	Korea (Asia)	FRS	Forestry
IDN	Indonesia (Asia)	FSH	Fishing
IND	India (Asia)	OMN	Mining (except fossil fuels)
THA	Thailand (Asia)	EIS	Energy intensive products
XSE	Other South-east Asia (Asia)	M_M	Metal and machinery
XSA	Other South Asia (Asia)	FOD	Foods
AUS	Australia (OECD90)	OMF	Other manufactures
NZL	New Zealand (OECD90)	WTR	Water
XRA	Rest of Asia-Pacific (Asia)	CNS	Construction
CAN	Canada (OECD90)	TRT	Transport
USA	USA (OECD90)	CMN	Communication
XE15	EU-15 in Western Europe (OECD90)	OSG	Public service
XE10	EU-10 in Eastern Europe (REF)	SER	Other service
RUS	Russia (REF)	COA	Coal
XRE	Rest of Europe (REF)	OIL	Crude oil
BRA	Brazil (LAM)	P_C	Petroleum products
MEX	Mexico (LAM)	GAS	Natural gas
ARG	Argentine (LAM)	GDT	Gas manufacture distribution
XLM	Other Latin America (LAM)	ELY[b]	Electricity
XME	Middle East (LAM)		
ZAF	South Africa (LAM)		
XAF	Other Africa (LAM)		

[a] ( ) shows the definition of 4 regions in SRES as follows; OECD90: OECD as of 1990, REF: Economic reform countries, Asia: Developing countries in Asia, and LAM: Latin America, Africa and Middle East

[b] In electricity generation, following sub sectors has been considered; Coal-fired, Oil-products-fired, Gas-fired, Nuclear, Hydro, Biomass, Waste, Geothermal, Solar, Wind, and Other renewables

As for the advanced technologies, IGCC and thermal power plant with CCS are available with and without the ability to capture and permanently store CO_2 (CCS). Resources, including coal, crude oil, natural gas and other mining products, are produced subject to finite, depletable, resource limits, whose magnitude and associated extraction costs are taken from (Rogner 1997). Similarly, agriculture, livestock, forestry and biomass energy production require land, a finite resource, in addition to other economic resources.

Each sector produces goods, which are delivered to final consumption, investment, intermediate demand and/or net exports. Aggregate investment demand in each period is set exogenously to meet a prescribed GDP growth rate. Future GDP values were taken from the Sustainability First scenario in UNEP/GEO3 (UNEP 2002) and GEO4 (UNEP 2007). The rate of energy efficiency improvement is also set exogenous using rates derived from the SRES B2 scenario (Nakicenovic and Swart 2000). AIM/CGE [Global] employs a putty-clay representation of capital. Capital is divided into an Old capital stock and New capital. Old capital cannot move between sectors, while New capital can be installed in any sector. Once New capital is assigned to a sector it becomes Old capital in all subsequent periods. The energy efficiency improvements and other technology changes are applied to New capital only. Productivity of aggregate capital is the weighted sum of technology levels in Old and New capital.

The AIM/CGE [Global] model is constrained to follow the global GHG emissions pathway obtained from the AIM/Impact [Policy] model. The global GHG emissions are assigned to regions in proportion to their population in 2050 and beyond. Between 2001 and 2050 regional GHG emissions limits are set by linear interpolation of the emissions in 2001 and limits assignments in 2050. In AIM/CGE [Global] GHG emission rights are freely traded between regions for all emissions.

The household sector is assumed to own all capital, labor, land and fuel resources in each region and to supply those resources to the economy's factor markets. The household sector's income is derived from sale of the factors of production. The household sector distributes its income between final consumption goods and services and savings. Savings rates are set equal to investment, which is set exogenously to meet a prescribed GDP growth rate as described above. The demand for new final goods and services is derived as the result of utility maximization subject to an unsaved income constraint in each period.

The model is calibrated to reproduce economic and energy activity levels in the year 2001 using GTAP6 (Dimaranan 2006) for economic activity levels and the IEA energy balance table (IEA 2007a, b) for energy and benchmarked GHG emission rates.

2.3 Land use downscaling model

AIM/CGE[Global] provides land use scenarios for 24 regions. These data were reconciled with the historical land use scenario implemented by the land use harmonization team at the University of New Hampshire including the UNH data on urban area, cropland, pastures, forests and unmanaged ecosystems (Hurtt et al., 2011; Klein Goldewijk et al. 2011). The 24 regions data are downscaled into 30 arc-second grid cells with the land use downscaling model and spatial distribution data of population and GDP. Table 3 shows the land use categories used in the AIM/CGE [Global] and the land use downscaling model.

The IIASA global population data are distributed proportionally to countries by using the UN medium variant from 2005 to 2050 (UN 2007) and UN long-term estimation from 2050 to 2100 (UN 2004). Gridded data taken from CIESIN (http://sedac.ciesin.columbia.edu/gpw/) are used as an initial distribution. In future years the spatial distribution is created by assuming that urban grid cells are increased in proportion to the increase in population and GDP in each country. Incremental rates of population growth in urban grid cells are

Table 3 Land cover/land use categories

Categories in AIM/CGE [Global] model	Categories in the land use downscaling model
Cropland	Bio-fuel cropland
	Other cropland
Forest	Managed forest
	Unmanaged forest
Grassland+	Pasture
	Natural grassland
Built-up	Built-up
Other	Other

estimated taking into account total urban population growth and urban sprawl by using urbanization rates taken from UN (2005). The gridded data of GDP are estimated by the methodology of Grubler et al. (2007) and UN population data of the rich and the poor (UNDP 2002).

The downscale is done as follows:

First, the spatial distribution of urban land is assigned. The expansion rate for urban areas is estimated for each country using a regression analysis where population, GDP, and the urbanization rate are used as the explanatory variables.

Next, regional croplands, including bio-fuel production, are downscaled using crop yield, GDP, population and slope angle (Monfreda et al. 2008). The 30 arc-second grid cells which are already allocated to urban area are left unchanged even if these grid cells are suitable for crop production. A similar procedure is employed to downscale land employed in other agricultural activities. For example, pasture land is allocated in the same manner but net primary production of grass is used instead of crop yield. VISIT data (Ito 2010) is used for Net primary Product. Leff et al. (2004) is cited for crop yield.

In the third stage, the growth rates of forest and grass land in each grid cell are decided by a global land cover map (Kinoshita et al. forthcoming). The data in 30 arc-second grid cells are converted into the data in half degree grid cells by summing up 60×60 30 arc-second grid cells.

2.4 Emission downscaling model

The spatial distribution of the future emissions was estimated with socio-economic data on 0.5° by 0.5° grids following methods described in Kinoshita et al. forthcoming, and Masui et al. (2009). The approach begins with an initial geospatial distribution of emissions on half degree grids for the year 2000 provided by Lamarque, et al. (2010). That distribution is updated in each subsequent period using the following method. Emission control totals are taken from the AIM/CGE [Global] model for each of its 24 regions. Beginning with the Lamarque, et al. initial map, the gridded distribution is updated in each subsequent period by distributing the change in emissions in the same proportion as the proxy variables in Table 4. The gridded changes in emissions were added to and/or subtracted from the gridded emissions for the previous time steps. If the resultant data had any grid points with a negative value, then the negative emission was set to zero at that grid point and the over-subscribed emissions were uniformly subtracted from the other grids, which contained positive emission values.

Table 4 Proxy variables for distributing the regional emissions for each sector

Sector	Proxy
Emissions from Power Plants, Energy Conversion, Extraction, and Distribution	Total population
Emissions from Solvents	GDP
Emissions from Waste (landfills, wastewater, non-energy incineration)	Total population
Emissions from Industry (combustion & processing)	GDP
Emissions from Residential and Commercial	Rural population
Emissions from Agriculture waste burning on fields	Cropland area

For the international shipping and aviation sectors, the initial spatial distributions of emissions were simply scaled with global total emissions and for the surface transport and agriculture (animals, rice and soil) sectors the initial distributions were scaled with the related sectoral emissions for each region.

2.5 Ecosystem model (VISIT)

The exchange of CO_2 between the atmosphere and terrestrial ecosystems is determined by the ecosystem model, Vegetation Integrative SImulator for Trace gases (VISIT). VISIT is the successor of Sim-CYCLE, a terrestrial carbon cycle model (Ito and Oikawa 2002; Ito 2005) used to assess emissions from biomass burning and land use change. VISIT simulates the exchange of CO_2 between the atmosphere and terrestrial ecosystem through photosynthesis and respiration, including "small" carbon fluxes such as land-use change and biomass-burning, emissions of biogenic volatile organic compounds, methane emissions, and soil carbon loss by erosion and leaching (Ito 2010). The spatial resolution of VISIT is $0.5\times0.5°$ grid cells. Its temporal resolution is monthly. The vegetation fire component for burnt area in VISIT is based on Glob-FIRM (Thonicke et al. 2001). Using the estimated monthly burnt area, emissions due to biomass burning are evaluated by considering available fuel load calculated for the grid-cell, burning efficiencies from Hoelzemann et al. (2004), and emission factors from the historical RCP emission database. The book-keeping method (Houghton et al. 1983) is used in the VISIT model to estimate carbon emissions due to net land use change. Emissions due to deforestation are estimated for the grid-cells using the land use change transition from primary and secondary land into cropland, pasture, and urban area. VISIT accounts for the delayed time decay for harvested products. In addition, absorption of carbon from regrowth of abandoned cropland and pasture is calculated using the changes in net ecosystem production following Houghton et al. (1983).

3 Reference scenario

RCP6 is a policy intervention scenario. That is, without policy intervention, modeled as a carbon tax, radiative forcing would exceed 6.0 Wm^{-2}. As a first step in the process of developing RCP6 we develop a "no-climate-policy" reference scenario. This scenario assumes that policies and measures undertaken to control other environmental problems are undertaken, but is constructed so that no policies motivated purely to control greenhouse gas emissions, beyond those already in place, are undertaken and that existing policies are not renewed when they expire. This reference scenario is constructed for comparison purposes only.

The reference scenario for RCP6 is an updated version of the SRES B2 [AIM] scenario (Nakicenovic and Swart 2000). Updates include demographic and economic assumptions. Demographic assumptions for the period to 2050 are updated to use the medium variant of UN (2007). For the period between 2050 and 2100 regional population grow rates are taken from UN (2004). In the reference scenario, the global population grows from 6.1 billion persons to 9.8 billion persons between 2000 and 2100, with a peak between 2080 and 2090. Global GDP grows from 30 trillion dollar in 2000 to 225 trillion dollars in 2100.

Primary energy supply in the world in 2100 reaches 1190 EJ/year and China becomes the biggest economy in terms of both GDP and primary energy demand. Renewable energy potential and other new technologies capacities follow the world energy outlook IEA (2008) and Masui et al. (2010). CO_2 emissions grow to 27.7GtC/year in 2100. Total radiative forcing grows from 2.0 Wm^{-2} in 2000 to 7.0 Wm^{-2} in 2100.

4 Major characteristics of the RCP6

RCP6 is obtained by imposing climate policies, as described in Section 2, to constrain radiative forcing not to exceed 6.0 Wm^{-2}. In the RCP6 scenario GHG emissions peak around 2060 and then decline, though GHG emission reductions, relative to the AIM reference scenario, start in 2010. Emissions are assumed to be limited cost-effectively in any period through a global market for emissions permits.

Radiative forcing in RCP6 is lower than in the reference scenario after 2030 (Fig. 2). For reference, RCP6 is displayed along with alternative implementations of the other RCP scenarios obtained using the AIM model and labeled AIM8.5, AIM4.5, and AIM2.6 respectively in Fig. 2. In the RCP6 scenario the global CO_2 emissions peak at 17.7 GtC/year in 2060 and diminish to 13.0 GtC/year by 2100 (Fig. 3). Although the global CO_2 emissions in 2100 in RCP6 are less than half of those in the reference scenario in 2100, they are 1.8 times greater than those in the year 2000. Cumulative CO_2 emissions reductions during the 21'st century, between the reference and RCP6 scenarios, are 463 GtC.

From the viewpoint of regional CO_2 emissions, managing emissions in Asia is of greatest importance. Rapid economic growth in Asia results in Asian CO_2 emissions exceeding 60% of the global total in 2100 in both the reference scenario and RCP6 (Fig. 4).

The global total primary energy supply in 2100 in RCP6 is 838 EJ/year. Beyond 2060 total primary energy supply growth slows (Fig. 5) while coal production declines. In

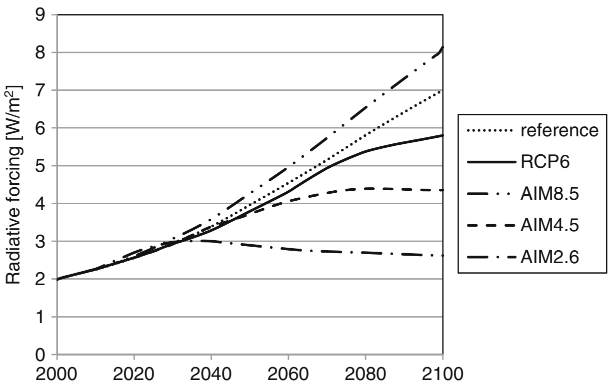
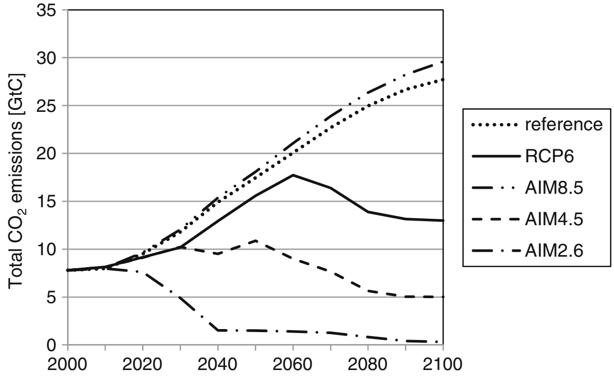


Fig. 2 Changes in radiative forcing

Fig. 3 Total CO_2 emissions in each scenario



contrast natural gas supplies increase rapidly, growing to 2.6 times their 2000 levels by 2100. The share of renewable energy (biomass, hydro, solar, wind and other renewable energy forms) rises from 12.9% in 2000 to 15.7% in 2100. Among the regions, China and India account for 39% of the global primary energy supply. As a result, Asia (excluding Middle East) consumes more than 50% of the global primary energy by the end of the 21st century (Fig. 6).

Global final energy demand (buildings, industry and transportation) increases from 297 EJ/year in 2000 to 760 EJ/year in 2100 (Fig. 7). In 2100, 172 EJ/year of the final energy is saved in RCP6 as compared with the reference case. The share of electricity in the final energy increases rapidly and reaches 47% in 2100. On the other hand, the share of solid fuels in the final energy declines during the century. As in the case of primary energy supply, the Asian share of global final energy demand exceeds 50% in 2100.

In RCP6 the power sector shifts away from coal fired production toward gas fired production (Fig. 8). The share of non-fossil fuel power plants including nuclear exceeds 30% in 2100. CO_2 emissions from electricity generation decline after 2060 in RCP6. This is the result of increased use of non-fossil energy forms and the deployment of CCS. In 2100 CCS technology is installed on 74% of the thermal power plants.

In RCP6 scenario, population and economic growth drive expansion in the built-up or urban area and in crop lands. The resulting increase in food, livestock, and energy crop demands between 2000 and 2100 drive an expansion of the cropland area by 26%, despite assumed improvements in crop yields. In RCP6 the grassland area declines by 10%, while the forested area increases marginally during the 21st century.

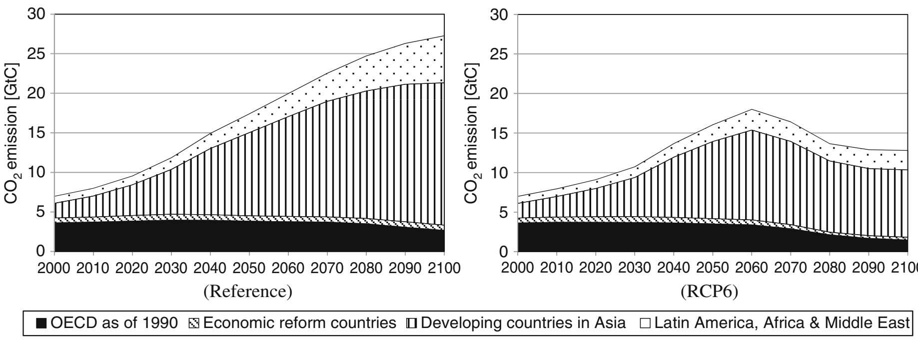


Fig. 4 CO_2 emissions for the four SRES regions

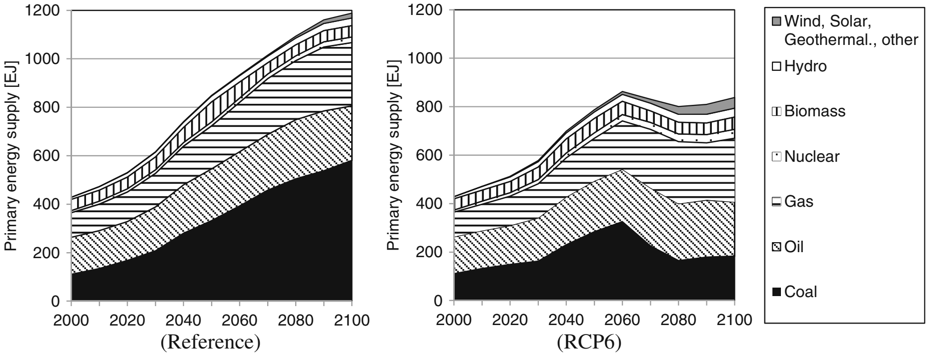


Fig. 5 Primary energy supply by sources

RCP6 and the reference produce very similar trajectories of land use, as shown in Fig. 9. Changes in cropland area and built-up or urban areas are similar in both RCP6 and the reference scenarios. Both forest area and grassland area decline over the 21st century (Fig. 9). One notable difference between the reference scenario and RCP6 is grassland and forest lands after 2060. To mitigate CH_4 emissions from livestock, the rate of expansion of the livestock herd is reduced, which in turn reduces the use of grasslands in RCP6 after 2060 compared to the reference scenario. The forested area in RCP6 increases slightly compared to the reference scenario to compensate for the slower grassland expansion.

The time path of the marginal cost of carbon or carbon price, used to control emissions of greenhouse gases in RCP6, is shown in Fig. 10. The carbon price rises sharply between 2060 and 2080, reaching $180/tC (2001 constant USD) in 2080. Beyond 2080 the RCP6 carbon price is relatively stabilize.

Carbon emissions are mitigated by shifting from coal to oil and gas, expanding the use of renewable energy options and by employing CCS in the thermal power generation. The increasing carbon price also drives a shift from industry toward service sector in RCP6. Reductions in global GDP relative to the reference scenario are single-digit percentages of GDP or smaller. In 2100, global GDP in RCP6 will be less than 3% smaller than in the reference scenario. This is equivalent to a reduction in the annual rate of GDP growth of 0.03%/year during the 21st century. If global emissions permit trade had not been

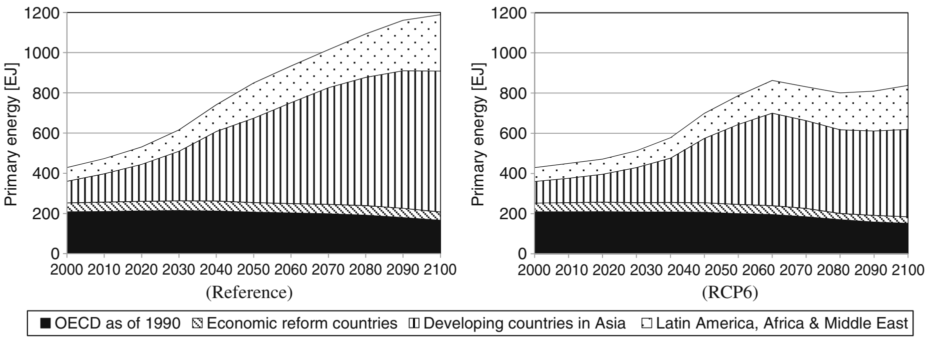


Fig. 6 Primary energy supply for the four SRES regions

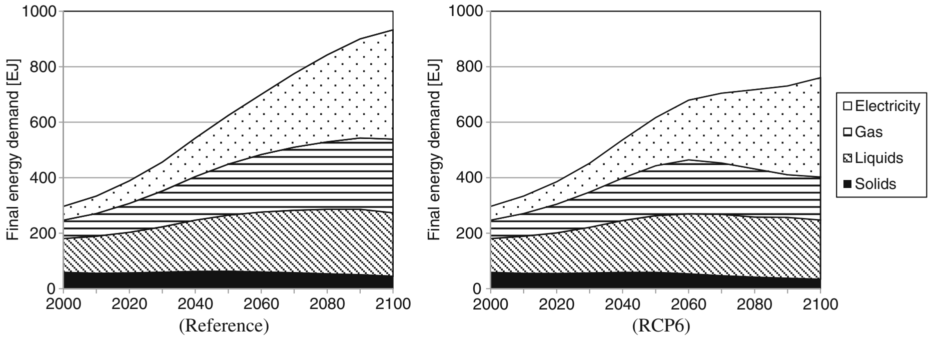


Fig. 7 Global final energy demand by energy type

introduced, global GDP reductions relative to the reference scenario would have been larger.

In RCP6 scenario global CH_4 emissions peak in 2060, and decline afterward. Figure 11 presents the spatial pattern of CH_4 emissions in 2000 and in 2100 for both RCP6 and the reference scenario. In the reference scenario, the CH_4 emissions in Brazil, India and Africa are greater in 2100 than in 2000 due to increased agricultural activities. CH_4 emissions are increase in the reference scenario in the Middle East region due increased energy sector activity. Global reference scenario N_2O emissions in 2100 are 55% greater than in the year 2000.

CH_4 and N_2O emissions from energy use decline in RCP6 relative to the reference scenario. However, CH_4 and N_2O emissions from agriculture and land use increase.

Local air pollutant emissions from SO_x and NO_x are determined by applying emissions coefficients to associated activity levels. These emissions coefficients are assumed to decline in all regions due to concerns about local air quality in both the reference scenario and RCP6. Emissions in the developed countries decline most rapidly among the regions. In Asia, emissions of SO_x and NO_x peak and decline, due to the rapid economic growth rate at the beginning of 21st century. In both the reference and RCP6 global air pollutant emissions gradually decline during the 21st century, but after 2060, the emission reduction in RCP6 becomes more rapid, as shown in Fig. 12.

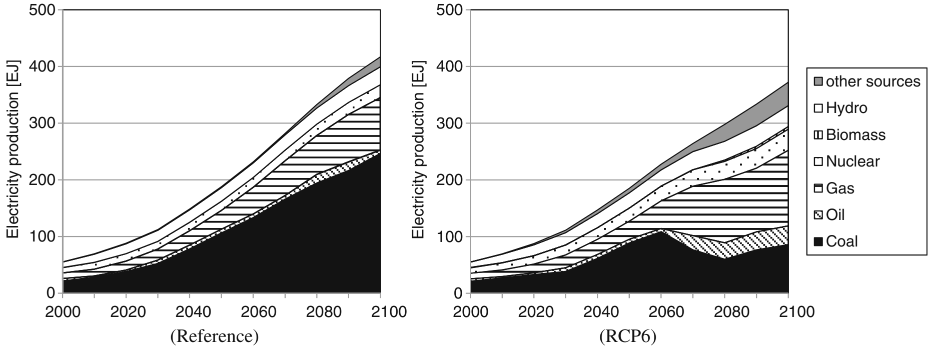


Fig. 8 Electricity generation by source

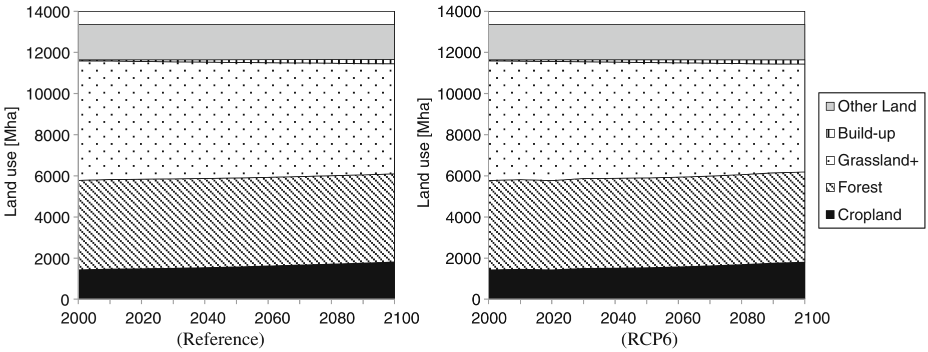


Fig. 9 Land use

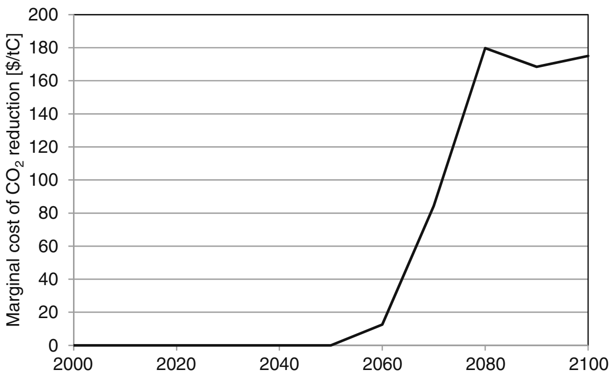
5 AIM implementation of other RCP scenarios

In addition to RCP6 the AIM modeling team has produced alternative implementations of the other three RCPs. The associated time paths for radiative forcing and CO_2 emissions are depicted in Figs. 2 and 3 respectively. In this section, we discuss some notable features that characterize the implementation in the AIM model. The AIM8.5 scenario is notable in that radiative forcing is higher than in the AIM reference scenario with its "no climate policy" assumption. By definition AIM8.5 is characterized by a level of radiative forcing of 8.5 Wm^{-2} in the year 2100, with radiative forcing still rising. In this case, the energy efficiency improvement is assumed to be smaller than in the reference scenario. Moreover, the extraction cost of coal in AIM8.5 is set lower than in the reference scenario, leading to greater coal use and higher emissions than in the reference scenario.

AIM4.5 requires the stabilization of radiative forcing in 2100 at 4.5 Wm^{-2}. Emissions mitigation is accomplished by the introduction of a global carbon tax, beginning in the year 2030. This tax is more stringent than was required in RCP6. The tax imposition first slows emissions growth relative to the reference scenario. CO_2 emissions reach their peak at approximately 10.9 GtC/year in 2050 and subsequently decline to 5.0 GtC/year in 2100.

RCP2.6 is the most stringent of the four RCPs. Not only must radiative forcing be limited to 2.6 Wm^{-2} in the year 2100, but radiative forcing must also be declining in the year 2100, though radiative forcing may exceed the target level in intermediate years. Emissions are limited in AIM2.6 by a carbon tax that is initiated immediately and rises steeply, eventually

Fig. 10 Marginal cost of CO_2 emission reduction in RCP6



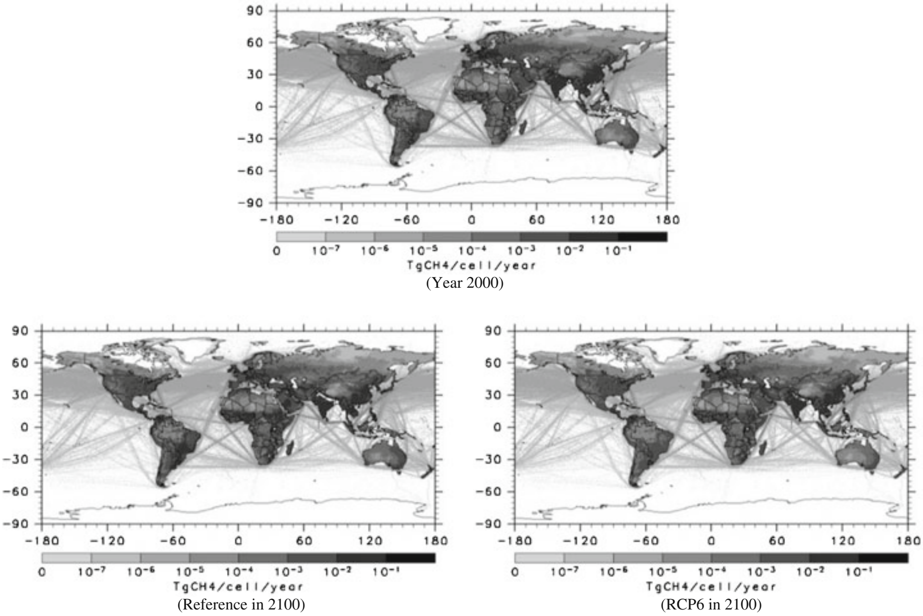


Fig. 11 The spatial distribution of CH_4 emissions

exceeding $1,000/tC (2001 constant USD). Global CO_2 emissions decline from present levels beginning immediately and fall to 0.3 GtC/year by the year 2100.

In both the AIM4.5 and AIM2.6 scenarios a broad portfolio of emissions mitigation technologies are deployed, with the deployment greatly accelerated in the AIM2.6 scenario. In both the AIM4.5 and AIM2.6 scenarios, renewable and nuclear energy production increases more aggressively than in either the reference scenario or RCP6, as does the deployment of energy conserving end-use technologies. In both scenarios CCS becomes an important element in the global energy system. Of particular interest is the expanded use of biomass energy, whose production becomes an increasingly important land use in the AIM4.5 and AIM2.6 scenarios.

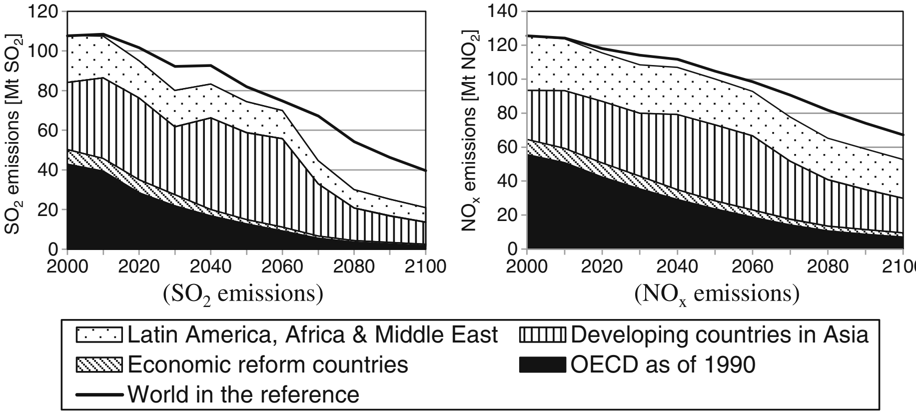


Fig. 12 The emissions of SO_x and NO_x in RCP6 (planes) and the reference (line)

Table 5 Carbon intensity change rates in AIM Reference and RCP6 Scenarios

	AIM Reference	RCP6
2000–2060	0.5%/year	0.4%/year
2060–2100	0.2%/year	−0.8%/year

(negative sign indicates rate of decline of CO_2/E)

6 Discussion and conclusions

RCP6 is a stabilization scenario. By definition radiative forcing must not exceed 6.0 Wm^{-2}. Radiative forcing in the AIM reference scenario, which includes no policies to limit greenhouse gas emissions explicitly motivated by climate change, rises to 7.0 Wm^{-2} by the year 2100. Thus, RCP6 includes explicit climate policy intervention as discussed earlier in this paper. A useful tool to help understand the mechanisms by which emissions were reduced was developed by Kaya (1989). The approach begins with the identity that CO_2 emissions can be written as the product of four terms:

$$CO_2 = (CO_2/E)*(E/GDP)*(GDP/Pop)*Pop$$

Where E is energy use, and Pop is population. The ratio CO_2/E is the average CO_2 emissions intensity of energy, E/GDP is the average energy intensity of the economy, GDP/Pop is the average per capita GDP, and Pop is the aggregate population of the region.

The instantaneous growth rate of CO_2 emissions can be written as the sum of the instantaneous rates of growth of the four diagnostic terms:

$$r_{CO2} = r_{CO2/E} + r_{E/GDP} + r_{GDP/Pop} + r_{Pop}$$

and, the difference between the AIM reference scenario and RCP6 can be thought of as literally the difference in the rates of growth of the four diagnostic terms.

Because global CO_2 emissions in RCP6 peak around 2060 and then decline through the rest of the century, we will focus on behavior of RCP6 relative to the reference scenario before and after the year 2060. Both AIM reference and RCP6 are assumed to share a common population scenario. The average annual global changes in GDP per capita are also similar between the two scenarios; 1.6% during 2000–2060 and 1.3–1.4% during 2060–2100. Carbon intensity change rates are shown in Table 5.

Positive values indicate increasing carbon intensity of average energy. This reflects a shift toward higher carbon-intensity fossil fuels such as coal, particularly prior to 2060. Energy use continues to become more carbon-intensive in the AIM reference scenario, but drops dramatically in RCP6.

The annual change in energy intensity improves, that is E/GDP declines, in both the AIM reference and RCP6 scenarios (Table 6). Note that while the rate of energy intensity

Table 6 Energy intensity change rates in AIM Reference and RCP6 Scenarios

	AIM Reference	RCP6
2000–2060	−1.1%/year	−1.2%/year
2060–2100	−0.9%/year	−1.5%/year

(negative sign indicates rate of decline of E/GDP) improvement in RCP6 is faster than in AIM reference both before and after 2060, the rate of improvement in RCP6 is dramatically faster than in AIM reference after 2060.

Growth rates for CO_2 emissions and the four diagnostic components of the Kaya identify are shown graphically in Fig. 13, below, for the world and four sub-regions, as defined in Nakicenovic and Swart (2000). Regional differences in economic growth and technology availability lead to patterns of change that differ from region to region, as shown in Fig. 13.

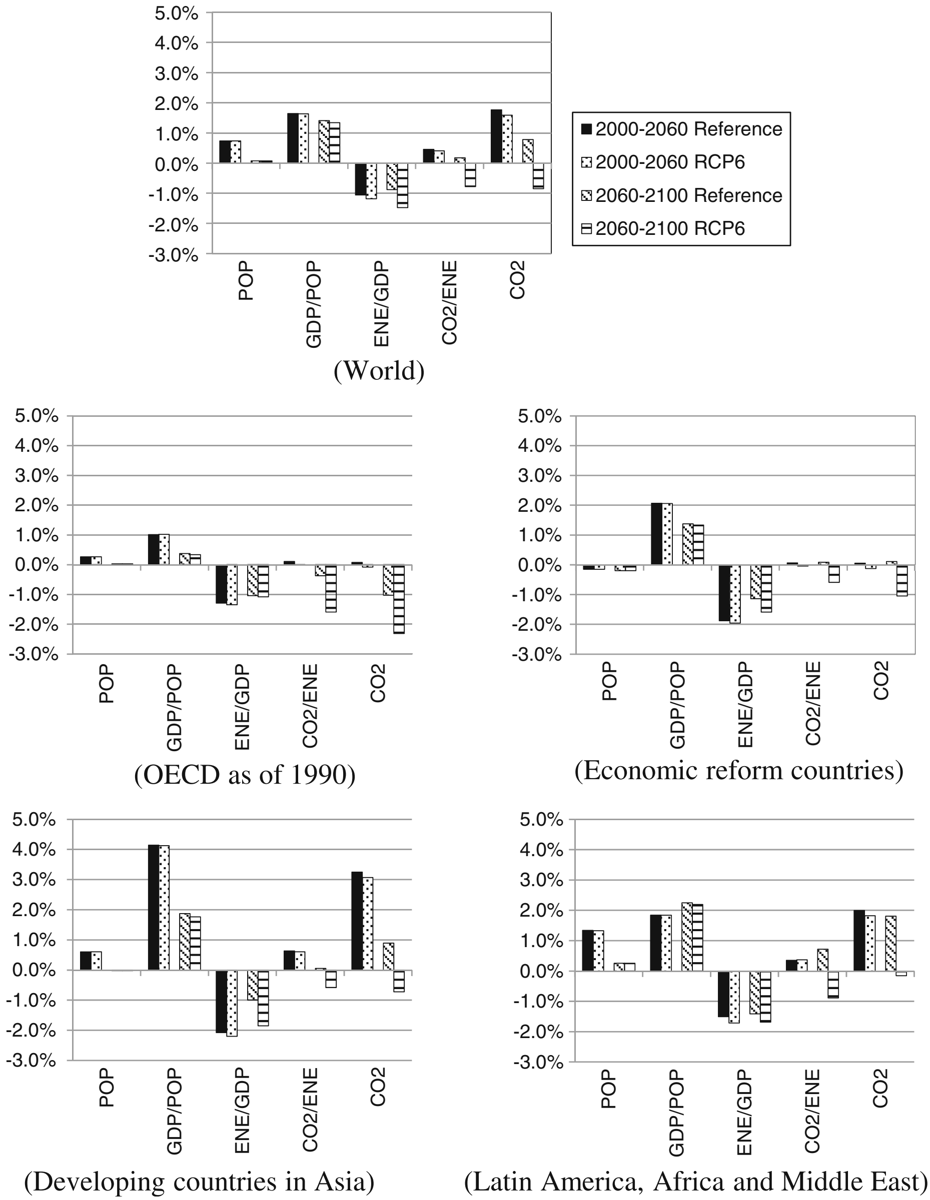


Fig. 13 Change of factors in Kaya Identity

OECD countries as of 1990 reduces its CO_2 emissions most rapidly after 2060, more than 2%/year. In Latin America, Africa and Middle East, the annual CO_2 reduction rate between 2060 and 2100 is 0.1%/year, while the rate is 0.7%/year in Asia. In the post-2060 period carbon-intensity improvements are more rapid than energy-intensity improvements in Asia. This contrasts to other regions for which, energy-intensity improves at a rate faster than 1.5%/year between 2060 and 2100. As a result, in those other regions, the contribution of the energy intensity improvement is greater than that of the carbon intensity improvement.

RCP6 is but one possible emissions path by which the world could arrive in the year 2100 with a radiative forcing level of 6.0 Wm^{-2}. Other papers in this volume exhibit alternative implementations of a scenario leading to 6 W/m^2, each of which differs in its detail from RCP6. But those four scenarios themselves only begin to explore the potential variety of the ways in which the world might evolve. Expanding the set of models producing alternative implementations of the RCP6 would expand the set of pathways to 6.0 Wm^{-2}. Beyond that, each scenario includes numerous assumptions about regional and global population, economic activity, technology, and policy. Changing any of these will change the pathway by which radiative forcing is limited to 6.0 Wm^{-2}.

Finally, we note that although mitigation of reference scenario emissions are required to achieve RCP6, that emissions mitigation is very modest prior to 2060. Furthermore, the CO_2-equivalent concentration limit for RCP6 is 855 ppm, taking RCP6 outside the range of most policy discussions. While not explicitly modeled in the development of RCP6, climate change would accompany this scenario. Depending on the climate sensitivity and the magnitude of the buffering capacity provided by the oceans, climate change could be very large by the year 2100. Climate change could be anticipated to feedback on emissions mitigation activities through numerous pathways ranging from the ease or difficulty of maintaining and expanding forests and growing bioenergy to building demands for space conditioning to the need to divert resources to adapt to the changing climate.

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