Chapters

1 Introductory Chapter

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Contents

Executive Summary

Since the first Intergovernmental Panel on Climate Change (IPCC) assessment report (FAR) (IPCC, 1990a), the quantity and depth of scientific research on climate change mitigation has grown enormously. In tandem with scholarship on this issue, the last two decades have seen relatively active efforts around the world to design and adopt policies that control ('mitigate') the emissions of pollutants that affect the climate. The effects of those emissions are felt globally; mitigation thus involves managing the global commons and requires a measure of international coordination among nations. But the actual policies that lead to mitigation arise at the local and national levels as well as internationally. Those policies have included, among others, market-based approaches such as emission trading systems along with regulation and voluntary initiatives; they encompass many diverse economic development strategies that countries have adopted with the goal of promoting human welfare and jobs while also achieving other goals such as mitigating emissions of climate pollutants. These policies also include other efforts to address market failures, such as public investments in research and development (R&D) needed to increase the public good of knowledge about new less emission-intensive technologies and practices. International diplomacy—leading to agreements such as the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol as well as various complementary initiatives such as the commitments pledged at the Copenhagen and Cancun Conferences of the Parties—has played a substantial role in focusing attention on mitigation of greenhouse gases (GHGs).

The field of scientific research in this area has evolved in parallel with actual policy experience allowing, in theory, insights from each domain to inform the other. Since the 4th assessment report (AR4) of IPCC (2007a; b) there have been numerous important developments in both the science and practical policy experience related to mitigation. There is growing insight into how climate change mitigation policies interact with other important social goals from the local to the national and international levels. There is also growing practical experience and scholarly research concerning a wide array of policy instruments. Scholars have developed much more sophisticated information on how public opinion influences the design and stringency of climate change mitigation policies.

Meanwhile, events in the world have had a large impact on how scientific researchers have seen the scale of the mitigation challenge and its practical policy outcomes. For example, a worldwide economic recession beginning around 2008 has affected patterns of emissions and investment in the world economy and in many countries has affected political priorities on matters related to climate change mitigation.

The present chapter identifies six conclusions. Where appropriate, we indicate not only the major findings but also our confidence in the finding and the level of supporting evidence. (For an overview of the language on agreement and confidence see Mastrandrea et al. (2011).

First, since AR4, annual global GHG emissions have continued to grow and reached 49.5 billion tonnes (giga tonnes or Gt) of carbon dioxide equivalents (CO_2eq) in the year 2010, higher than any level prior to that date, with an uncertainty estimate at ±10 % for the 90 % confidence interval. On a per-capita basis, emissions from industrialized countries that are listed in Annex I of the UNFCCC are on average 2.5 times of those from developing countries. However, since AR4, total emissions from countries not listed in Annex I have overtaken total emissions from the Annex I industrialized countries (see glossary for Annex I countries). Treating the 27 members of the EU as a single country, about ten large countries—from the industrialized and developing worlds—account for 70 % of world emissions. (*robust evidence, high agreement*) [Section 1.3]. The dominant driving forces for anthropogenic emissions include population, the structure of the economy, income and income distribution, policy, patterns of consumption, investment decisions, individual and societal behaviour, the state of technology, availability of energy resources, and land-use change. In nearly all countries it is very likely that the main short-term driver of changes in the level of emissions is the overall state of the economy. In some countries there is also a significant role for climate policies focused on controlling emissions. (*medium evidence, medium agreement*) [1.3]

Second, national governments are addressing climate change in the context of other national priorities, such as energy security and alleviation of poverty. In nearly all countries the most important driving forces for climate policy are not solely the concern about climate change. (*medium evidence, medium agreement*) [1.2 and 1.4]. Studies on policy implementation show that improvements to climate policy programs need to engage these broader national priorities. Despite the variety of existing policy efforts and the existence of the UNFCCC and the Kyoto Protocol, GHG emissions have grown at about twice the rate in the recent decade (2000–2010) than any other decade since 1970. (*robust evidence, high agreement*) [1.3.1]

Third, the current trajectory of global annual and cumulative emissions of GHGs is inconsistent with widely discussed goals of limiting global warming at 1.5 to 2 degrees Celsius above the pre-industrial level (*medium evidence, medium agreement*). [1.2.1.6 and 1.3.3] The ability to link research on mitigation of emissions to actual climate outcomes, such as average temperature, has not substantially changed since AR4 due to a large number of uncertainties in scientific understanding of the physical sensitivity of the climate to the build-up of GHGs discussed in Working Group I of the IPCC (WGI). Those physical uncertainties are multiplied by the many socioeconomic uncertainties that affect how societies would respond to emission control policies (*low evidence, high agreement*). Acknowledging these uncertainties, mitigating emissions along a pathway that would be cost-effective and consistent with likely avoiding warming of more than 2 degrees implies that nearly all governments promptly engage in international cooperation, adopt stringent national and international emission control policies, and deploy rapidly a wide array of low- and zero-emission technologies. Modelling studies that adopt assumptions that are less ideal—for example, with international cooperation that emerges slowly or only restricted availability of some technologies—show that achieving this 2 degree goal is much more costly and requires deployments of technology that are substantially more aggressive than the least-cost strategies (*robust evidence, medium agreement*) [1.3.3]. The assumptions needed to have a likely chance of limiting warming to 2 degrees are very difficult to satisfy in real world conditions (*medium evidence; low agreement*). The tenor of modelling research since AR4 suggests that the goal of stabilizing warming at 1.5 degrees Celsius is so challenging to achieve that relatively few modelling studies have even examined it in requisite detail (*low evidence, medium agreement*) [1.3.3].

Fourth, deep cuts in emissions will require a diverse portfolio of policies, institutions, and technologies as well as changes in human behaviour and consumption patterns (*high evidence; high agreement*). There are many different development trajectories capable of substantially mitigating emissions; the ability to meet those trajectories will be constrained if particular technologies are removed from consideration. It is virtually certain that the most appropriate policies will vary by sector and country, suggesting the need for flexibility rather than a singular set of policy tools. In most countries the actors that are relevant to controlling emissions aren't just national governments. Many diverse actors participate in climate policy from the local to the global levels—including a wide array of nongovernmental organizations representing different environmental, social, business and other interests. (*robust evidence, medium agreement*) [1.4]

Fifth, policies to mitigate emissions are extremely complex and arise in the context of many different forms of uncertainty. While there has been much public attention to uncertainties in the underlying science of climate change—a topic addressed in detail in the WGI and II reports—profound uncertainties arise in the socioeconomic factors addressed here in WGIII. Those uncertainties include the development and deployment of technologies, prices for major primary energy sources, average rates of economic growth and the distribution of benefits and costs within societies, emission patterns, and a wide array of institutional factors such as whether and how countries cooperate effectively at the international level. In general, these uncertainties and complexities multiply those already identified in climate science by WGI and WGII. The pervasive complexities and uncertainties suggest that there is a need to emphasize policy strategies that are robust over many criteria, adaptive to new information, and able to respond to unexpected events. (*medium evidence, medium agreement*) [1.2].

Sixth, there are many important knowledge gaps that additional research could address. This report points to at least two of them. First is that the scholarship has developed increasingly sophisticated techniques for assessing risks, but so far those risk management techniques have not spread into widespread use in actual mitigation strategies. Risk management requires drawing attention to the interactions between mitigation and other kinds of policy responses such as adaptation to climate change; they require more sophisticated understanding of how humans perceive risk and respond to different kinds of risks. And such strategies require preparing for possible extreme climate risks that may implicate the use of geoengineering technologies as a last resort in response to climate emergencies (*limited evidence, low agreement*). Second, the community of analysts studying mitigation has just begun the process of examining how mitigation costs and feasibility are affected by 'real world' assumptions such as possible limited availability of certain technologies. Improving this line of research could radically improve the utility of studies on mitigation and will require integration of insights from a wide array of social science disciplines, including economics, psychology, political science, sociology and others.

1.1 Introduction

Working Group III (WGIII) of the Intergovernmental Panel on Climate Change (IPCC) is charged with assessing scientific research related to the mitigation of climate change. 'Mitigation' is the effort to control the human sources of climate change and their cumulative impacts, notably the emission of greenhouse gases (GHGs) and other pollutants, such as black carbon particles, that also affect the planet's energy balance. Mitigation also includes efforts to enhance the processes that remove GHGs from the atmosphere, known as sinks (see glossary (Annex I) for definition). Because mitigation lowers the anticipated effects of climate change as well as the risks of extreme impacts, it is part of a broader policy strategy that includes adaptation to climate impacts—a topic addressed in more detail in WGII. There is a special role for international cooperation on mitigation policies because most GHGs have long atmospheric lifetimes and mix throughout the global atmosphere. The effects of mitigation policies on economic growth, innovation, and spread of technologies and other important social goals also implicate international concern because nations are increasingly inter-linked through global trade and economic competition. The economic effects of action by one nation depend, in part, on the action of others as well. Yet, while climate change is fundamentally a global issue, the institutions needed for mitigation exist at many different domains of government, including the local and national level.

This chapter introduces the major issues that arise in mitigation policy and also frames the rest of the WGIII Contribution to the AR5. First we focus on the main messages since the publication of AR4 in 2007 (Section 1.2). Then we look at the historical and future trends in emissions and driving forces, noting that the scale of the mitigation challenge has grown enormously since 2007 due to rapid growth of the world economy and the continued lack of much overt effort to control emissions. This trend raises questions about the viability of widely discussed goals such as limiting climate warming to 2 degrees Celsius since the pre-industrial period (Section 1.3). Then we look at the conceptual issues—such as sustainable development, green growth, and risk management—that frame the mitigation challenge and how those concepts are used in practice (Section 1.4). Finally, we offer a roadmap for the rest of the volume (Section 1.5).

1.2 Main messages and changes from previous assessment

Since AR4, there have been many developments in the world economy, emissions, and policies related to climate change. Here we review six of the most consequential trends and then examine their implications for this Fifth Assessment Report by the IPCC (AR5).

1.2.1 Sustainable development

Since AR4 there has been a substantial increase in awareness of how climate change interacts with the goal of sustainable development (see Chapter 4 in this volume and WGII Chapter 20). While there is no single widely accepted definition of sustainable development, the concept implies integrating economic growth with other goals such as eradication of poverty, environmental protection, job creation, security, and justice (World Commission on Environment and Development, 1987; UNDP, 2009; ADB et al., 2012; OECD, 2012; ILO, 2012; United Nations, 2012). Countries differ enormously in which of these elements they emphasize, and for decades even when policymakers and scientific analysts have all embraced the concept of sustainable development they have implied many different particular goals. Since AR4, new concepts have emerged that are consistent with this broader paradigm, such as 'green growth' and 'green economy'—concepts that also reflect the reality that policy is designed to maximize multiple objectives. The practical implications of sustainable development are defined by societies themselves. In many respects, this multi-faceted understanding of sustainable development is not new as it reflects the effort in the social sciences over the last century to develop techniques for measuring and responding to the many positive and negative externalities that arise as economies evolve—concepts discussed in more detail in Chapter 3 of this volume.

New developments since AR4 have been the emergence of quantitative modelling frameworks that explore the synergies and tradeoffs between the different components of sustainable development including climate change (e.g., McCollum et al., 2011; Riahi et al., 2012; Howells et al., 2013).

Scientific research has examined at least three major implications of sustainable development for the mitigation of emissions. First, since AR4 there have been an exceptionally large number of studies that have focused on how policies contribute to particular elements of sustainable development. Examples include:

- The ways that biofuel programs have an impact on poverty alleviation, employment, air quality, rural development, and energy/ food security (see 11.13), such as in Brazil (La Rovere et al., 2011) and the United States (Leiby and Rubin, 2013).
- The socioeconomic implications of climate and energy policies in the EU (Böhringer and Keller, 2013; Boussena and Locatelli, 2013).
- The impacts of Chinese energy efficiency targets on the country's emissions of warming gases (Hu and Rodriguez Monroy, 2012; Paltsev et al., 2012) and the evolution of energy technologies (Xie, 2009; Zhang, 2010; Guo, 2011; Ye, 2011; IEA, 2013).
- The government of India's Jawaharlal Nehru National Solar Mission (JNNSM) that utilizes a wide array of policies with the goal of making solar power competitive with conventional grid power by 2022 (Government of India, 2009).
- The Kyoto Protocol's Clean Development Mechanism (CDM), which was explicitly designed to encourage investment in projects that mitigate GHG emissions while also advancing sustainable development (UNFCCC, 2012d; Wang et al., 2013). Since AR4, researchers have examined the extent to which the CDM has actually yielded such dividends for job creation, rural development, and other elements of sustainable development (Rogger et al., 2011; Subbarao and Lloyd, 2011).

Chapters in this report that cover the major economic sectors (Chapters 7–11) as well as spatial development (Chapter 12) examine such policies. The sheer number of policies relevant to mitigation has made it impractical to develop a complete inventory of such policies let alone a complete systematic evaluation of their impacts. Since AR4, real world experimentation with policies has evolved more rapidly than careful scholarship can evaluate the design and impact of such policies.

A second consequence of new research on sustainable development has been closer examination of the interaction between different policy instruments. Since the concept of sustainable development implies a multiplicity of goals and governments aim to advance those goals with a multiplicity of policies, the interactions between policy interventions can have a large impact on the extent to which goals are actually achieved. Those interactions can also affect how policy is designed, implemented, and evaluated—a matter that is examined in several places in this report (Chapters 3–4, 14–15).

For example, the European Union (EU) has implemented an Emission Trading Scheme (ETS) that covers about half of the EU's emissions, along with an array of other policy instruments. Since AR4 the EU has expanded the ETS to cover aviation within the EU territory. Some other EU policies cover the same sectors that are included in the ETS (e.g., the deployment of renewable energy supplies) as well as sectors that are outside the ETS (e.g., energy efficiency regulations that affect buildings or agricultural policies aimed at promoting carbon sinks). Many of these policies adopted in tandem with the ETS are motivated by policy goals, such as energy security or rural economic development, beyond just concern about climate change. Even as the price of emission credits under the ETS declined since AR4—implying that the ETS itself was having a less binding impact on emissions—the many other mitigation-related policies have remained in place (Chapters 14 and 15).

Such interactions make it impossible to evaluate individual policies in isolation from other policies that have overlapping effects. It has also given rise to a literature that has grown substantially since AR4 that explores how policies and measures adopted for one purpose might have the 'co-benefit' of advancing other goals as well. Most of that literature has looked at non-monetary co-benefits (see Sections 5.7, 7.9, 8.7, 9.7, 10.8, 11.7, 11.A.6)—for example, an energy efficiency policy adopted principally with the goal of advancing energy security might also lead to lower emissions of GHGs or other pollutants. The concept of co-benefits, however, has also raised many challenges for economic evaluation of policies, and since AR4 there have been substantial efforts to clarify how the interactions between policies influence economic welfare. Such research has underscored that while the concept of 'co-benefits' is widely used to create the impression that policies adopted for one goal yield costless improvements in other goals, the interactions can also yield adverse side-effects (see Sections 3.6.3, 4.2 and 6.6).

Third, the continued interest in how climate change mitigation interacts with goals of sustainable development has also led to challenging new perspectives on how most countries mobilize the political, financial, and administrative resources needed to mitigate emissions. More than two decades ago when the topic of climate change was first extensively debated by policymakers around the world, most scholarship treated GHG emissions as an externality that would require new policies designed explicitly with the goal of controlling emissions. Concerns about climate change would lead to policy outcomes tailored for the purpose of mitigation, and those outcomes would interact with the many other goals of sustainable development. Since AR4 policy experience and scholarship have focused on a different perspective—that for most countries a substantial portion of 'climate policy' would emerge as a derivative of other policies aimed at the many facets of sustainable development. A range of policy interventions were identified in theory to enable integration and optimization of climate change policies with other priorities such as land use planning and protection of water resources (Muller, 2012; Pittock et al., 2013; Dulal and Akbar, 2013). Similarly, many of the policies that would reduce emissions of GHGs could also have large beneficial effects on public health (Ganten et al., 2010; Li and Crawford-Brown, 2011; Groosman et al., 2011; Haines, 2012) (see Sections 6.6, 7.9.2 and WGII 11.9).

These new perspectives on the interactions between climate change and sustainable development policies have led to a more realistic view of how most governments are addressing the challenges of mitigation. However, since AR4 it has also become clear that the totality of the global effort remains inconsistent with widely discussed goals for protecting the climate, such as limiting warming to 1.5 or 2 degrees Celsius. Despite the slowing down of emissions growth rate in the wake of the global financial crisis, annual volume of total emissions from emerging countries has been surging from the new century (see Section 1.3 for more details). And the mitigation progress in the developed world is slower than expectation, especially when carbon emissions embodied in trade is considered (Steinberger et al., 2012; Aichele and Felbermayr, 2012). Moreover, per capita energy consumption and emissions of some developing countries remain far lower than that of developed countries, suggesting that per capita emissions will rise as economies converge (Olivier et al., 2012).

1.2.2 The world macroeconomic situation

Shortly after the publication of AR4 in 2007, the world encountered a severe and deep financial crisis (Sornette and Woodard, 2010). The crisis, which spread rapidly in the second half of 2008, destabilized many of the largest financial institutions in the United States, Europe, and Japan, and shocked public confidence in the global financial system. The crisis also wiped out an estimated USD 25 trillion in value from the world's publicly traded companies, with particularly severe effects on banks (Naudé, 2009; IMF, 2009). The effects of the crisis are evident in economic growth—shown in Figure 1.1. The year 2009 witnessed the first contraction in global GDP since the Second World War (Garrett, 2010). International trade of goods and services had grown rapidly since the turn of the millennium—from 18 % of world GDP in 2000 to 28 % in 2008 (WTO, 2011). The crises caused global trade to drop to 22 % in 2009 before rebounding to 25 % in 2010. The effects of the recent economic crisis have been concentrated in the advanced industrialized countries (te Velde, 2008; Lin, 2008; ADB, 2009, 2010). While this particular crisis has been large, studies have shown that these events often recur, suggesting that there is pervasive over-confidence that policy and investment strategies can eliminate such cyclic behaviour (Reinhart and Rogoff, 2011).

Figure 1.1 reveals that countries were affected by the global economic crisis in different ways. The recessions were generally most severe in the advanced industrialized countries, but the contagion of recessions centred on the high income countries has spread, especially to countries with small, open, and export-oriented economies—in large part due to the decline in exports, commodity prices, and associated revenues. The crisis has also affected foreign direct investment (FDI) and official development assistance (ODA) (IMF, 2009, 2011) with few exceptions such as in the area of climate change where ODA for climate mitigation and adaptation increased substantially until 2010 before a decline in 2011 (OECD, 2013). The crisis also had substantial effects on unemployment across most of the major economies and on public budgets. The slow recovery and deceleration of import demand from key advanced economies continued to contribute to the noticeable slowdown in the emerging market and developing economies during 2012 (IMF, 2013). As well, some of the major emerging market economies suffered from the end of their national investment booms (IMF, 2013).

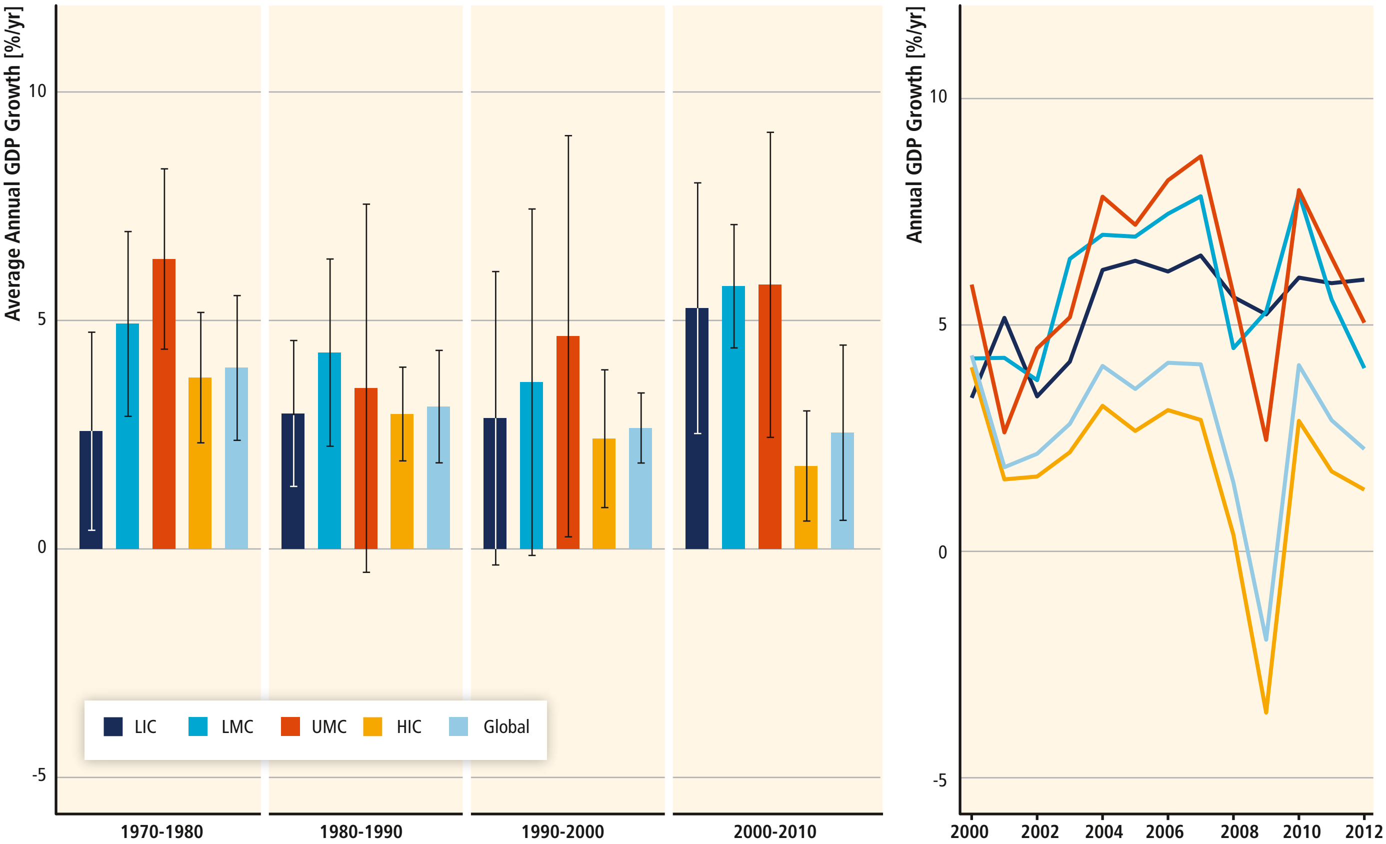


Figure 1.1 | Annual real growth rates of GDP by decade (left panel) and since 2000 (right panel) for four groups of countries as defined by the World Bank (World Bank, 2013): high-income, mature industrialized countries (HIC), upper-middle-income countries (UMC), lower-middle-income (LMC), and low-income countries (LIC) and globally. The category of 49 least developed countries (LDCs) as defined according to the United Nations (United Nations, 2013b) overlaps heavily with the 36 countries that the World Bank classifies as 'low-income'. Estimates weighted by economic size and variations to one standard deviation are shown. Growth rates weighted by size of the economy; whiskers on the decadal averages (left panel) show variation to one standard deviation within each category and decade. Sources: MER converted real growth rates from World Bank (2013) and IMF (2013b).

The continued growth of developing economies, albeit at a slower pace than before the crisis, helps to explain why global commodity prices, such as for oil and metals, have quickly rebounded (see Figure 1.2). Another factor that helps explain continued high prices for some commodities are reductions in supply in response to weakening demand. Among the many implications of high and volatile commodity prices are continued concerns about the availability and security of energy and food supply, especially in the least-developed countries. Those concerns have also reshaped, to some degree, how problems such as global climate change are viewed in many countries and societies. Where climate change mitigation has linked to these broader economic and energy security concerns it has proven politically easier to mobilize action; where they are seen in conflict the other economic and security priorities have often dominated (Chandler et al. 2002; IEA 2007; ADB 2009).

The implications of these macroeconomic patterns are many, but at least five are germane to the challenges of climate change mitigation:

- First, the momentum in global economic growth has shifted to the emerging economies—a pattern that was already evident in the 2000s before the crisis hit. Although accelerated by the recent financial crisis, this shift in production, investment, and technology to emerging economies is a phenomenon that is consistent with the expectation that in a globalized world economy capital resources will shift to emerging economies if they can be used with greater marginal productivity commensurate with associated risks (Zhu, 2011). With that shift has been a shift in the growth of greenhouse gas emissions to these emerging economies as well.

- Second, much of this shift has arisen in the context of globalization in investment and trade, leading to higher emissions that are 'embodied' in traded goods and services, suggesting the need for additional or complementary accounting systems that reflect the ultimate consumption of manufacturing goods that cause emissions rather than just the territorial place where emissions occurred during manufacturing (Houser et al., 2008; Davis and Caldeira, 2010; Peters et al., 2011, 2012a) (see also Chapter 5).

- Third, economic troubles affect political priorities. As a general rule, hard economic times tend to focus public opinion on policies that yield immediate economic benefits that are realized close to home

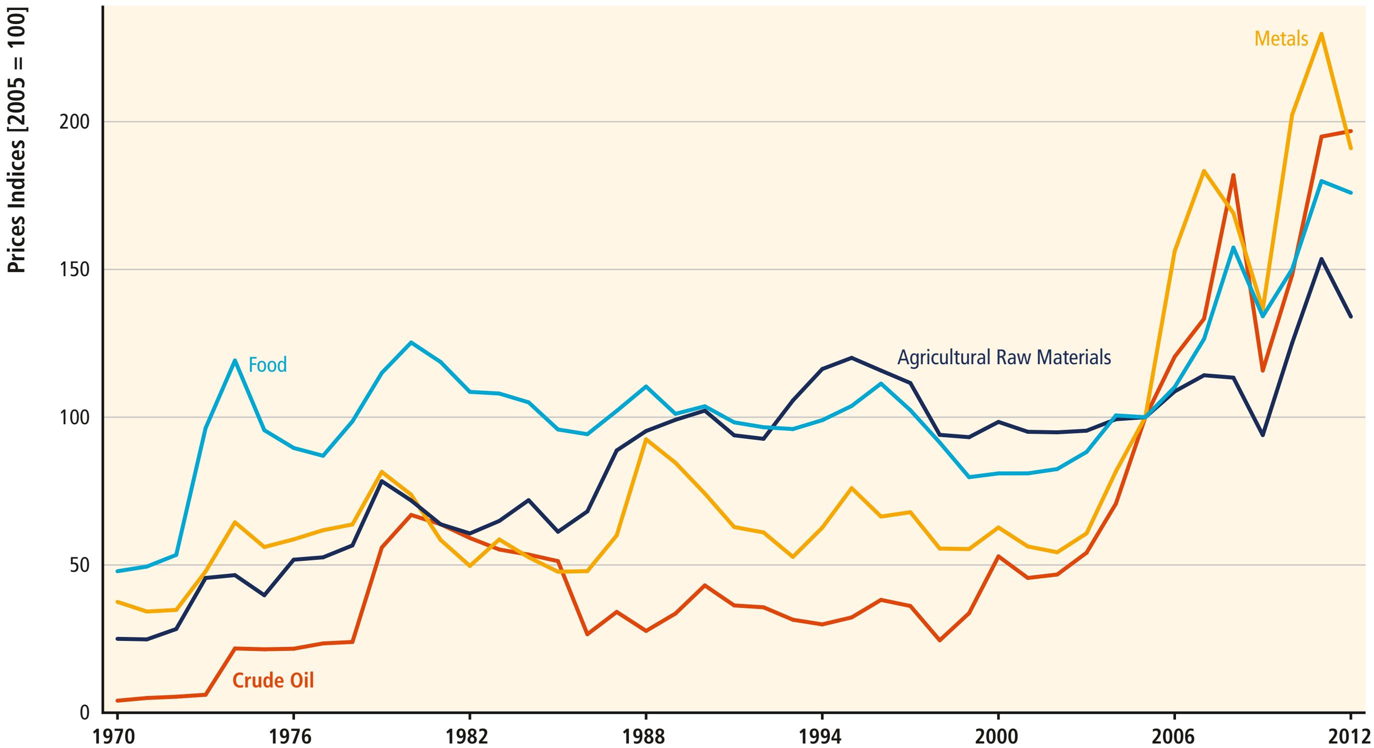


Figure 1.2 | Price indices for four major baskets of commodities: agricultural raw materials, food, crude oil, and metals. Source: IMF (2013a).

(Kahler and Lake, 2013). Long-term goals, such as global climate protection, suffer unless they are framed to resonate with these other, immediate goals. Chapter 2 of this volume looks in more detail at the wider array of factors that affect how humans perceive and manage risks that are spread out over long time horizons.

- Fourth, economic slowdown may also reduce the rate of technological progress that contributes to addressing climate change, such as in energy efficiency (Bowen et al., 2009), but for alternative views, see (Peters et al., 2012b). The crisis also has accelerated shifts in the global landscape for innovation (Gnamus, 2009). The largest emerging economies have all built effective systems for innovation and deployment of new technologies—including low emission technologies. Thus 'technology transfer' now includes 'South-South' although a central role remains for 'North-South' diffusion of technologies as part of a global effort to mitigate emissions (see also Chapters 5 and 16).

- Fifth, commodity prices remain high and volatile despite sluggish economic growth in major parts of the world economy. High costs for food have amplified concerns about competition between food production and efforts to mitigate emissions, notably through the growing of bioenergy crops (see 11.13). High prices for fossil fuels along with steel and other commodities affect the cost of building and operating different energy systems, which could in turn affect mitigation since many of the options for cutting emissions (e.g., power plants with carbon capture and storage technology) are relatively intensive users of steel and concrete. Relatively expensive energy will, as well, encourage conservation and efficiency. Since AR4 there have been substantial changes in the availability, cost, and performance of energy systems—a topic to which we now turn.

1.2.3 The availability, cost and performance of energy systems

The purpose of energy systems—from resource extraction to refining and other forms of conversion, to distribution of energy services for final consumption—is to provide affordable energy services that can catalyze economic and social development. The choice of energy systems depends on a wide array of investment and operating costs, the relative performance of different systems, infrastructures, and lifestyles. These choices are affected by many factors, such as access to information, status, access to technology, culture, price, and performance (Garnaut, 2011). The assessment of different energy options depends critically on how externalities, such as pollution, are included in the calculations.

Following a decade of price stability at low levels, since 2004 energy prices have been high and volatile (see Figure 1.2). Those prices have gone hand-in-hand with substantial geopolitical consequences that have included a growing number of oil importing countries focusing on policies surrounding energy security (e.g., Yergin, 2011). Some analysts interpret these high prices as a sign of imminent 'peak production' of exhaustible resources with subsequent steady decline, while others have argued that the global fossil and fissile resource endowment is plentiful (Rogner, 2012). Concerns about the scarcity of resources have traditionally focused on oil (Aleklett et al., 2010), but more recently the notions of peak coal (Heinberg and Fridley, 2010), peak gas, and peak uranium (EWG, 2006) have also entered the debate (see 7.4).

Sustained high prices have encouraged a series of technological innovations that have created the possibility of large new supplies from unconventional resources (e.g., oil sands, shale oil, extra-heavy oil, deep gas, coal bed methane (CBM), shale gas, gas hydrates). By some estimates, these unconventional oil and gas sources have pushed the 'peak' out to the second half of the 21st century (GEA, 2012), and they are a reminder that 'peak' is not a static concept. These unconventional sources have raised a number of important questions and challenges, such as their high capital intensity, high energy intensity (and cost), large demands on other resources such as water for production and other potential environmental consequences. Consequently, there are many contrasting viewpoints about the future of these unconventional resources (e.g., Hirsch et al., 2006; Smil, 2011; IEA, 2012a; Jordaan, 2012; Rogner et al., 2012).

The importance of these new resources is underscored by the rapid rise of unconventional shale gas supplies in North America—a technology that had barely any impact on gas supplies at the time that the AR4 was being finalized in 2006, but that by 2010 accounted for one-fifth of North American gas supply with exploratory drilling elsewhere in the world now under way. This potential for large new gas supplies—not only from shale gas but also coal-bed methane, deep gas, and other sources—could lower emissions where gas competes with coal if gas losses and additional energy requirements for the fracturing process can be kept relatively small. (A modern gas-fired power plant emits about half the CO_2 per unit of electricity than a comparable coal-fired unit.) In the United States, 49 % of net electricity generation came from coal in 2006; by 2011 that share had declined to 43 % and by 2012 that share had declined to 37 % and could decline further as traditional coal plants face new environmental regulations as well as the competition from inexpensive natural gas (EIA, 2013a; b; d). Worldwide, however, most baseline projections still envision robust growth in the utilization of coal, which already is one of the fastest growing fuels with total consumption rising 50 % between 2000 and 2010 (IEA, 2011a). The future of coal hinges, in particular, on large emerging economies such as China and India as well as the diffusion of technologies that allow coal combustion with lower emissions (GEA, 2012).

An option of particular interest for mitigating emissions is carbon dioxide capture and storage (CCS), which would allow for the utilization of coal while cutting emissions. Without CCS or some other advanced coal combustion system, coal is the most emission intensive of all the major fossil fuels yet, as we discuss below, consumption of coal is expanding rapidly. Thus, since AR4, CCS has figured prominently in many studies that look at the potential for large cuts in global emissions (IEA, 2010a, 2011b; GEA, 2012). However, CCS still has not attracted much tangible investment. By mid-2012 there were eight large-scale projects in operation globally and a further eight under construction. The total CO_2 emissions avoided by all 16 projects in operation or under construction will be about 36 million tonnes a year by 2015, which is less than 0.1 % of total expected world emissions that year (Global CCS Institute, 2012). CCS is much discussed as an option for mitigation but not much deployed. The fuller implementation of large-scale CCS systems generally requires extensive funding and an array of complementary institutional arrangements such as legal frameworks for assigning liability for long-term storage of CO_2. Since AR4, studies have underscored a growing number of practical challenges to commercial investment in CCS (IEA 2010b) (see also Chapter 7).

Since AR4, innovation and deployment of renewable energy supplies has been particularly notable (IEA, 2012a; GEA, 2012). The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011) provides a comprehensive assessment of the potential role of renewables in reducing GHG emissions. Globally wind electricity generating capacity has, for example, experienced double-digit annual growth rates since 2005 with an increasing share in developing countries. While still being only a small part of the world energy system, renewable technology capacities, especially wind but also solar, are growing so rapidly that their potential for large scale growth is hard to assess but could be very large (IEA, 2011b; GEA, 2012). Renewable energy potentials exist not only for stationary users via electricity but also for transportation through biofuels and electric-powered vehicles (see 11.13). Renewable energy technologies appear to hold great promise, but like all major sources of energy they also come with an array of concerns. Many renewable sources of electricity are variable and intermittent, which can make them difficult to integrate into electric grids at scale (see Chapter 7; Chapter 8 in IPCC, 2011). Some biofuels are contested due to fears for food security and high lifecycle greenhouse gas emissions of some fuel types (see Chapter 2 in IPCC, 2011; Delucchi, 2010). Other concerns are financial, since nearly every major market for renewable energy has relied heavily on a variety of policy support such as subsidies, leading investors and analysts alike to wonder whether and how these energy sources will continue to be viable for investors if subsidies are curtailed. Indeed, some governments concerned about the size of public budgets have pared back subsidies and claimed that additional cutbacks will be forthcoming.

Since AR4, there have also been substantial advances in the technological possibilities for making energy systems more efficient and responsive. The use of energy efficient devices, plants, and equipment has been legislated in many jurisdictions (RISØ, 2011). Integrating information and communication technology (ICT) into energy networks offers the potential to deliver and use energy more efficiently and flexibly, which could make it much easier to integrate variable and intermittent renewable power sources into existing electric grids. (Improved energy storage technologies could also play a central role.) This interconnection offers the promise of energy systems—especially in electricity, where the potential for pervasive use of ICT is often called a 'smart grid'—that integrate demand response with supplies, allowing for smooth and reliable operation of grids even with fluctuating renewable supplies (EPRI, 2011). Innovations of this type may also interact with behavioural changes that can have large effects on emissions as well. For example, greater flexibility and efficiency could encourage consumers to use more energy, partially offsetting the benefits of these investments in smarter energy supply networks. Or, close attention to energy supplies could encourage shifts in behaviour that are much more frugal with energy (see Chapter 7).

A central challenge in shifting to clean energy supplies and to creating much more efficient end-use of energy is that many energy technologies require large capital costs with long time horizons. Thus, even when such technologies are cost-effective they may face barriers to entry if investors and users are not confident that needed policy and market support will be reliable. Innovations in financing—for example, mechanisms that allow households to lease solar panels rather than pay the full cost up front—can play a role in addressing such issues, as can public schemes to fund initial deployment of new technologies. Such arrangements are part of a broader effort often called 'market transformation' that, if implemented well, can lead to new trajectories for deployment of technologies that otherwise would face many barriers to entry (IEA, 2010c).

Since AR4, a large number of governments have begun to explore the expansion or introduction of nuclear power. They have also faced many challenges in the deployment and management of this technology. Countries with active nuclear power programmes have been contemplating replacing aging plants with new builds or expanding the share of nuclear power in their electricity mix for reasons of economics, supply security, and mitigation of climate change. In addition, more than 20 countries, currently, that have never had commercial reactors have launched national programmes in preparation for the introduction of the technology, and several newcomer countries have entered contractual arrangements with vendors (IAEA, 2011).

After the Fukushima accident in March 2011, an event that forced Japan to review its energy policy substantially, the future patterns in nuclear power investment have become more difficult to parse. Some countries have scaled back nuclear investment plans or ruled out new build (e.g., Switzerland, Belgium); some, notably Germany, have decided to close existing reactors. In the United States, since AR4, several reactors have been slated for closure and owners have announced that still more closures are possible—mainly for reasons of economic competitiveness since aging reactors can be costly to maintain in the face of less expensive gas-fired electricity. At the same time, in 2013 construction began on four new reactors in the United States—the first new construction in that country in three decades. Several countries preparing the introduction of nuclear power have extended the time frame for the final go-ahead decisions; only few in a very early stage of preparation for the introduction stopped their activities altogether. In other countries, including all the countries that have been most active in building new reactors (e.g., China, India, Russia, and South Korea), there aren't many noticeable effects from Fukushima and the investment in this energy source is accelerating, despite some scale-back in the wake of Fukushima (IEA, 2012a). These countries' massive investments in nuclear were much less evident, especially in China, India and South Korea, at the time of AR4.

The Fukushima accident has also increased investment in deployment of new, safer reactor designs such as so-called 'Generation III' reactors and small modular reactors (see Chapter 7.5.4). Despite all of these new investment activities, standard baseline projections for the world energy system see nuclear power declining slightly in share as total demand rises and other electric power sources are more competitive (IEA, 2012a; EIA, 2013c). In many countries, the future competitiveness of nuclear power hinges on the adoption of policies that account for the climate change and energy security advantages of the technology.

1.2.4 International institutions and agreements

For more than two decades formal intergovernmental institutions have existed with the task of promoting coordination of national policies on the mitigation of emissions. In 1992, diplomats finalized the United Nations Framework Convention on Climate Change (UNFCCC), which entered into force in 1994. The first session of the Conference of the Parties (COP) to that Convention met in Berlin in 1995 and outlined a plan for new talks leading to the Kyoto Protocol in 1997, which entered into force in 2005. The main regulatory provisions of the Kyoto Protocol concerned numerical emission targets for industrialized countries (listed in Annex B of the Protocol[1]) during the years 2008 to 2012. When AR4 concluded in 2007, diplomats were in the early stages of negotiations for possible amendment of the Kyoto treaty while also exploring other mechanisms to encourage additional long-term cooperation on mitigation. The regulatory targets of the original Kyoto treaty would expire at the end of 2012. Those negotiations had been expected to finish at the COP 15 meeting in Copenhagen in 2009, but a wide number of disagreements made that impossible. Instead, talks continued while, in tandem, governments made an array of pledges that they solidified at the 2010 COP meeting in Cancun. These 'Cancun pledges' concern the policies they would adopt to mitigate emissions and other related actions on the management of climate risks; some of those pledges are contingent upon actions by other countries. The

[1] In this chapter, Annex B countries are categorized as: countries that are members of Annex B; countries originally listed in Annex B but which are not members of the Kyoto Protocol (non-members are USA and Canada). Countries not listed in Annex B are referred to as non-Annex B.

91 countries that adopted these pledges account for the vast majority (about 80 %) of world emissions (UNFCCC, 2011, 2012a; b; UNEP, 2012). If fully implemented, the pledges might reduce emissions in 2020 about one-tenth below the emissions level that would have existed otherwise—not quite enough to return emissions to 2005 levels—and it would be very hard to attain widely discussed goals of stabilizing warming at 1.5 or 2 degrees without almost immediate and full participation in international agreements that coordinate substantial emission reductions (Figure 1.9). International agreements are discussed in detail in Chapter 13 of this report.

At this writing, diplomatic talks are focused on the goal of adopting a new agreement that would raise the level of ambition in mitigation and be in effect by 2020 (UNFCCC, 2012c). In tandem, governments have also made a number of important decisions, in particular the adoption at Doha in 2012 of the second commitment period of the Kyoto Protocol, from 2013 to 2020. However, five developed countries originally listed in Annex B of the Kyoto Protocol are not participating in the second commitment period: Canada, Japan, New Zealand, Russia, and the United States (UNFCCC, 2013b).

The growing complexity of international diplomacy on climate change mitigation, which has been evident especially since AR4 and the Copenhagen meeting, has led policymakers and scholars alike to look at many other institutional forms that could complement the UN-based process. Some of these initiatives imply diplomatic efforts on separate parallel tracks (see Chapter 13). Proposals exist within the Montreal Protocol on Substances that Deplete the Ozone Layer to regulate some of the gases that have replaced ozone-destroying chemicals yet have proved to have strong impacts on the climate. A wide array of other institutions has become engaged with the climate change issue. The G8—the group of Canada, France, Germany, Italy, Japan, Russia, the UK, and the USA that convenes regularly to address a wide array of global economic challenges—has repeatedly underscored the importance of limiting warming to 2 degrees and implored its members to take further actions. The G20, a much broader group of economies has put climate change matters on its large agenda; the G20 has also helped to organize active efforts to reform fossil fuel subsidies and to implement green growth strategies. The UN, itself, has a large number of complementary diplomatic efforts on related topics, such as the 'Rio+20' process.

Many other institutions are now actively addressing particular aspects of climate change mitigation, such as the International Renewable Energy Agency (IRENA), which focuses on renewable energy; the Climate and Clean Air Coalition (CCAC), which focuses on how limits on short-lived pollutants such as black carbon can help slow climate change, the International Atomic Energy Agency (IAEA), which focuses on nuclear power, the International Civil Aviation Organization (ICAO) and the International Maritime Organization (IMO) that have focused on emissions from bunker fuels, and many others with expertise in particular domains. The International Energy Agency (IEA) is now extensively engaged in analyzing how developments in the energy sector could affect patterns of emissions (e.g., IEA, 2012). Looking across these many different activities, international institutions that have engaged the climate change topic are highly decentralized rather than hierarchically organized around a single regulatory framework (Keohane and Victor, 2011). Since AR4, research on decentralized international institutions has risen sharply (Alter and Meunier, 2009; Zelli et al., 2010; Johnson and Urpelainen, 2012), building in part on similar concepts that have emerged in other areas of research on collective action (e.g., McGinnis, 1999; Ostrom, 2010).

Since AR4, there has been a sharp increase in scholarly and practical attention to how climate change mitigation could interact with other important international institutions such as the World Trade Organization (WTO) (see also Chapter 13 of this volume) (Brewer, 2010). Relationships between international trade agreements and climate change have been a matter of long standing interest in climate diplomacy and are closely related to a larger debate about how differences in environmental regulation might affect economic competitiveness as well as the spread of mitigation and adaptation technology (Gunther et al., 2012). A potential role for the WTO and other trade agreements also arises because the fraction of emissions embodied in internationally traded goods and services is rising with the globalization of manufacturing (see 1.2.1.2 above and 1.3.1 below). Trade agreements might also play a role in managing (or allowing the use of) trade sanctions that could help enforce compliance with mitigation commitments—a function that raises many legal questions as well as numerous risks that could lead to trade wars and an erosion of political support that is essential to the sustainability of an open trading system (Bacchus et al., 2010). For example, Article 3 of the UNFCCC requires that "[m]easures taken to combat climate change, including unilateral ones, should not constitute a means of arbitrary or unjustifiable discrimination or a disguised restriction on international trade." (UNFCCC, 1992). The impacts of mitigation on trade issues are also related to concerns that have been raised about how emission controls could reduce national employment and income (ILO, 2012, 2013).

Since the AR4 in 2007, the scholarly community has analyzed the potentials, design, and practices of international cooperation extensively. A body of research has emerged to explain why negotiations on complex topics such as climate change are prone to gridlock (Murase, 2011; Victor, 2011; Yamaguchi, 2012). There is also a large and vibrant research program by political scientists and international lawyers on institutional design, looking at issues such as how choices about the number of countries, type of commitments, the presence of enforcement mechanisms, schemes to reduce cost and increase flexibility, and other attributes of international agreements can influence their appeal to governments and their practical effect on behaviour (see e.g., the comprehensive reviews and assessment on these topics by Hafner-Burton, Victor, and Lupu, 2012 as well as earlier research of Abbott et al., 2000; and Koremenos, Lipson, and Snidal, 2001). Much of that research program has sought to explain when and how international institutions, such as treaties, actually help solve common problems. Such research is part of a rich tradition of scholarship aimed at explaining whether and how countries comply with their international commitments (Downs et al., 1996; Simmons, 2010). Some of that research focuses on policy strategies that do not involve formal legalization but, instead, rely more heavily on setting norms through industry organizations, NGOs, and other groups (Vogel, 2008; Buthe and Mattli, 2011). The experience with voluntary industry standards has been mixed; in some settings these standards have led to large changes in behaviour and proved highly flexible while in others they have little or no impact or even divert attention (Rezessy and Bertoldi, 2011).

One of the many challenges in developing and analyzing climate change policy is that there are long chains of action between international institutions such as the UNFCCC and the ultimate actors whose behaviour might be affected, such as individuals and firms. We note that there have been very important efforts to engage the business community on mitigation as well as adaptation to facilitate the market transformations needed for new emission technologies and business practices to become widespread (WEF, 2009; UN Global Compact and UNEP, 2012) (see Chapter 15). While there are diverse efforts to engage these many different actors, measuring the practical impact on emissions has been extremely difficult and much of the scholarship in this area is therefore highly descriptive.

1.2.5 Understanding the roles of emissions other than fossil fuel CO_2

Much policy analysis has focused on CO_2 from burning fossil fuels, which comprise about 60 % of total global greenhouse gas emissions in 2010 (see Section 1.3.1 below). However, the UNFCCC and the Kyoto Protocol cover a wider array of CO_2 sources and of warming substances—including methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs) and sulphur hexafluoride (SF_6). Nitrogen trifluoride (NF_3) was added as a GHG under the Kyoto Protocol for its second commitment period. This large list was included, in part, to create opportunities for firms and governments to optimize their mitigation efforts flexibly across different substances. The effects of different activities on the climate varies because the total level of emissions and the composition of those emissions varies. For example, at current levels the industrial and power sectors have much larger impacts on climate than agriculture (Figure 1.3).

A variety of studies have shown that allowing for trading across these different gases will reduce the overall costs of action; however, many studies also point to the complexity in agreeing on the correct time horizons and strategies for policy efforts that cover gases with such different properties (Reilly et al., 2003; Ramanathan and Xu, 2010; Shindell et al., 2012). In addition to the gases regulated under the Kyoto Protocol, many of the gases that deplete the ozone layer—and are regulated under the Montreal Protocol on Substances that Deplete the Ozone Layer—are also strong greenhouse gases (Velders et al., 2007). Since AR4 a variety of short-lived climate pollutants (SLCPs) have come under scrutiny (UNEP, 2011a; Shindell et al., 2012; Victor et al., 2012; Smith and Mizrahi, 2013). Those include tropospheric ozone (originating from air pollutant emissions of nitrogen oxides and various forms of incompletely oxidized carbon) and aerosols (such as black carbon and organic carbon and secondary such as sulphates) that affect climate forcing (see Chapter 8, Section 8.2.2 and Section 5.2). This remains an area of active research, not least because some studies suggest that the climate impacts of short-lived pollutants like black carbon could be much larger or smaller (Ramanathan and Carmichael, 2008; Bond et al., 2013) (WGI, Chapters 7 and 8). Such pollutants could have a large role in mitigation strategies since they have a relatively swift impact on the climate—combined with mitigation of long-lived gases like CO_2 such strategies could make it more easily feasible to reach near-term temperature goals, but there are still many debates over the right balance of mitigation effort on short-lived and long-lived pollutants (Ramanathan and Xu, 2010; Penner et al., 2010; Victor et al., 2012; Smith and Mizrahi, 2013). By contrast, other aerosols—notably the sulphate aerosol formed from SO_2 emissions from the industrial and power sectors, shipping, and large-scale biomass burning—have a net cooling effect because they interact with clouds to reflect sunlight back to space (see Section 5.2 and WGI, Chapter 7.4; (Fuglestvedt et al., 2009).

Starting with the FAR, the IPCC has calculated global warming potentials (GWPs) to convert climate pollutants into common units over 20, 100, and 500 year time horizons (Chapter 2, IPCC, 1990b). Indeed, when GWPs were first presented by IPCC the analysis included the statement that "[t]hese three different time horizons are presented as candidates for discussion and should not be considered as having any special significance" (see Chapter 2, page 59 in IPCC, 1990b). In the Kyoto Protocol, diplomats chose the middle value—100 years—despite the lack of any published conclusive basis for that choice (Shine, 2009). That approach emphasizes long-lived pollutants such as CO_2, which are essential to stopping climate warming over many decades to centuries. As shown in Table 1.1, when GWPs are computed with a short time horizon the share of short-lived gases, notably methane, in total warming is much larger and that of CO_2 becomes proportionally smaller. The uncertainty in the GWPs of non-CO_2 substances increases with time horizon and for GWP_{100} the uncertainty is about 30 % to 40 % (90 % confidence interval) (IPCC, 2013a). If policy decisions are taken to emphasize SLCPs as a means of altering short-term rates of climate change rises then alternative GWPs or other metrics and mitigation strategies may be needed (IPCC, 2009; Fuglestvedt et al., 2010; Victor et al., 2012; Daniel et al., 2012; Smith et al., 2012). Additional accounting systems may also be needed.

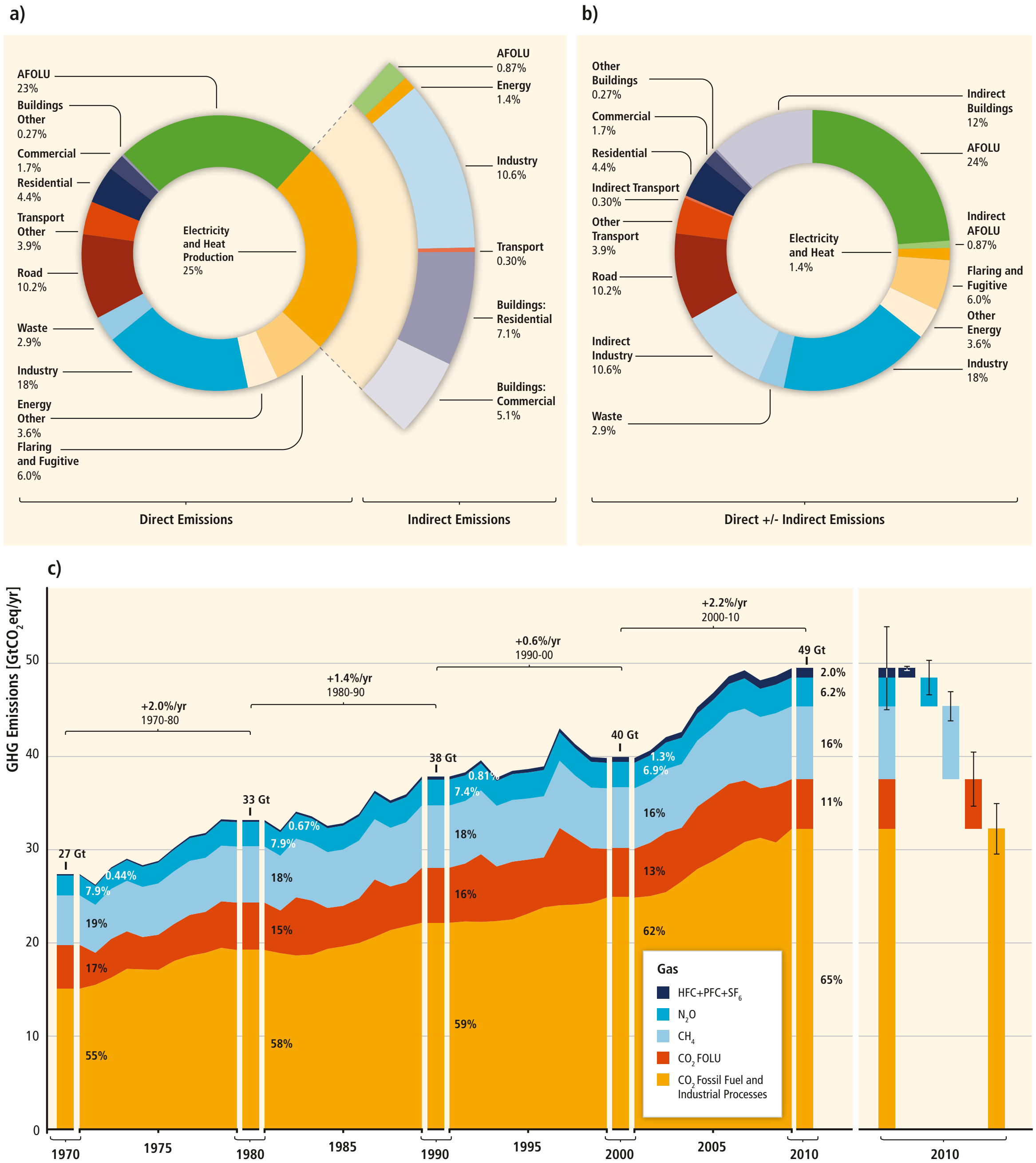


Figure 1.3 | Panel A (top left): Allocation of total GHG emissions in 2010 (49.5 $GtCO_2eq/yr$) across the five sectors examined in detail in this report (see Chapters 7–11). Pullout from panel A allocates indirect CO_2 emission shares from electricity and heat production to the sectors of final energy use. Panel B (top right): Allocates that same total emissions (49.5 $GtCO_2eq/yr$) to reveal how each sector's total increases or decreases when adjusted for indirect emissions. Panel C (lower panel): Total annual GHG emissions by groups of gases 1970–2010, along with estimated uncertainties illustrated for 2010 (whiskers). The uncertainty ranges provided by the whiskers for 2010 are illustrative given the limited literature on GHG emission uncertainties. Sources: Historic Emission Database IEA/EDGAR dataset (JRC/PBL, 2013, IEA, 2012a), see Annex II.9. Data shown for direct emissions on Panels A and B represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emissions sources in the FOLU (Forestry and Other Land Use) sub-sector—additional detail on Agriculture and FOLU ('AFOLU', together) fluxes is in Chapter 11, Section 11.2 and Figure 11.2 and 11.6. Emissions weighted with 100-year GWPs as used in the original Kyoto Protocol (i.e., values from the SAR as those values are now widely used in policy discussions) and, in general, sectoral and national/regional allocations as recommended by the 1996 IPCC guidelines (IPCC, 1996). Using the most recent GWP-100 values from the AR5 (see WGI Section 8.6) global GHG emission totals would be slightly higher (52 $GtCO_2eq$) and non-CO_2 emission shares are 20 % for CH4, 5 % for N_2O and 2 % for F-gases. Error bars in panel 1.3c show the 90 % confidence interval of the emission estimates based on these sources: CO_2 from fossil fuel and industrial processes ±8.4 % (Andres et al., 2012; Kirschke et al., 2013) CO_2 from FOLU ±2.9 $GtCO_2/yr$ (estimates from WGI table 6.1 with central value shown on figure 1.3c is per EDGAR/IEA); Methane ±20 % (Kirschke et al. 2013); Nitrous oxide ±60 % (WGI, table 6.9); F-gases ±20 % (UNEP, 2012). Readers are cautioned, however, that the literature basis for all of these uncertainty figures is very weak. There have been very few formal, documented analysis of emissions uncertainty for any gas. Indicative uncertainty for total emissions is from summing the squares of the weighted uncertainty of individual gases (see 5.2.3.4 for more detail), which yields a total uncertainty of +/–9 % for a 90 % confidence interval in 2010. We note, however, that there is insufficient published information to make a rigorous assessment of global uncertainty and other estimates suggest different uncertainties. The calculation leading to 9 % assumes complete independence of the individual gas-based estimates; if, instead, it is assumed that extreme values for the individual gases are correlated then the uncertainty range may be 19 %. Moreover, the 9 % reported here does not include uncertainties related to the choice of index (see table 1.1) and Section 1.2.5.

Table 1.1 | Implications of the choice of Global Warming Potential (GWP) for mitigation strategy. Table shows the main geophysical properties of the major Kyoto gases and the implications of the choice of values for GWPs with different time horizons (20, 100, or 500 years) on the share of weighted total emissions for 2010; other IPCC chapters report detail on alternative indexes such as Global Temperature change Potential (GTP) (Chapter 3; WGI Chapter 8). At present, the 100-year GWPs are used most widely, and we show those values as reported in the IPCC Second Assessment Report (SAR) in 1995 and subsequently used in the Kyoto Protocol. Note that CO_2 is removed by multiple processes and thus has no single lifetime (see WGI Box 6.1). We show CF_4 as one example of the class of perfluorocarbons (PFCs) and HFC-134a and HFC-23 as examples of hydrofluorocarbons (HFCs). All other industrial fluorinated gases listed in the Kyoto Protocol ('F-gases') are summed. We do not show warming agents that are not included in the Kyoto Protocol, such as black carbon. Emissions reported in JRC/PBL (2013) using GWPs reported in IPCC's Second, Fourth and Fifth Assessment Reports (IPCC, 1995, 2007c, 2013a). The AR4 was used for GWP-500 data; interpretation of long time horizon GWPs is particularly difficult due to uncertainties in carbon uptake and climate response—differences that are apparent in how different models respond to different pulses and scenarios for CO_2 and the many nonlinearities in the climate system (see WGI, Supplemental Material 8.SM.11.4 and Joos et al., 2013) and thus IPCC no longer reports 500 year GWPs. Due to changes in the GWP values from AR4 to AR5 the 500-year shares are not precisely comparable with the other GWPs reported here. Geophysical properties of the gases drawn from WGI, Appendix 8.A, Table 8.A.1—final draft data).

Kyoto gases	Geophysical properties		GWP-weighted share of global GHG emissions in 2010			
	Atmospheric lifetime (year)	Instantaneous forcing (W/m^2/ppb)	SAR (Kyoto) 100 years	WGI (20 and 100 year from AR5 & 500 year from AR4) 20 years	100 years	500 years
CO_2	various	1.37×10^{-5}	76 %	52 %	73 %	88 %
CH_4	12.4	3.63×10^{-4}	16 %	42 %	20 %	7 %
N_2O	121	3.00×10^{-3}	6.2 %	3.6 %	5.0 %	3.5 %
F-gases:			2.0 %	2.3 %	2.2 %	1.8 %
HFC-134a	13.4	0.16	0.5 %	0.9 %	0.4 %	0.2 %
HFC-23	222	0.18	0.4 %	0.3 %	0.4 %	0.5 %
CF_4	50,000	0.09	0.1 %	0.1 %	0.1 %	0.2 %
SF_6	3,200	0.57	0.3 %	0.2 %	0.3 %	0.5 %
NF_3 *	500	0.20	not applicable	0.0 %	0.0 %	0.0 %
Other F-gases **	various	various	0.7 %	0.9 %	0.8 %	0.4 %

* NF_3 was added for the second commitment period of the Kyoto period, NF_3 is included here but contributes much less than 0.1 %.

** Other HFCs, PFCs and SF_6 included in the Kyoto Protocol's first commitment period. For more details see the Glossary (Annex I).

1.2.6 Emissions trajectories and implications for Article 2

Chapter 1 of the WGIII AR4 found that, without major policy changes, the totality of policy efforts do not put the planet on track for meeting the objectives of Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC) (IPCC, 2007a). Since then, emissions have continued to grow—a topic we examine in more detail below. Article 2 of the UNFCCC describes the ultimate objective of the Convention. It states:

> *The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner. (UNFCCC, 1992).*

Interpreting the UNFCCC goal is difficult. The first part of Article 2, which calls for stabilization of GHG concentration at levels that are not 'dangerous,' requires examining scientific climate impact assessments as well as normative judgments—points that are explored in detail in the WGII contribution. The second part of Article 2 is laden with conditions whose interpretation is even less amenable to scientific analysis. In light of the enormous variations in vulnerability to climate change across regions and ecosystems, it is unlikely that scientific evidence will conclude on a single such goal as 'dangerous'. Variations in what different societies mean by 'dangerous' and the risks they are willing to endure further amplify that observation. Article 2 requires that societies balance a variety of risks and benefits—some rooted in the dangers of climate change itself and others in the potential costs and benefits of mitigation and adaptation.

Since the publication of AR4 a series of high-level political events have sought to create clarity about what Article 2 means in practice. For example, the Bali Action Plan, adopted at COP 13 held in Bali, Indonesia, in December 2007, cited AR4 as a guide for negotiations over long-term cooperation to manage climate change. At the L'Aquila G8 Summit in 2009, five months before the COP15 meeting in Copenhagen, leaders "recognized the broad scientific view that the increase in global average temperature above pre-industrial levels ought not to exceed 2 °C," and they also supported a goal of cutting emissions at least 80 % by 2050 (G8 Leaders, 2009). Later that year, an COP 15, delegates 'took note' of the Copenhagen Accord which recognized "the scientific view that the increase in global temperature should be below 2 degree Celsius," and later meetings arrived at similar conclusions (Decision1/CP.16). Ever since the 2009 Copenhagen Conference the goal of 1.5 degrees has also appeared in official UN documents, and some delegations have suggested that a 1 degree target be adopted. Some scholars suggest that these goals can create focal points that facilitate policy coordination, although there is a variety of perspectives about whether these particular goals are playing that role, in part because of growing evidence that they will be extremely difficult or impossible to attain (Schneider and Lane, 2006; National Research Council of the National Academies, 2011; Victor, 2011; Helm, 2012). Readers should note that each major IPCC assessment has examined the impacts of multiplicity of temperature changes but has left political processes to make decisions on which thresholds may be appropriate (WGIII AR4 Chapter 1).

At present, emissions are not on track for stabilization let alone deep cuts (see Section 1.3 below). This reality has led to growing research on possible extreme effects of climate change and appropriate policy responses. For example, Weitzman (2009) raised the concern that standard policy decision tools such as cost-benefit analysis and expected utility theory have difficulty dealing with climate change decisions, owing to the difficulty in assessing the probability of catastrophic impacts. Partly driven by these concerns, the literature on geoengineering options to manage solar radiation and possibly offset climate change along with technologies that allow removal of CO_2 and other climate-altering gases from the atmosphere has been increasing exponentially (see 6.9). Because they have theoretically high leverage on climate, geoengineering schemes to alter the planet's radiation balance have attracted particular attention; however, because they also create many risks that are difficult if not impossible to forecast, only a small but growing number of scientists have considered them seriously (Rickels et al. 2011; Gardiner 2010; IPCC 2012; Keith, Parson, and Morgan 2010).

1.3 Historical, current and future trends

Since AR4 there have been new insights into the scale of the mitigation challenge and the patterns in emissions. Notably, there has been a large shift in industrial economic activity toward the emerging countries—especially China—that has affected those nations' emission patterns. At the same time, emissions across the industrialized world are largely unchanged from previous levels. Many countries have adopted policies to encourage shifts to lower GHG emissions from the energy system, such as through improved energy efficiency and greater use of renewable energy technologies.

1.3.1 Review of four decades of greenhouse gas emissions

While there are several sources of data, the analysis here relies on the EDGAR data set (JRC/PBL, 2013) [see Annex II.9 Methods and Metrics for a complete delineation of emission categories]. We focus here on all major direct greenhouse gases (GHGs) related to human activities—including carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), and sulphur hexafluoride (SF_6). We also examine various ozone-depleting substances (ODS), which are regulated under the Montreal Protocol due to their effects on the ozone layer but also act as long-lived GHG: chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and halons. Due to lack of comparable data we do not here examine black carbon, tropospheric ozone precursors, cooling aerosols, and nitrogen trifluoride (NF_3.) For the analyses that follow we use 100-year GWPs from the SAR because they are widely used by governments, but we are mindful that other time horizons and other global warming metrics also merit attention (see 1.2.5 above).

By sector, the largest sources of greenhouse gases were the sectors of energy production (34 %, mainly CO_2 from fossil fuel combustion), and agriculture, forestry and land-use (AFOLU) (24 %, mainly CH_4 and N_2O) (Figure 1.3a). Within the energy sector, most emissions originate from generation of electricity that is, in turn, used in other sectors. Thus, accounting systems in other sectors often refer to direct emissions from the sector (e. g., CO_2 emissions caused in industry during the production of cement) as well as 'indirect' emissions that arise outside the boundaries of that particular economic sector (e. g., the consumption of electric power in buildings causes indirect emissions in the energy supply sector (Figure 1.3a and 1.3b). Looking at the total source of greenhouse gases at present CO_2 contributes 76 %; CH_4 about 16 %, N_2O about 6 % and the combined F-gases about 2 % (Figure 1.3c).

Following the breakdown in sectors discussed in this report (Chapters 7 to 11), Figure 1.3c looks at emissions over time by gas and sector. Figure 1.4 looks at those patterns over time according to different groups of countries, which reveals the effects of periodic economic slowdowns and contractions on emissions. Globally, emissions of all greenhouse gases increased by about 75 % since 1970. Over the last two decades, a particularly striking pattern has been the globalization of production and trade of manufactured goods (see Section 1.2.1.2 above). In effect, high-income countries are importing large embodied emissions from the rest of the world, mainly the upper middle-income countries (Figure 1.5).

Overall, per-capita emissions in the highly industrialized countries are roughly flat over time and remain, on average, about 5 times higher than those of the lowest income countries whose per-capita emissions are also roughly flat. Per-capita emissions from upper-middle income countries have been rising steadily over the last decade (see inset to Figure 1.4). There are substantial differences between mean and median per-capita emissions, reflecting the huge variation within

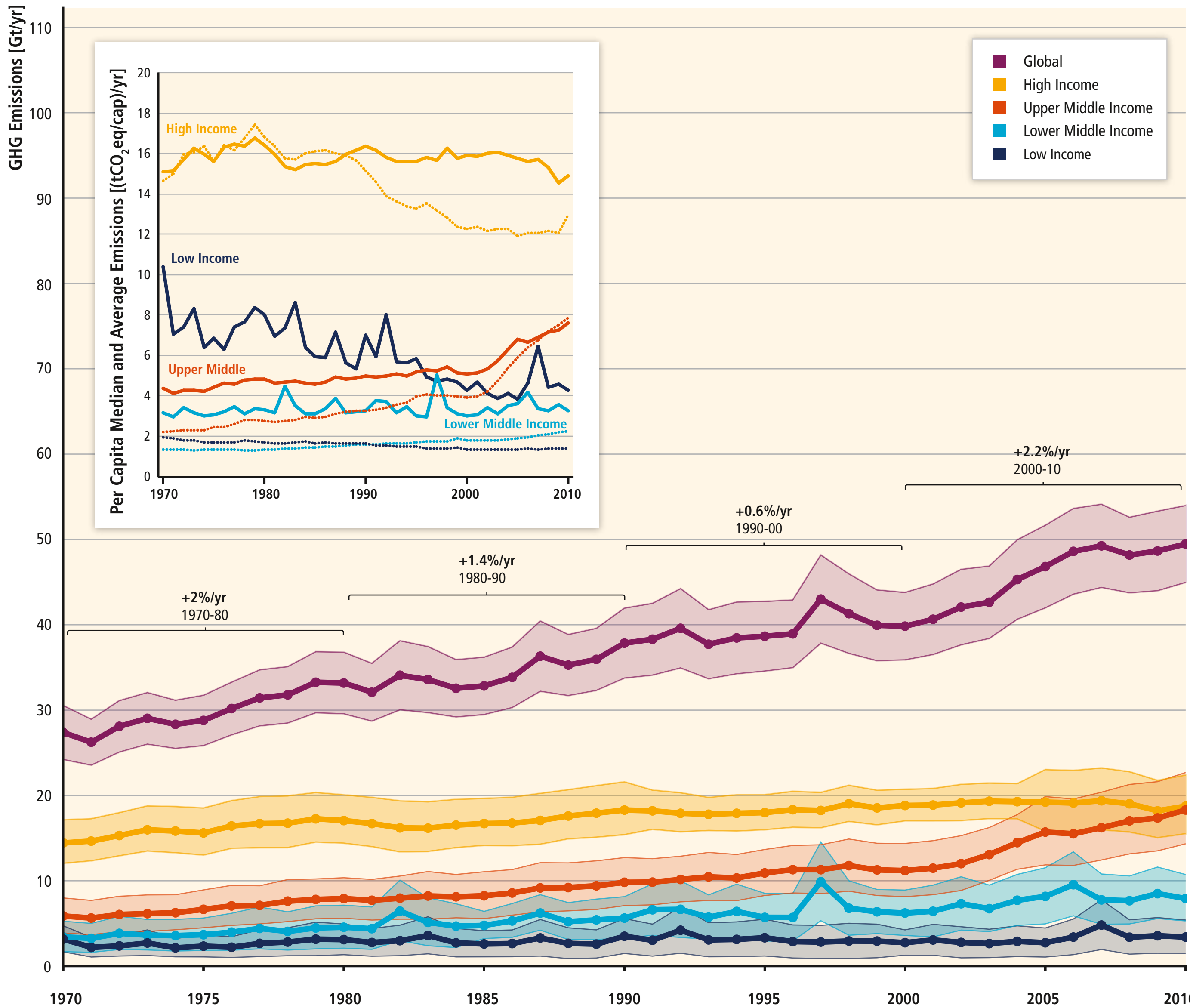


Figure 1.4 | Global growth in emissions of GHGs by economic region. Main figure shows world total (top line) and growth rates per decade, as well as the World Bank's four economic regions (see Figure 1.1 caption for more detail). Inset shows trends in annual per capita mean (solid lines) and median (dotted lines) GHG emissions by region 1970–2010 in tonnes of CO_2eq (t/cap/yr) (United Nations, 2013a). Global totals include bunker fuels; regional totals do not. The data used is from the same sources reported in Figure 1.3c. Error bars are approximated confidence interval of 1 standard deviation, derived by aggregating individual country estimates by gas and sector of the 16th and 84th emission percentiles provided by the MATCH analysis (Höhne et al., 2011); data also available at http://www.match-info.net/. However, we note that this probably over-states actual uncertainty in the totals, since individual country uncertainty estimates under this method are implicitly taken to be completely correlated. Thus, for the global totals we estimate a 90 % uncertainty range using the same method as discussed for Figure 1.3c. While in 2010 the uncertainty using that method is 9 %, over the full time period of Figure 1.4 the value varies from 9 % to 12 % with an average value of 10 %. We caution that multi-country and global uncertainty estimates remain an evolving area of research (see caption 1.3c and Section 5.2.3). Uncertainties shown on this chart are at best indicative of the unknowns but are not a definitive assessment.

these categories. Some very low income countries have extremely low per-capita emissions while some upper middle income developing countries have per-capita emissions comparable with those of some industrialized nations.

Emissions from the energy sector (mainly electricity production) and from transportation dominate the global trends. Worldwide power sector emissions have tripled since 1970 (see Figure 7.3), and transport has doubled (see Figure 8.1). Since 1990 emissions from electricity and heat production increased by 27 % for the group of OECD countries; in the rest of the world the rise has been 64 % (see Figure 7.5). Over the same period, emissions from road transport increased by 29 % in OECD countries and 61 % in the other countries (see Figure 8.3). Emissions from these systems depend on infrastructures such as power grids and roads, and thus there is also large inertia as those infrastructures are slow to change (Davis et al., 2010).

Forest related GHG emissions are due to biomass burning and decay of biomass remaining after forest burning and after logging. In addition, the data shown includes CO_2 emissions from decomposition of drained peatland and from peat fires (Olivier and Janssens-Maenhout, 2012). The forest related figures presented here are in line with the synthesis paper by Houghton et al. (2012) on recent estimates of carbon fluxes from land use and land cover change.

There has been a large effort to quantify the uncertainties in the historical emissions since AR4 was published. Such efforts have been difficult due to the small number of truly independent data sources, especially at the finest level of resolution such as emissions from particular sectors and countries. Uncertainties are particularly large for greenhouse gas emissions associated with agriculture and changes in land use. By contrast, recent estimates of emissions from fossil fuel combustion varied by only 2.7 % across the most widely used data sources (Macknick, 2011). In addition to variations in the total quantity of fossil fuel combusted, the coefficients used by IPCC to calculate emissions also vary from 7.2 % for coal use in industry to 1.5 % for diesel used in road transport (Olivier et al., 2010). Emissions from agriculture and land-use change are estimated to vary by 50 % (Tubiello et al., 2013), and a recent study that compared 13 different estimates of total emissions from changes in land use found broadly comparable results (Houghton et al., 2012). Since land use is a small fraction of total CO_2 emissions the total estimate of anthropogenic CO_2 emissions has uncertainty of only ±10 % (UNEP, 2012). Looking beyond CO_2, estimates for all other warming gases are generally more uncertain. Estimated uncertainties for global emissions of methane, nitrous oxide, and fluorine based gases are ±25 %, ±30 %, and ±20 % respectively (UNEP, 2012).

Statistically significant uncertainty quantifications require large independent and consistent data sets or estimates, which generally do not exist for historical GHG emission data. In such cases, uncertainty is referred to as 'indicative uncertainty' based on the limited information available that does not meet the standard of a rigorous statistical analysis (see 5.2.3).

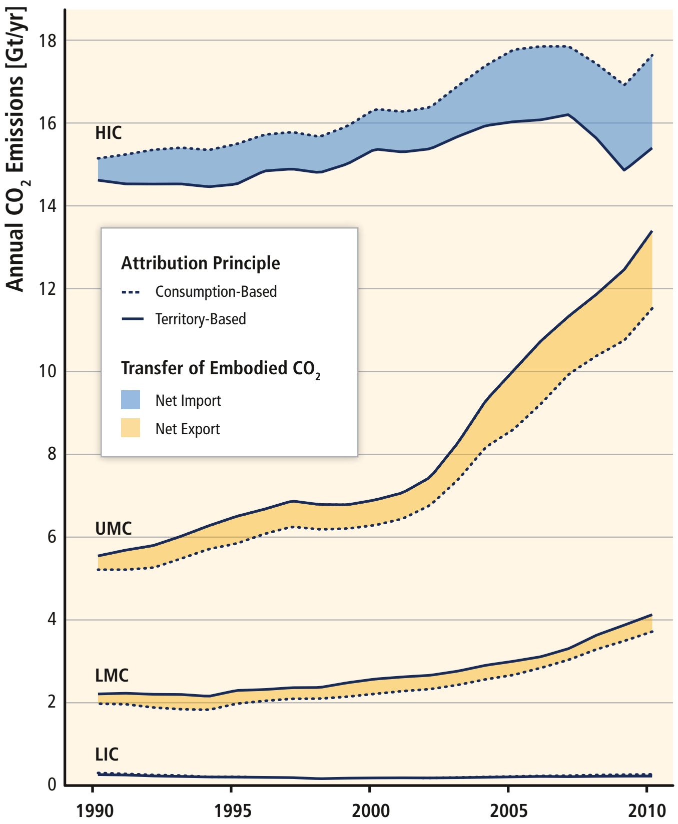


Figure 1.5 | CO_2 emissions from fossil fuel combustion for the four economic regions attributed on the basis of territory (solid line) and final consumption (dotted line) in gigatonnes of CO_2 per year (Gt/yr). The shaded areas are the net CO_2 trade balance (difference) between each of the four country groupings (see Figure 1.1) and the rest of the world. Blue shading indicates that the region is a net importer of emissions, leading to consumption-based CO_2 emission estimates that are higher than traditional territory-based emission estimates. Yellow indicates the reverse situation—net exporters of embodied emissions. Low-income countries, because they are not major players in the global trade of manufactured products, have essentially no difference between territory and consumption based estimates. For high-income countries and upper-middle-income countries, embodied emissions have grown over time. Figures based on Caldeira and Davis (2011) and Peters et al. (2012b), but with data from Eora, a global multi-regional input-output model (Lenzen et al., 2012, 2013).

When adjusting emission statistics to assign indirect GHG emissions from electricity and heat consumption to end-use sectors, as is done in panel 1.3b, the main sectors affected are the industrial and buildings sectors. Those sectors' shares in global GHG emissions then increase by 11 % and 12 % to reach levels of 31 % (industry) and 19 % (buildings). The addition of these so-called 'Scope 2' emissions is sometimes done to show or analyze the more comprehensive impact of total energy consumption of these end-use sectors to total energy-related emissions.

Figure 1.4 looks at these patterns from the global perspective over time. The AR4 worked with the most recent data available at the time (2004). Since then, the world has seen sustained accelerated annual growth of emissions—driven by CO_2 emissions from fossil fuel combustion. There was a temporary levelling off in 2008 linked to high fuel prices and the gathering global economic crisis, but the sustained economic growth in the emerging economies has since fuelled continued growth in world emissions. This is particularly evident in the economic data (Figure 1.1) showing that the large group of countries other than the highly industrialized nations continue to grow despite the world economic crisis. However, growth rates globally, including in these rapidly rising countries, have been slower than the levels seen in the 1990s, which portends less rapid growth in world emissions.

Figure 1.6 shows global GHG emissions since 1970 in 20-year intervals for the five economic sectors covered in Chapters 7–11, i.e., Energy Systems, Transport, Buildings, Industry and Agriculture, Forestry and Other Land Use (AFOLU). International transport ('bunkers') are shown separately as these can neither be attributed to any of these economic sectors or country grouping. In every country grouping except low-income countries, total emissions have risen since 1970 with the largest increases evident in energy systems. The only major sector that does not display these globally rising trends is AFOLU as a growing number of countries adopt policies that lead to better protection of forests, improved yields in agriculture reduce pressure to convert natural forests to cropland, and other trends allow for a 'great restoration' of previously degraded lands (Ausubel et al., 2013). In low-income countries total emissions are dominated by trends in AFOLU; in all other country groupings the energy system plays the central role in emissions.

It is possible to decompose the trends in CO_2 emissions into the various factors that 'drive' these outcomes—an exercise discussed in more detail in Chapter 5. One way to decompose the factors contributing to total emissions is by the product of population, GDP per capita, energy intensity (total primary energy supply per GDP) and the carbon intensity of the energy system (carbon emitted per unit energy). This approach is also known as the 'Kaya Identity' (Kaya, 1990) and resonates with similar earlier work (Holdren and Ehrlich, 1974). A variety of studies have done these decompositions (Raupach et al., 2007; Steckel et al., 2011; Cline, 2011; Akimoto et al., 2013). Figure 1.7 shows such an analysis for the global level, and Chapter 5 in this report offers more detailed decompositions.

The analysis reveals enhanced growth in the 2000s of global income, which drove higher primary energy consumption and CO_2 emissions.

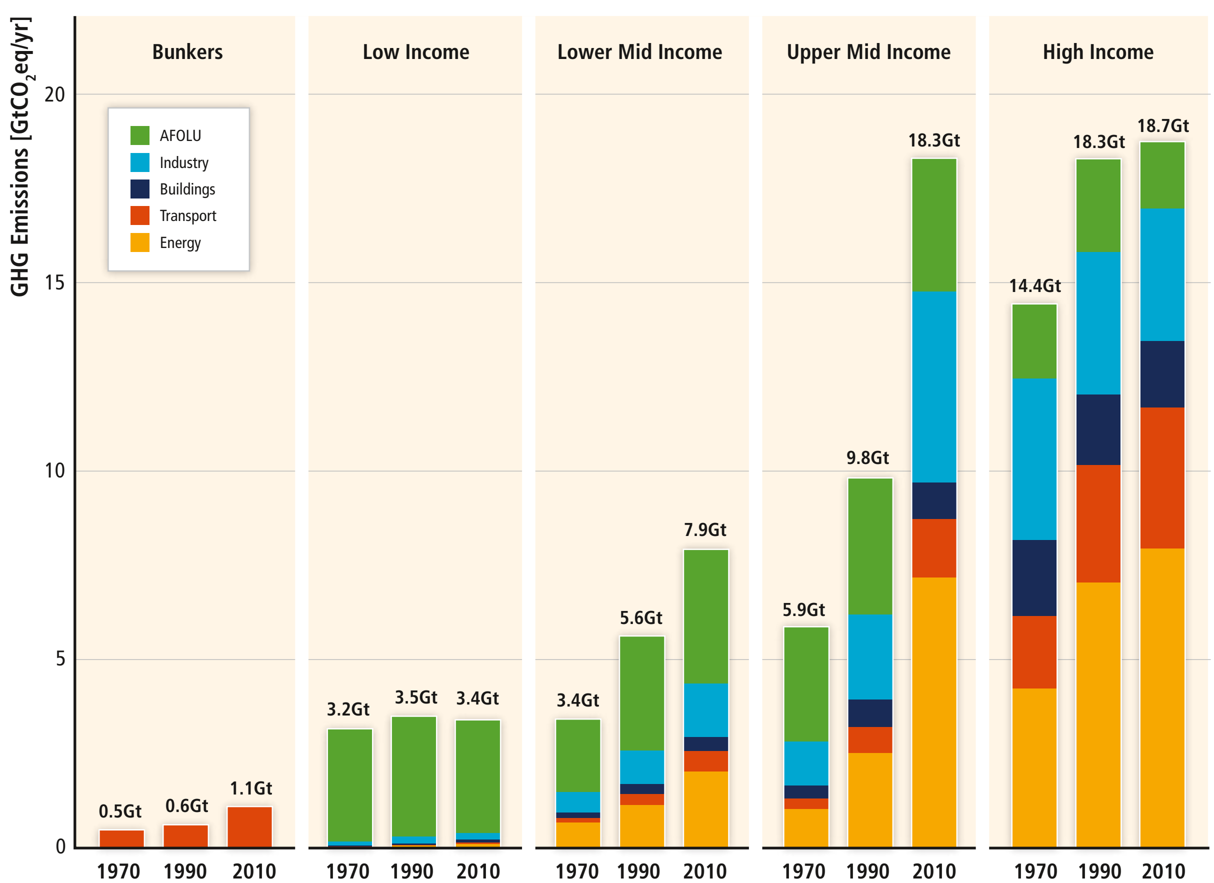


Figure 1.6 | Greenhouse gas emissions measured in gigatonnes of CO_2eq per year (Gt/yr) in 1970, 1990 and 2010 by five economic sectors (Energy supply, Transport, Buildings, Industry, as well as Agriculture, Forestry and Other Land Use (AFOLU) and four economic regions (see caption to Figure 1.1). 'Bunkers' refer to emissions from international transportation and thus are not, under current accounting systems, allocated to any particular nation's territory. Note: The direct emission data from JRC/PBL (2013) (see Annex II.9) represents land-based CO_2 emissions from forest and peat fires and decay that approximate to CO_2 flux from anthropogenic emissions sources in the FOLU (Forestry and Other Land Use) sub-sector. For a more detailed representation of AFOLU GHG flux (Agriculture and FOLU) see Chapter 11, Section 11.2 and Figure 11.2 and 11.6. Source: same sources as reported for Figure 1.3c. We do not report uncertainties because there isn't a reliable way to estimate uncertainties resolved by regional group and sector simultaneously.

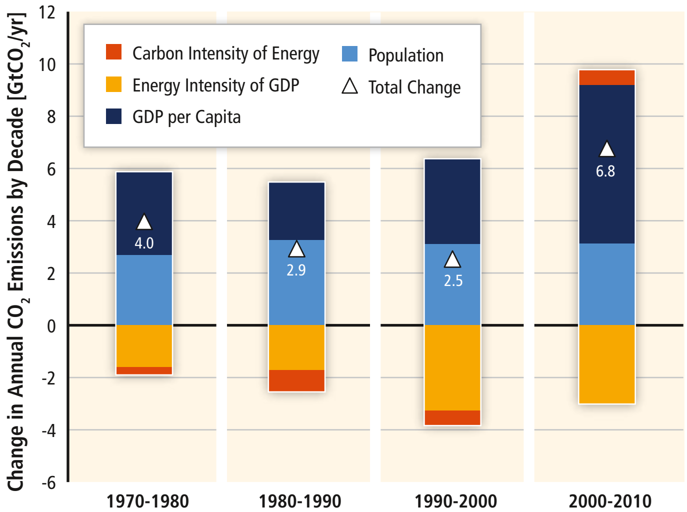


Figure 1.7 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors; population (light blue), GDP per capita (dark blue), energy intensity of GDP (yellow) and carbon intensity of energy (red orange). The bar segments show the changes associated with each factor alone, holding the respective other factors constant. Total emission changes are indicated by a white triangle. The change in emissions over each decade is measured in gigatonnes of CO_2 per year [$GtCO_2$/yr]; economic output is converted into common units using purchasing power parities; the use of market exchange rates would lower the share associated with economic output although that would still be the largest single factor. Source: updated from Steckel et al. (2011) using data from IEA (2012c; d).

(That pattern levelled around 2009 when the global recession began to have its largest effects on the world economy.) Also notable is carbon intensity: the ratio of CO_2 emissions to primary energy. On average, since 1970 the world's energy system has decarbonized. However, in the most recent decade there has been a slight re-carbonization. In the portions of the global economy that have grown most rapidly, low-carbon and zero-carbon fuels such as gas, nuclear power and renewables have not expanded as rapidly as relatively high-carbon coal.

Interpreting the Kaya Identity using global data masks important regional and local differences in these drivers. For example, the demographic transition in China is essentially completed while in Africa population growth remains a sizable driver. Technology—a critical factor in improving energy and carbon intensities as well as access to energy resources—varies greatly between regions (see Chapters 5 and 7). The recent re-carbonization is largely the result of expanded coal combustion in developing countries driven by high rates of economic growth, while across the highly industrialized world carbon intensity has been declining due to the shift away from high carbon fuels (notably coal) to natural gas, renewables, and also to nuclear in some countries. The simple Kaya identity relies on broad, composite indicators that neither explain causalities nor explicitly account for economic structures, behavioural patterns, or policy factors, which again vary greatly across regions. Technological change might allow for radically lower emissions in the future, but the pattern over this four-decade history suggests that the most important global driver of emissions is economic growth.

Although the average per capita income levels in the large emerging economies in 2010 were approximately 30 % or less of the per capita income levels of OECD countries in 1980, their levels of carbon intensity and energy intensity are comparable with those of North America in the early 1980s (IEA, 2012b).

1.3.2 Perspectives on mitigation

Looking to the future, it is important to be mindful that the energy system, which accounts for the majority of GHG emissions, is slow to change even in the face of concerted policy efforts (Davis et al., 2010; WEF, 2012; GEA, 2012). For example, many countries have tried to alter trends in CO_2 emissions with policies that would make the energy supply system more efficient and shift to low emission fuels, including renewables and nuclear power (Chapter 7).

There are many different perspectives on which countries and peoples are accountable for the climate change problem, which should make the largest efforts, and which policy instruments are most practical and effective. Many of these decisions are political, but scientific analysis can help frame some of the options. Here we look at six different perspectives on the sources and possible mitigation obligations for world emissions—illustrated in Figure 1.8 and elsewhere in the chapter. This discussion engages questions of burden sharing in international cooperation to mitigate climate change, a topic addressed in more detail in Chapter 4.

One perspective, shown in panel A of Figure 1.8, concerns total emissions and the countries that account for that total. Twenty countries account for 75 % of world emissions; just five countries account for about half. This perspective suggests that while all countries have important roles to play, the overall impact of mitigation efforts are highly concentrated in a few.

A second perspective, shown in panel B of Figure 1.8, concerns the accumulation of emissions over time. The climate change problem is fundamentally due to the 'stock' of emissions that builds up in the atmosphere. Because of the long atmospheric lifetime of CO_2, a fraction of the CO_2 emitted to the atmosphere from James Watt's steam engine that in the late 18th century helped trigger the Industrial Revolution still remains in the atmosphere. Several studies have accounted in detail for the sources of emissions from different countries over time, taking into account the geophysical processes that remove these gases (Botzen et al., 2008; Höhne et al., 2011; Wei et al., 2012). Attributing past cumulative emissions to countries is fraught with uncertainty and depends on method applied and emissions sources included. Because the uncertainties differ by source of emissions, panel B first shows just cumulative emissions from industrial sources (left bar) and then adds the lowest and highest estimates for emissions related to changes in land use (middle two bars). Many studies on the concept of 'historical responsibility' look at cumulative emissions since 1751, but that approach ignores the fact that widespread knowledge of the potential harms of climate change is only a more recent phenomenon—dating, perhaps, to around 1990 when global diplomatic talks that led to the UNFCCC were fully under way. Thus the right bar in panel B shows cumulative emissions for all sources of CO_2 (including a central estimate for sources related to changes in land use) from 1990 to 2010. Each of these different methods leads to a different assignment of responsible shares and somewhat different rankings. Other studies have examined other time horizons (e.g., Le Quéré et al., 2012). Many scholars who use this approach to analysing historical responsibility and similar approaches to assessing possible future contributions often refer to a fixed 'carbon budget' and identify the 'gap' between that fixed budget and allowable future emissions (e.g., IPCC, 2013b; UNEP, 2011b; Chapter 6).

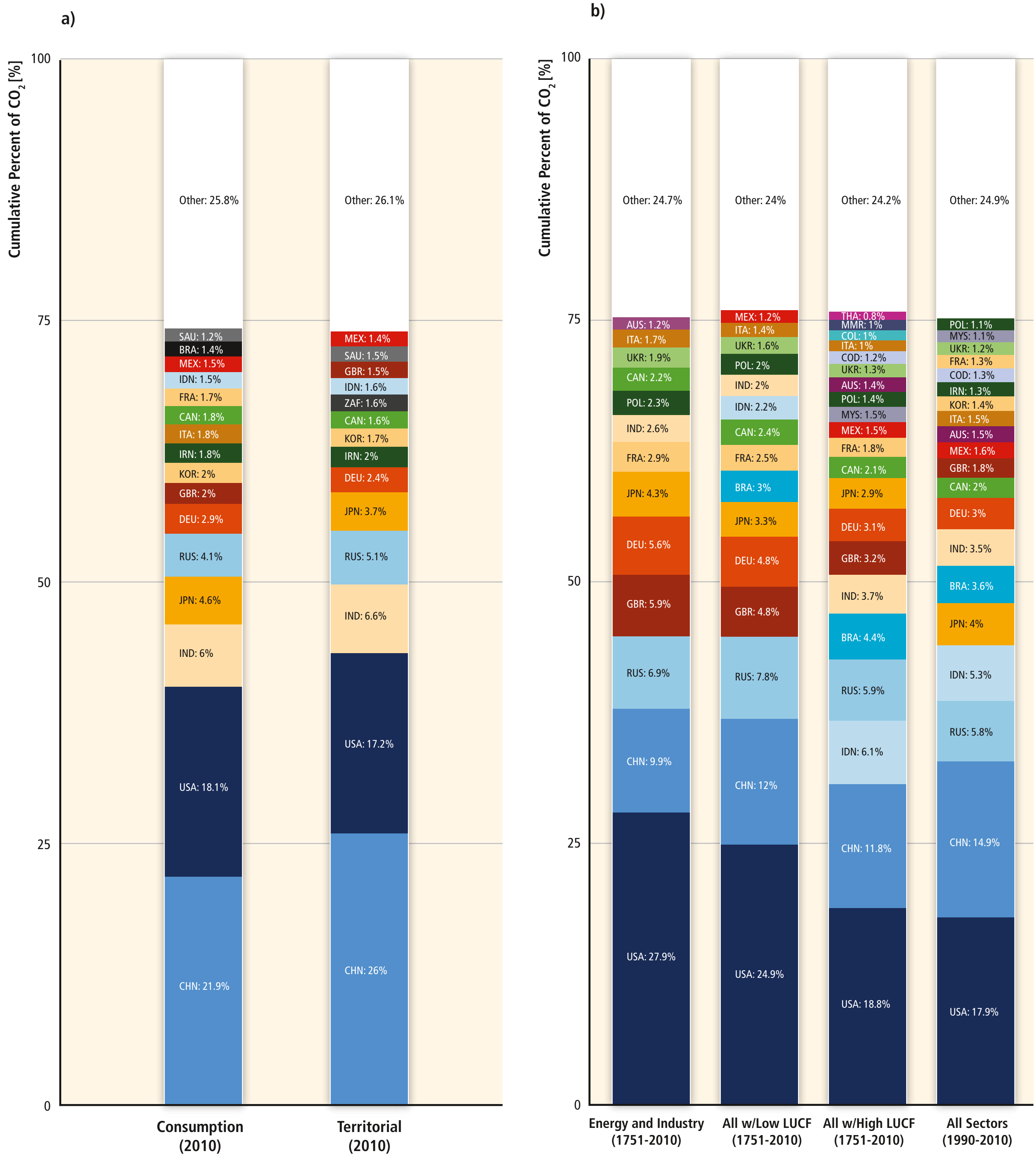
A few studies have extended the concepts of historical responsibility to include other gases as well (den Elzen et al., 2013; Smith et al., 2013). For simplicity, however, in panel B we report total cumulative emissions of just CO_2, the long-lived gas that accounts for the vast majority of long-term climate warming. Adding other gases requires a model that can account for the different atmospheric lifetimes of those gases, which introduces yet more uncertainty and complexity in the analysis of historical responsibility. The results of such analysis are highly sensitive to choices made in the calculation. For example, the share of developed countries can be almost 80 % when excluding non-CO_2 GHGs, Land Use, Land-Use Change, and Forestry, and recent emissions (until 2010) or about 47 % when including these emissions (den Elzen et al., 2013). As a general rule, because emissions of long-lived gases are rising, while emissions of the distant past are highly uncertain, their influence is overshadowed by the dominance of the much higher emissions of recent decades (Höhne et al., 2011).

A third perspective concerns the effects of international trade. So far, nearly all of the statistics presented in this chapter have been organized according to the national territory where the emissions are released into the atmosphere. In reality, of course, some emissions are 'embodied' in products that are exported and discussed in more detail in Section 1.2.2. A tonne of steel produced in China but exported to the United States results in emissions in China when the fundamental demand for the steel originated in the United States. Comparing the emissions estimated from consumption and production (left and right bars of panel A) shows that the total current accounting for world emissions varies considerably—with the largest effects on China and the United States—although the overall ranking does not change much when these trade effects are included. Figure 1.5 earlier in this chapter as well as Section 1.2.1.2 present much more detailed information on this perspective.

A fourth perspective looks at per-capita emissions, shown in panel C of Figure 1.8. This perspective draws attention to fundamental differences in the patterns of development of countries. This panel shows the variation in per-capita emissions for each of the four country groupings. The large variation in emissions in low-income country reflects the large role for changes in land use, such as deforestation and degradation. There are some low-income countries with per-capita emissions that are higher than high-income nations. Some studies have suggested that debates over concepts such as 'common but differentiated responsibility'—the guiding principle for allocating mitigation efforts in talks under the UNFCCC—should focus on individuals rather than nations and assign equal per-capita emission rights to individuals (Chakravarty et al., 2009). Still other studies have looked at the historical cumulative per-capita emissions, thus combining two of the different perspectives discussed here (Teng et al., 2012). Looking within the categories of countries shown in panel C, some developing countries already have higher per-capita emissions than some industrialized nations.

A fifth perspective is the carbon efficiency of different economies. Economies vary in how they convert inputs such as energy (and thus emissions associated with energy consumption) into economic value. This efficiency is commonly measured as the ratio of emission to unit economic output (CO_2/GDP) and illustrated in panel D of Figure 1.8. Typically, economies at an earlier stage of development rely heavily on extractive industries and primary processing using energy intensive methods often reinforced with subsidies that encourage excessive consumption of energy. As the economy matures it becomes more efficient and shifts to higher value-added industries, such as services, that yield low emissions but high economic output. This shift also often includes a change from higher carbon primary fuels to less carbon-intensive fuels. From this perspective, emission obligations might be adjusted to reflect each country's state of economic development while creating incentives for countries to transition to higher economic output without concomitant increases in emissions.

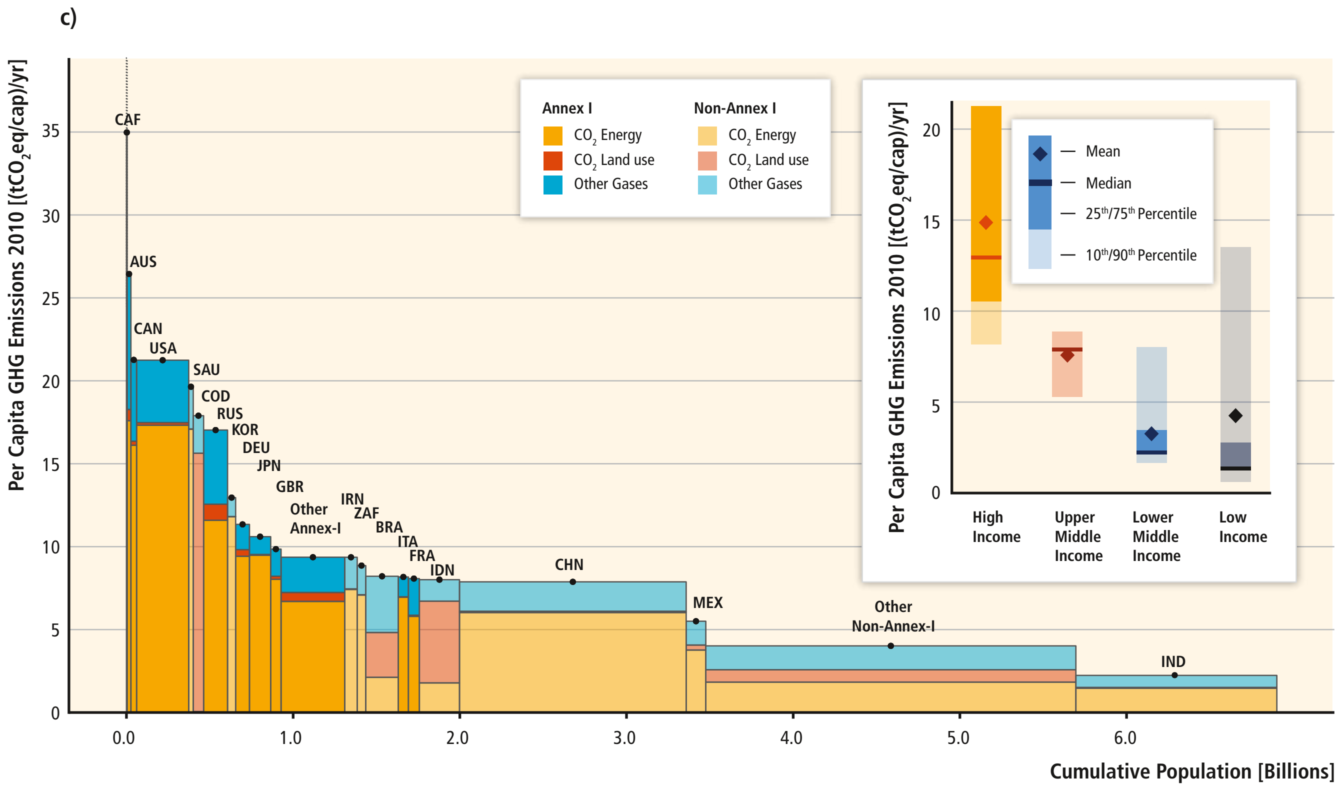
A sixth perspective (panel E of Figure 1.8) looks at the change of emissions between 1990 and 2010. 1990 is a base year for most of the Annex B countries in the Kyoto Protocol. That panel divides the world into three groups—the countries (listed in Annex B) that agreed to targets under the Kyoto Protocol and which formally ratified the Protocol; countries listed in Annex B but which never ratified the treaty (United States) or withdrew (Canada); and countries that joined the Kyoto Protocol but had no formal quantitative emission control targets under the treaty. If all countries listed in Annex B had joined and remained members of the Protocol those countries, on average, would have reduced emissions more than 5 % between 1990 and the compliance period of 2008–2012. From 1990 to 2008–2011, the Annex B nations have reduced their collective emissions by 20 % excluding the United States and Canada and by 9 % if including them, even without obtaining emission credits through the Kyoto Protocol's Clean Development Mechanism (CDM) (UNFCCC, 2013a). (As already noted, the United States never ratified the Kyoto Protocol; Canada ratified but later withdrew.) However, some individual countries will not meet their national target without the CDM or other forms of flexibility that allow them to assure compliance. The trends on this panel reflect many distinct underlying forces. The big decline in Ukraine, Russia, the 12 new members of the EU (EU+12) and one of the original EU members (Germany, which now includes East Germany) reflect restructur-

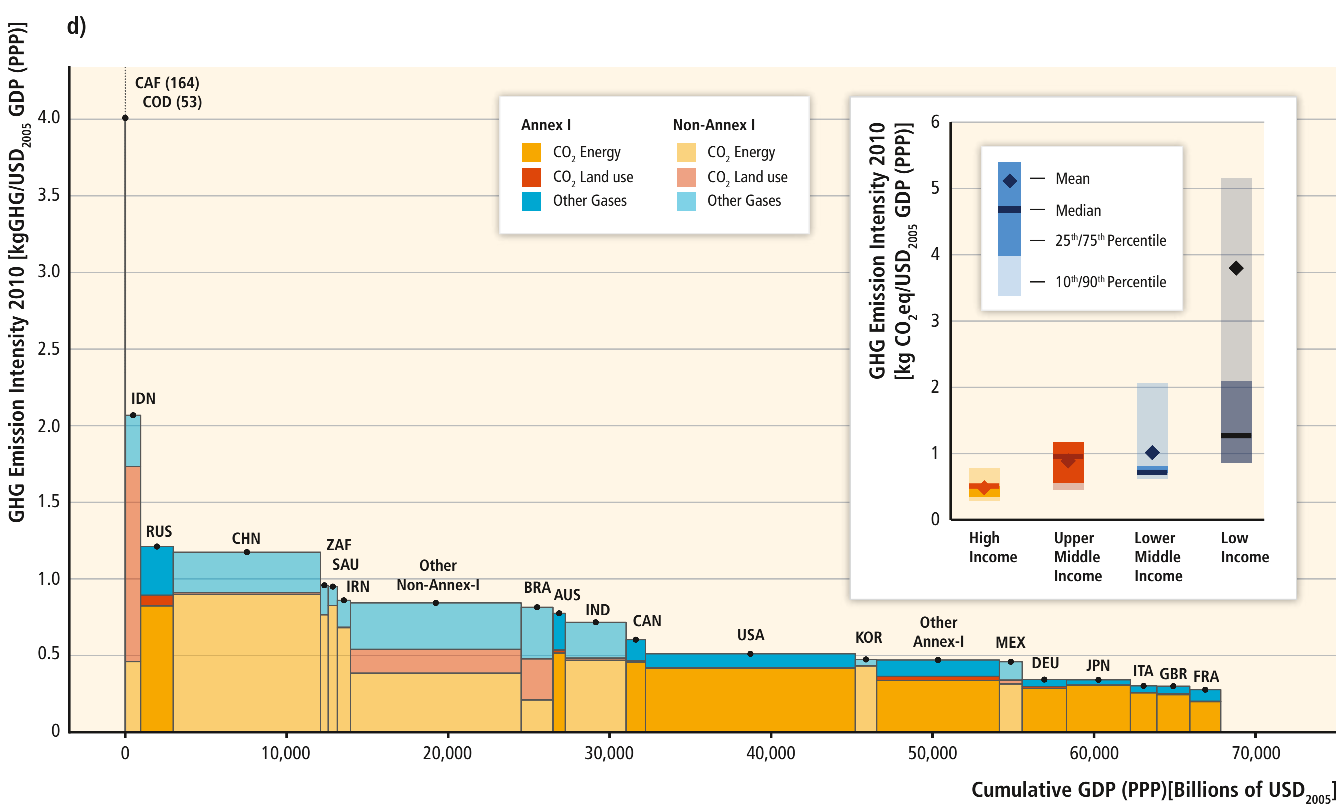


a)
Cumulative Percent of CO2 [%]
100
75
50
25
0
Other: 25.8%
SAU: 1.2%
BRA: 1.4%
MEX: 1.5%
IDN: 1.5%
FRA: 1.7%
CAN: 1.8%
ITA: 1.8%
IRN: 1.8%
KOR: 2%
GBR: 2%
DEU: 2.9%
RUS: 4.1%
JPN: 4.6%
IND: 6%
USA: 18.1%
CHN: 21.9%
Other: 26.1%
MEX: 1.4%
SAU: 1.5%
GBR: 1.5%
IDN: 1.6%
ZAF: 1.6%
CAN: 1.6%
KOR: 1.7%
IRN: 2%
DEU: 2.4%
JPN: 3.7%
RUS: 5.1%
IND: 6.6%
USA: 17.2%
CHN: 26%
Consumption (2010)
Territorial (2010)
b)
Cumulative Percent of CO2 [%]
Other: 24.7%
AUS: 1.2%
ITA: 1.7%
UKR: 1.9%
CAN: 2.2%
POL: 2.3%
IND: 2.6%
FRA: 2.9%
JPN: 4.3%
DEU: 5.6%
GBR: 5.9%
RUS: 6.9%
CHN: 9.9%
USA: 27.9%
Other: 24%
MEX: 1.2%
ITA: 1.4%
UKR: 1.6%
POL: 2%
IND: 2%
IDN: 2.2%
CAN: 2.4%
FRA: 2.5%
BRA: 3%
JPN: 3.3%
DEU: 4.8%
GBR: 4.8%
RUS: 7.8%
CHN: 12%
USA: 24.9%
Other: 24.2%
THA: 0.8%
MMR: 1%
COL: 1%
ITA: 1%
COD: 1.2%
UKR: 1.3%
AUS: 1.4%
POL: 1.4%
MYS: 1.5%
MEX: 1.5%
FRA: 1.8%
CAN: 2.1%
JPN: 2.9%
DEU: 3.1%
GBR: 3.2%
IND: 3.7%
BRA: 4.4%
RUS: 5.9%
IDN: 6.1%
CHN: 11.8%
USA: 18.8%
Other: 24.9%
POL: 1.1%
MYS: 1.1%
UKR: 1.2%
FRA: 1.3%
COD: 1.3%
IRN: 1.3%
KOR: 1.4%
ITA: 1.5%
AUS: 1.5%
MEX: 1.6%
GBR: 1.8%
CAN: 2%
DEU: 3%
IND: 3.5%
BRA: 3.6%
JPN: 4%
IDN: 5.3%
RUS: 5.8%
CHN: 14.9%
USA: 17.9%
Energy and Industry (1751-2010)
All w/Low LUCF (1751-2010)
All w/High LUCF (1751-2010)
All Sectors (1990-2010)

⇒

1


c)
Per Capita GHG Emissions 2010 [(tCO2eq/cap)/yr]
Cumulative Population [Billions]
Annex I
CO2 Energy
CO2 Land use
Other Gases
Non-Annex I
CO2 Energy
CO2 Land use
Other Gases
CAF
AUS
CAN
USA
SAU
COD
RUS
KOR
DEU
JPN
GBR
Other Annex-I
IRN
ZAF
BRA
ITA
FRA
IDN
CHN
MEX
Other Non-Annex-I
IND
0.0
1.0
2.0
3.0
4.0
5.0
6.0
0
5
10
15
20
25
30
35
Per Capita GHG Emissions 2010 [(tCO2eq/cap)/yr]
Mean
Median
25th/75th Percentile
10th/90th Percentile
High Income
Upper Middle Income
Lower Middle Income
Low Income


d)
GHG Emission Intensity 2010 [kgGHG/USD2005 GDP (PPP)]
Cumulative GDP (PPP)[Billions of USD2005]
Annex I
CO2 Energy
CO2 Land use
Other Gases
Non-Annex I
CO2 Energy
CO2 Land use
Other Gases
CAF (164)
COD (53)
IDN
RUS
CHN
ZAF
SAU
IRN
Other Non-Annex-I
BRA
AUS
IND
CAN
USA
KOR
Other Annex-I
MEX
DEU
JPN
ITA
GBR
FRA
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
GHG Emission Intensity 2010 [kg CO2eq/USD2005 GDP (PPP)]
Mean
Median
25th/75th Percentile
10th/90th Percentile
High Income
Upper Middle Income
Lower Middle Income
Low Income

⇒

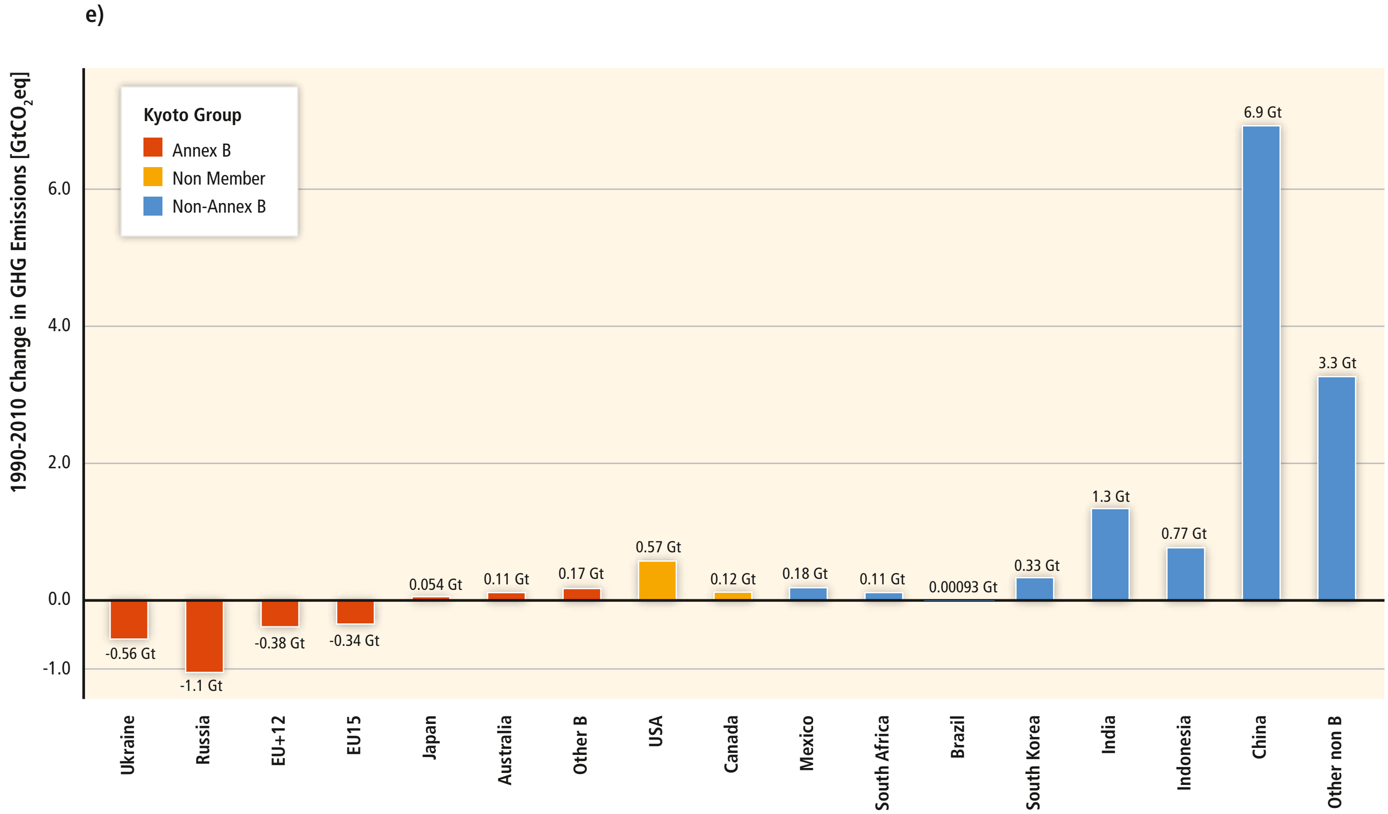


Figure 1.8 | Multiple perspectives on climate change mitigation. Panel A: 2010 emission, ranked in order for the top 75 % of global total. Left bar shows ranking with consumption-based statistics, and right bar shows territorial-based (see Figure 1.5 for more detail). Panel B: Cumulative emissions since 1750 (left three bars) and since 1990 (right bar) for four different methods of emission accounting. The first method looks just at industrial sources of CO_2 (left bar); the second method adds to those industrial sources the lowest plausible estimate for emissions related to changes in land use (second bar), the third uses the highest plausible estimate for land use (third bar) and the final method uses median estimates for land use emissions along with median industrial emissions. (We focus here on uncertainty in land use emissions because those have higher variation than industrial sources.) Panel C: ranking of per-capita emissions by country as well as (inset) for the four groupings of countries Shadings show the 10th to 90th percentile range (light) as well as the 25th to 75th percentile range (dark); horizontal bars identify the median and diamonds the mean. Panel D: Ranking of carbon intensity of economies (emissions per unit GDP, weighted with purchasing power parity) as a function of total size of the economy as well as (inset) for the four groupings of countries Shadings show the 10th to 90th percentile range (light) as well as the 25th to 75th percentile range (dark); horizontal bars identify the median and diamonds the mean. Country names are abbreviated using the three letter standardization maintained by the International Organization for Standardization (ISO, standard 3166). Panel E: Emissions changes from 1990 to 2012 divided into Annex B of the Kyoto Protocol (countries with quantified emission targets, red orange), countries that were eligible for Annex B but are not members (Canada and the United States, yellow) and non-Annex B countries (blue). Sources: Panel A: based on Peters et al., 2011 data; Panel B: based on MATCH data (Höhne et al., 2011). High and low plausible values for land use emissions are two different datasets provided in the MATCH analysis (see Figure 1.4 for more detail and caveat); since the MATCH analysis is based on actual emission data up to 2005, the last four years are were taken from the Historic Emission Database EDGAR/IEA emission data (JRC/PBL, 2013, IEA, 2012a, See Annex II.9). Panel C: JRC/PBL, 2013 and United Nations, 2013a; Panel D: emissions from JRC/PBL, 2013 and national income PPP-adjusted from World Bank *World Development Indicators*; Panel E: JRC/PBL, 2013.

ing of those economies in the midst of a large shift away from central planning. Some of those restructuring economies used base years other than 1990, a process allowed under the Kyoto Protocol, because they had higher emissions in earlier years and a high base year arithmetically leads to larger percentage reductions. The relatively flat emissions patterns across most of the industrialized world reflect the normal growth patterns of mature economies. The sharp rise in emerging markets, notably China and India, reflect their rapid industrialization—a combination of their stage of development and pro-growth economic reforms.

There are many ways to interpret the message from this sixth perspective, which is that all countries collectively are likely to comply with the Kyoto Protocol. One interpretation is that treaties such as the Kyoto Protocol have had some impacts on emissions by setting clear standards as well as institutional reforms that have led countries to adjust their national laws. From that perspective, the presence of the Kyoto obligations is why nearly all the countries that ratified the Kyoto obligations are likely to comply. Another interpretation is that the Kyoto Protocol is a fitting illustration of the concept of 'common but differentiated responsibility', which holds that countries should undertake different efforts and that those most responsible for the underlying problem should do the most. Still another interpretation is that choice of Kyoto obligations largely reveals 'selection effects' through which countries, in effect, select which international commitments to honour. Countries that could readily comply adopted and ratified binding limits; the others avoided such obligations—a phenomenon that, according to this perspective, is evident not just in climate change agreements but other areas of international cooperation as well (e.g., Downs, Rocke, and Barsoom, 1996; Victor 2011).

Still other interpretations are possible as well, with varied implications for policy strategies and the allocation of burdens and benefits among peoples and nations.

1.3.3 Scale of the future mitigation challenge

Future emission volumes and their trajectories are hard to estimate, and there have been several intensive efforts to make these projections. Most such studies start with one or more 'business-as-usual (BAU)' projections that show futures without further policy interventions, along with scenarios that explore the effects of policies and sensitivities to key variables. Chapter 5 looks in more detail at the long-term historical trends in such emissions, and Chapter 6 examines the varied models that are widely used to make emission projections. Using the WGIII AR5 Scenario Database, comprised of those models described in Chapter 6 (See Annex II.10), Figure 1.9 also shows the emission trajectories over the long sweep of history from 1750 through the present and then projections out to 2100.

The long-term scenarios shown on Figure 1.9 illustrate the emissions trajectories that would be needed to stabilize atmospheric concentrations of greenhouse gases at the equivalent of around 450 ppm (430–480) and 550 ppm (530–580) CO_2eq by 2100. The scenarios centered on 450 ppm CO_2eq are likely (> 66 % chance) to avoid a rise in temperature that exceeds 2 degrees above pre-industrial levels. Scenarios reaching 550 ppm CO_2eq have less than a 50 % chance of avoiding warming more than 2 degrees, and the probability of limiting warming to 2 degrees further declines if there is significant overshoot of the 550 ppm CO_2eq concentration. It is important to note that there is no precise relationship between such temperature goals and the accumulation of emissions in the atmosphere largely because the sensitivity of the climate system to changes in atmospheric concentrations is not known with precision. There is also uncertainty in the speed at which future emissions will be net removed from the atmosphere by natural processes since those processes are not perfectly understood. If removal processes are relatively rapid and climate sensitivity is low, then a relatively large quantity of emissions might lead to small changes in global climate. If those parameters prove to have less favourable values then even modest increases in emissions could have big impacts on climate. These uncertainties are addressed in much more detail in WGI Chapter 12 and discussed in Chapter 6 of this report as well. While these uncertainties in how the natural system will respond are important, recent research suggests that a wide range of uncertainties in social systems—such as the design of policies and other institutional factors—are likely to be a much larger factor in determining ultimate impacts on warming from human emissions (Rogelj et al., 2013a; b).

Figure 1.9 underscores the scale of effort that would be needed to move from BAU emissions to goals such as limiting warming to 2 degrees. The rapid rise in emissions since 1970 (left inset) is in stark contrast with the rapid decline that would be needed over the coming century. Because it is practically difficult to orient policy around very long term goals, the middle inset examines the coming few decades—the period during which emissions would need to peak and then decline if stabilization concentrations such as 450 or 550 ppm CO_2eq are to be achieved.

A variety of studies have probed whether national emission reduction pledges, such as those made in the aftermath of the Copenhagen conference, would be sufficient to put the planet on track to meet the 2 degree target (Den Elzen et al., 2011; Rogelj et al., 2011). For example, Den Elzen et al. (2011) found the gap between allowable emissions to maintain a 'medium' chance (50–66 %) of meeting the 2 degree target and the total reduction estimated based on the pledges made at and after COP 15, are as big as 2.6–7.7 GtCO_2e in 2020; that analysis assumed that countries would adopt least-cost strategies for mitigation emissions, but if less idealized scenarios are followed, then the gap would be even larger. A large number of other studies also look at the size of the gap between emission trajectories and the levels needed to reach goals such as 2 degrees (Clarke et al., 2009; Cline, 2011; Yamaguchi, 2012). By logical extension, limiting warming to 1.5 degrees (or even 1 degree, as some governments and analysts suggest should be the goal) is even more challenging. In a major inter-comparison of energy models, eight of 14 scenarios found that stabilizing concentrations at 450 ppm CO_2eq (which would be broadly consistent with stabilizing warming at 2 degrees) would be achievable under optimal conditions in which all countries participated immediately in global regulation of emissions and if a temporary overshooting of the 450 ppm goal were allowed (Clarke et al., 2009). As a general rule, it is still difficult to assess scientifically whether the Cancun pledges (which mainly concern the year 2020) are consistent with most long-term stabilization scenarios because a wide range of long-term scenarios is compatible with a wide range of 2020 emissions; as time progresses to 2030 and beyond, there is a tighter constraining relationship between allowable emissions and long-term stabilization (Riahi et al., 2013). The middle inset in figure 1.9 shows those pledges and suggests that they may be consistent with some scenarios that stabilize concentrations at around 550 ppm CO_2eq but are inconsistent with the least cost scenarios that would stabilize concentrations at 450 ppm CO_2eq.

There is no simple relationship between the next few decades and long-term stabilization because lack of much mitigation in the next decades can, in theory, be compensated by much more aggressive mitigation later in the century—if new zero- and negative-emission technologies become available for widespread use. That point is illustrated in the upper right inset which shows how assumptions about the timing of mitigation and the availability of technologies affects a subset of scenarios that stabilize concentrations between 450 ppm CO_2eq and 550 ppm CO_2eq. Least cost, optimal scenarios depart immediately from BAU trajectories. However, such goals can be reached even if there are delays in mitigation over the next two decades provided that new technologies become available that allow for extremely rapid reductions globally in the decades immediately after the delay.

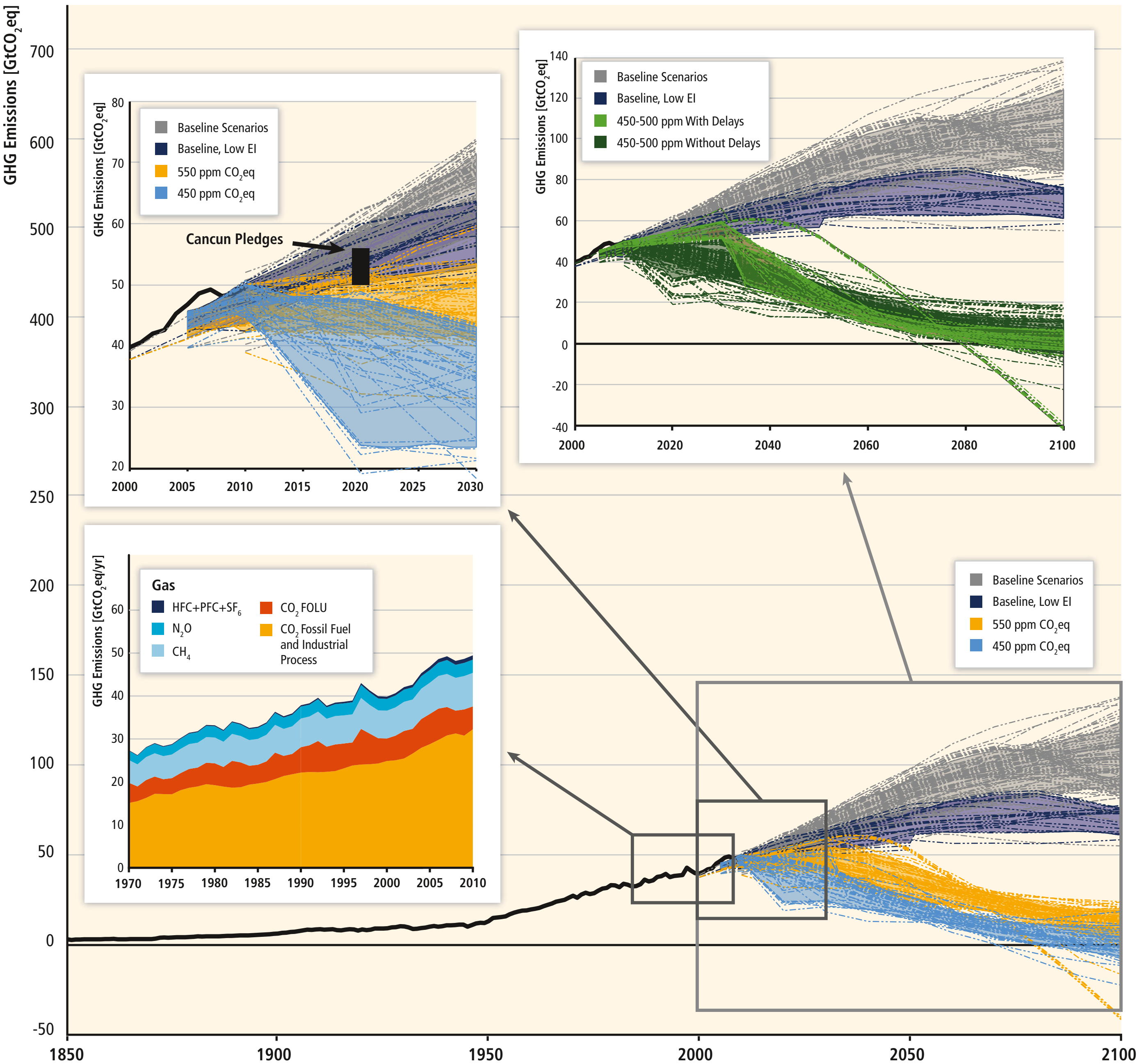


Figure 1.9 | The scale of the mitigation effort needed. Main figure shows the sweep of history from 1750 to 2010 (actual emission estimates) and published projections out to the future. Projections include baseline scenarios that do not assume new mitigation policies (grey shading), baseline scenarios that assume aggressive spread of energy efficiency technologies and changes in behaviour (purple shading), mitigation scenarios that reach concentration levels of about 550 ppm CO_2eq (yellow) and 450 ppm CO_2eq (blue). (The mitigation scenarios include those that assume optimal regulation over time and those with delays to 2030). The bottom left inset shows recent historical emissions and is the same as Figure 1.3c. The top left inset shows the same scenarios from the main figure, but with more detail over the next few decades, including the relationship between the Cancun pledges and the various stabilization scenarios. The top right panel looks instead at long-term patterns in emissions and explores the effects of delays to 2030. It focuses on a subset of the mitigation scenarios from the main panel that are consistent with limiting atmospheric concentrations of CO_2 to about 450 ppm CO_2eq to 500 ppm CO_2eq—a goal broadly consistent with limiting warming to about 2 degrees above pre-industrial levels by 2100 and thus a topic that many models have examined in some detail. The dark green fans show model estimates for optimal least cost strategies for stabilization; light green fans show least cost mitigation with emissions that track baseline scenarios until 2030 and then make deep cuts with the assumption that new technologies come into place. Chart also shows in light black a subset of scenarios based on the premise that very large quantities of net negative emissions (about 40 GtCO$_2$eq/yr by 2100) can be achieved and thus illustrate how assumptions of negative emissions technology may influence the expected time path of emissions. The black scenarios, the output of just one model, entail substantial overshoot of concentrations before stabilization is achieved and unlikely to limit warming to 2 degrees (see Chapter 6). Sources: Historical data drawn from EDGAR/IEA databases reported in IEA, 2012a See Annex II.9; projections drawn from the WGIII AR5 Scenarios Database described in greater detail in Annex II.10; estimates of the impact of the Copenhagen pledges reported in Chapter 13.

Determining the exact cost required to achieve any particular goal is difficult because the models that are used to analyze emissions must contend with many uncertainties about how the real world will evolve. While the list of those uncertainties is long, the model outcomes are particularly sensitive to five that are discussed in much more detail in Chapter 6:

- **Participation**. Studies typically analyze scenarios in which all nations participate with the same timing and level of effort, which also probably leads to the least costly total level of effort. However, a variety of 'delayed participation' scenarios are also analyzed, and with delays it becomes more difficult (and costly) to meet mitigation goals (Bertram et al., 2013; Riahi et al., 2013; Rogelj et al., 2013b; Luderer et al., 2013).

- **International institutions**. Outcomes such as global participation will require effective institutions, such as international agreements on emission reductions and schemes like international trading of emission offsets and financial transfers. If those institutions prove difficult to create or less than optimally effective then global mitigation goals are harder to reach.

- **Technology**. The least cost outcomes (and greatest ease in meeting mitigation goals) require that all emission control technologies be available as quickly as possible. In many models, meeting aggressive goals also requires the availability of negative emission technologies—for example, power plants fired with biomass and including carbon dioxide capture and storage. No such plant actually exists in the world today and with pessimistic assumptions about the availability of such technologies it becomes much harder or impossible to reach aggressive mitigation goals (Edenhofer et al., 2010; Tavoni et al., 2012; Eom et al., 2013; Kriegler et al., 2013).

- **Economic growth**. Typically, these models assume that if economic growth is high then so are emissions (and, in some models, so is the rate of technological innovation). Of course, in the real world, countries can delink economic output and emissions, such as through mitigation policy. More pessimistic assumptions about growth can make emission goals easier to reach (because there is a smaller gap between likely and desired emissions) or harder to reach (because technologies will not be invented as quickly).

- **Peak timing**. Because long-term climate change is driven by the accumulation of long-lived gases in the atmosphere (notably CO_2), these models are sensitive to the exact year at which emissions peak before emission reductions slow and then stop accumulation of carbon in the atmosphere. Models that allow for early peaks create more flexibility for future years, but that early peak also requires the early appearance of mitigation technologies. Later peak years allow for delayed appearance of new technologies but also require more aggressive efforts after the peak. Some models also allow for an 'overshoot' of peak concentrations, which makes it easier for the model to reach long-term stabilization but lowers the odds that stabilization will limit actual warming to a particular target.

In general, only when the most flexible assumptions are made—such as permission for some temporary overshooting of goals and allowing models the maximum flexibility in the technologies that are utilized—is the result a least cost outcome. Since AR4, the modeling community has devoted much more attention to varying those assumptions to allow for less flexible assumptions that are typically better tuned to real world difficulties. These more realistic assumptions are often called 'second best' or 'less idealized'. At present, with the most flexible idealized assumptions several models suggest that the goal of reaching 2 degrees is feasible. With a variety of less ideal—but more realistic—assumptions that goal is much more difficult to reach, and many models find the goal infeasible or exceptionally expensive. These practical difficulties suggest that while optimal analyses are interesting, the real world may follow pathways that are probably more costly and less environmentally effective than optimal outcomes. They are also a reminder that such models are a portrayal of the world that

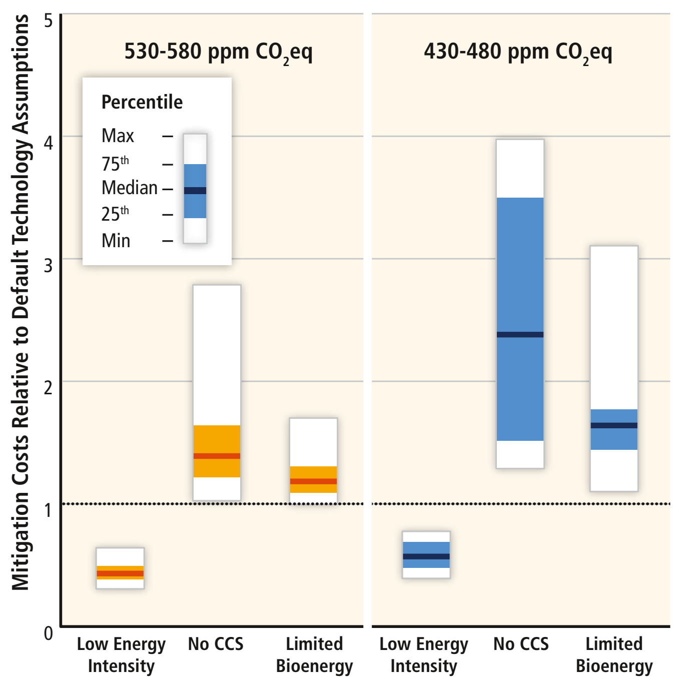


Figure 1.10 | The effects of real world assumptions on mitigation costs. Relative mitigation cost increase in case of technology portfolio variations compared to a scenario with default technology assumptions for stabilizing atmospheric GHG concentrations centered on 450 ppm (430–480 ppm, right) and 550 ppm (530–580 ppm, left) CO_2eq in the year 2100. Boxplots show the 25th to 75th percentile range with median value (heavy line) and unshaded area the total range across all reported scenarios, with the caveat that the numbers of scenarios used in such analyses is relatively small. Scenario names on x-axis indicate the technology variation relative to the default assumptions: Low Energy Intensity= energy intensity rising at less than standard values, such as due to extensive use of energy efficiency programs and technologies (N = 7, 12); No CCS = CCS technologies excluded (N = 3, 11); Limited Bioenergy = maximum of 100 EJ/yr bioenergy supply (N = 7, 12). Source: redrawn from Figure 5 in Kriegler et al. (2013) and Figure 6.24.

is necessarily simplified and highly dependent on assumptions. There can be many unforeseen changes that make such goals easier or more difficult to reach. For example, unexpectedly high economic growth and expansion of coal-fired electricity has raised emissions and made goals harder to reach; unexpected innovations in renewables, energy efficiency and natural gas are possibly making climate goals easier to reach.

The importance of these real world approaches to analysis is illustrated in Figure 1.10, which shows how different assumptions about energy intensity (which is related to human behaviour) and the availability of technologies affect the estimated total cost. Compared with costs under default technology assumption, if energy intensity is assumed to improve rapidly (Low EI) the total cost for mitigating to 430–480 ppm CO_2eq (right boxplot) or 530–580 ppm CO_2eq (left boxplot) then costs are cut in half. (These low EI scenarios are shown, as well, in purple on Figure 1.9—they lead, systematically, to emissions that are significantly lower than standard BAU scenarios.) Most studies that look at technological and behavioural assumptions conclude that real-world costs could be higher than typical, optimal estimates. For example, if CCS technologies are not available then the cost of meeting 450 ppm stabilization could be 1.5 times to 4 times greater than compared to full CCS availability. Similarly, if there is limited bioenergy supply then costs could be dramatically higher than standard least cost estimates.

1.4 Mitigation challenges and strategies

While this report addresses a wide array of subjects related to climate change, our central purpose is to discuss mitigation of emissions. The chapters that follow will examine the challenges for mitigation in more detail, but five are particularly notable. These challenges, in many respects, are themes that will weave through this report and appear in various chapters.

1.4.1 Reconciling priorities and achieving sustainable development

Climate change is definitely one of the most serious challenges human beings face. However, it is not the only challenge. For example, a survey of the Millennium Development Goals (MDGs) offers examples of the wider array of urgent priorities that governments face. These goals, worked out in the context of the United Nations Millennium Declaration in September 2000, cover eight broad areas of development that span eradicating extreme poverty and hunger, reducing child mortality, combating HIV/AIDS, malaria and other diseases. Within those broad areas the MDGs include 18 specific targets. For example, halving, between 1990 and 2015, the proportion of people whose income is less than $1 a day, and halving, between 1990 and 2015, the proportion of people who suffer from hunger, are among targets under the goal of eradicate extreme poverty and hunger. (Since then, the official poverty level has been revise upwards to $1.25/day by the World Bank.) MDGs are unquestionably the urgent issues human beings should cope with immediately and globally. Achieving such goals along with an even broader array of human aspirations is what many governments mean by 'sustainable development' as echoed in many multilateral statements such as the declaration from the Rio +20 conference in 2012 (United Nations, 2012).

All countries, in different ways, seek sustainable development. Each puts its priorities in different places. The need to make tradeoffs and find synergies among priorities may be especially acute in the least developed countries where resources are particularly scarce and vulnerabilities to climate change are systematically higher than in the rest of the world (see Box 1.1). Those priorities also vary over time—something evident as immediate goals such as job creation and economic growth have risen in salience in the wake of the global financial crisis of the late 2000s. Moreover, sustainable development requires tradeoffs and choices because resources are finite. There have been many efforts to frame priorities and determine which of the many topics on global agendas are most worthy. Making such choices, which is a highly political process, requires looking not only at the present but also posterity (Summers, 2007). Applying standard techniques for making tradeoffs—for example, cost-benefit analysis (CBA)—is extremely difficult in such settings, though the importance of CBA itself is well recognized (Sachs, 2004) (See Section 3.6). Important goals, such as equity, are difficult to evaluate alongside other goals that can more readily be monetized. Moreover, with climate change there are additional difficulties such as accounting for low probability but high impact catastrophic damages and estimating the monetary value of non-market damages (Nussbaum, 2000; Weitzman, 2009).

1.4.2 Uncertainty and risk management

The policy challenge in global climate change is one of risk management under uncertainty. The control of emissions will impose costs on national economies, but the exact amount is uncertain. Those costs could prove much higher if, for example, policy instruments are not designed to allow for flexibility. Or they could be much lower if technological innovation leads to much improved energy systems. Mindful of these uncertainties, there is a substantial literature on how policy design can help contain compliance costs, allowing policymakers to adopt emission controls with greater confidence in their cost (Metcalf, 2009).

Perhaps even more uncertain than the costs of mitigation are the potential consequences of climate change. As reviewed elsewhere in the IPCC assessment, there is growing recognition of the importance of considering outcomes at high magnitudes of climate change, which could lead to strong feedbacks and very large impacts—for example, higher sea levels and substantial impacts on natural ecosystems (IPCC, 2014 (forthcoming); see also WGI, Chapters 11–14 and Annex I). Investments in adaptation, which vary in their feasibility, can help reduce exposure to climate impacts and may also lessen uncertainty in the assessment of possible and probable impacts (World Bank, 2010).

Since risks arise on both fronts—on the damages of climate change and on the costs of mitigation responses—scholars often call this a 'risk-risk' problem. In the case of climate change, management in this context of risk and uncertainty must contend with another large challenge. Mitigation actions and effects of climate change involve a multitude of actors working at many different levels, from individual firms and NGOs to national policy to international coordination. The interest of those different actors in undertaking climate change mitigation also varies. Moreover, this multitude faces a large array of decisions and can deploy many different instruments that interact in complex ways. Chapter 2 explores the issues involved with this multitude of actors and instruments. And Chapter 3 introduces a framework for analysing the varied policy instruments that are deployed and assessing their economic, ecological, ethical and other outcomes.

Box 1.1 | Least Developed Countries: mitigation challenges and opportunities

The Least Developed Countries (LDCs) consist of 49 countries and over 850 million people, located primarily in Africa and Asia—with 34 LDCs in Africa alone (UNFPA, 2011). These countries are characterised by low income (three-year average gross national income per capita of less than USD 992), weak human assets index (nutrition, health, school enrolment, and literacy), and high economic vulnerability criterion (UNCTAD, 2012a). Despite their continued marginalization in the global economy, these countries' economies grew at about 6 % per year from 2000 to 2008, largely stimulated by the strong pull-effect of the Asian emerging economies (Cornia, 2011). However, the global economic downturn and the worsening Eurozone crisis have had an effect on most LDC economies. In 2011, LDCs grew by 4.2 %, 1.4 percentage lower than the preceding year, hence mirroring the slowdown of growth worldwide (UNCTAD, 2012a). Many of the traditional domestic handicaps remain as LDC economies continue to be locked into highly volatile external transactions of commodities and low-productivity informal activities, having neither the reserves nor the resources needed to cushion their economies and adjust easily to negative shocks.

Regarding the social trends, LDCs as a group have registered encouraging progress towards achieving some of the Millennium Development Goals (MDGs), especially in primary school enrolment, gender parity in primary school enrolment, HIV/AIDS prevalence rates and the share of women in non-agricultural wage employment (Sachs, 2012). However, poverty reduction has been less successful; only four (of 33) LDCs are on track to cut the incidence of extreme poverty to half 1990 levels by 2015 (UNCTAD, 2011). In line with this, the Istanbul Programme of Action, adopted at the 4th UN Conference on the Least Developed Countries (LDC-IV) highlighted the importance of building the productive base of LDCs' economies and promoting the process of structural transformation involving an increase in the share of high productivity manufacturing and an increase in agricultural productivity (UNCTAD, 2012b).

The LDCs' continued reliance on climate-sensitive activities such as agriculture means that adapting to climate change remains a central focus of economic development. If climate changes become acute the additional burden of adaptation could draw resources away from other activities, such as mitigation. Alternatively, more acute attention to adaptation could help mobilize additional efforts for mitigation within these countries and other countries that are the world's largest emitters. The scientific literature has not been able to determine exactly when and how adaptation and mitigation are complementary or competing activities in LDCs; what is clear, however, is that meeting the climate and development challenge entails integrating mitigation and adaptation actions in the context of sustainable development (Ayers and Huq, 2009; Martens et al., 2009; Moomaw and Papa, 2012). In LDCs, like all other countries, investment in new infrastructures offers the opportunity to avoid future GHG emissions and lower mitigation costs (Bowen and Fankhauser, 2011). Other emissions avoidance options are also available for LDCs in areas of innovative urban development, improvements in material productivity (Dittrich et al., 2012) and the application of enhanced land use efficiency through intensified agricultural practices and sustainable livestock management (Burney et al., 2010).

There could be significant additional costs associated with the expansion of infrastructure in LDCs aimed at decoupling GHG emissions and development. Paying these costs in countries with extremely scarce resources could be a challenge (Krausmann et al., 2009). Moreover, the additional costs could deter private investors in low carbon interventions, leaving the public sector with additional burdens, at least in the short-term (UN DESA, 2009; Collier and Venables, 2012). For most LDC governments, creating the conditions for accelerated economic growth and broad-based improvements in human well-being will remain the main driver of national development policies and could lead to the perception—if not the reality—that development and mitigation are conflicting goals.

Scientific research on risk management has several implications for managing the climate change problem. One is the need to invest in research and assessment that can help reduce uncertainties. In relation to climate change these uncertainties are pervasive and they involve investments across many intellectual disciplines and activities, such as engineering (related to controlling emissions) and the many fields of climate science (related to understanding the risks of climate change). In turn, these knowledge generating and assessment processes must be linked to policy action in an iterative way so that policymakers can act, learn, and adjust while implementing policy measures that are 'robust' across a variety of scenarios (McJeon et al., 2011). Another major implication is the need to examine the possibilities of extreme climate impacts. These so called 'tail' risks in climate impacts could include relatively rapid changes in sea level, feedbacks from melting permafrost that amplify the concentrations of greenhouse gases in the atmosphere, or possibly a range of so far barely analyzed outcomes (see generally Weitzman 2011). There are many options that could play a role in these risk management strategies such as adaptation, rapid deployment of low or negative emission technologies (e.g., nuclear, advanced renewables, or bioenergy plants that store their emissions underground) and geoengineering. Many of these options raise governance and risk management challenges of their own.

1.4.3 Encouraging international collective action

Unlike many matters of national policy, a defining characteristic of the climate change issue is that most of its sources are truly global. Nearly all climate-altering gases have atmospheric lifetimes sufficiently long that it does not matter where on the planet they are emitted. They spread worldwide and affect the climate everywhere. Thus, national governments develop their own individual policies with an eye to what other nations are likely to do and how they might react (Victor, 2011). Even the biggest emitters are mostly affected by emissions from other countries rather than principally their own pollution. International collective action is unavoidable.

As the level of ambition to manage the risks of climate change rises, collective action can help governments achieve efficient and effective outcomes in many ways. Those include not just coordination on policies to control emissions but also collective efforts to promote adaptation to climate change. International coordination is also needed to share information about best practices in many areas. For example, many of the promising options for reducing emissions involve changes in behaviour; governments are learning which policies are most effective in promoting those changes and sharing that information more widely can yield practical leverage on emissions (Aldy and Stavins, 2007; Dubash and Florini, 2011) (see also Chapter 13). Coordination is also essential on matters of finance since many international goals seek action by countries that are unwilling or unable to pay the cost fully themselves (see Chapter 16) (WEF, 2011). Extremely short-lived pollutants, such as soot, do not mix globally yet these, too, entrain many issues of international cooperation. Often this pollution moves across regional borders. And coordination across borders can also help promote diffusion of best practices to limit these pollution sources.

International cooperation, including financial transfers, can also help diffuse knowledge and capabilities to countries as they adapt to the effects of climate change (UNFCCC, 2008, 2012c; World Bank, 2010). Indeed, in response to these many logics for international cooperation on mitigation and adaptation extensive intergovernmental and other coordinating efforts are under way (see Section 1.2.1.4 and also Chapter 13).

One of the central challenges in international cooperation is that while national governments play central roles—for example, negotiating, and implementing treaties—effective cooperation must also engage a large number of other actors, notably in the private sector. Moreover, governments and other actors cooperate not only at the global level through universal forums such as the United Nations but also in a wide array of regional forums. One result of these multiple processes that entrain public institutions as well as private actors is decentralized and overlapping systems for government (see Chapter 13).

1.4.4 Promoting investment and technological change

Radical delinking of GDP growth with emissions will probably require massive changes in technology. Achieving those changes will require closer attention to policies that affect technology innovation and deployment. Technologies vary in many ways—they have different maturity stages and potential for improvement through 'learning'; they have different mitigation potentials and require different policy responses in developing and developed countries. Many studies have looked in detail at how this diversity of technology policy approaches might influence emissions and climate policy in the future (UN DESA, 2009, 2011; WBCSD, 2009; IEA, 2012d).

Nearly all low GHG technology options share one commonality—a shift in the cost structure of supplying energy services from operating/fuel costs to upfront capital costs. Thus policy options are particularly focused on how to create credible assurances for investors who pay these capital costs. Policies that reduce demand for energy—notably those that mobilize investments in energy efficiency in both end use and supply—can play pivotal roles by limiting the total cost needed to transform energy supplies. The rate at which these changes in energy systems can occur is an important area of research. The high fixed cost of infrastructures also create 'lock-in' effects that help explain why it is difficult to change real world emission patterns quickly (Davis et al., 2010; IEA, 2012a).

International cooperation, finance, and technology transfer all have important roles to play as a catalyst to accelerate technology progress at each stage in the lifecycle of a technology (see Chapter 13 on international cooperation). Business plays a central role in this process of innovation and diffusion of technologies. For example, massive improvements in wind turbine technology have arisen through cooperation between innovators and manufacturers in many different markets. Similarly, business has played central roles in innovating and applying energy efficiency technologies and practices that can help cut costs and allow higher profits and additional employment opportunities. (ILO, 2012, 2013). Numerous studies indicate that it will be difficult to achieve widely discussed goals such as limiting warming to 2 degrees at least without drastic efficiency improvements (but also life style changes) (UNECE, 2010; Huntington and Smith, 2011; OECD, 2011; IEA, 2012d; Riahi et al., 2012). Innovations are needed not just in technology but also lifestyles and business practices that often evolve in tandem with technology. For example, after the Fukushima Daiichi accident in March 2011, changes in Japanese life style and behaviour curbed nationwide domestic household electricity demand by 5 % during the winter 2011/12 compared with the previous year after accounting for degree day differences (Ministry of Environment, Japan, 2012). Similarly, electricity demand in the Tokyo area was around 10 % lower in the summer 2011 than in 2010 and about 40 % of the reduction of demand resulted from behavioural changes that allowed for greater conservation of electricity used for air-conditioning (Nishio and Ofuji, 2012).

As a practical matter, strategies for innovating and deploying new technologies imply shifts in policy on many different fronts. In addition to the role for businesses, the public sector has a large role to play in affecting the underlying conditions that affect where and how firms actually make long-lived and at times financially risky investments. Those conditions include respect for contracts, a predictable and credible scheme for public policy, protection of intellectual property, and relatively efficient mechanisms for creating contracts and resolving disputes. These issues, explored in more detail in Chapter 16, are hardly unique to climate change. In addition, there may be large roles for the public sector in making public investments in basic technology that the private sector, on its own, would not adequately provide—a topic covered in more detail in Chapters 3.11 and 15.6.

1.4.5 Rising attention to adaptation

For a long time, nearly all climate policy has focused on mitigation. Now, with some change in climate inevitable (and a lot more likely) there has been a shift in emphasis to adaptation. While adaptation is primarily the scope of WGII, there are important interactions between mitigation and adaptation in the development of a mitigation strategy. If it is expected that global mitigation efforts will be limited, then adaptation will play a larger role in overall policy strategy. If it is expected that countries (and natural ecosystems) will find adaptation particularly difficult, then societies should become more heavily invested in the efforts to mitigate emissions.

Mitigation and adaptation also have quite different implications for collective action by nations. A strategy that relies heavily on mitigation requires collective action because no nation, acting alone, can have much impact on the global concentration of GHGs. Even the biggest nations account for only about one-quarter of global emissions. By contrast, most activities relevant for adaptation are local—while they may rely, at times, on international funding and know-how they imply local expenditures and local benefits. The need for (and difficulty of) achieving international collective action is perhaps less daunting than for mitigation (Victor, 2011).

Developing the right balance between mitigation and adaptation requires many tradeoffs and difficult choices (See WG II Chapter 17 for a more detailed discussion). In general, societies most at risk from climate change—and thus most in need of active adaptation—are those that are least responsible for emissions. That insight arises, in part, from the fact that as economies mature they yield much higher emissions but they also shift to activities that are less sensitive to vagaries of the climate. Other tradeoffs in striking the mitigation/adaptation balance concern the allocation of resources among quite different policy strategies. The world has spent more than 20 years of diplomatic debate on questions of mitigation and has only more recently begun extensive discussions and policy planning on the strategies needed for adaptation. As a practical matter, the relevant policymakers also differ. For mitigation many of the key actions hinge on international coordination and diplomacy. For adaptation the policymakers on the front lines are, to a much greater degree, regional and local officials such as managers of infrastructures that are vulnerable to extreme weather and changes in sea level.

1.5 Roadmap for WG III report

The rest of this report is organized into five major sections.

First, Chapters 2–4 introduce fundamental concepts and framing issues. Chapter 2 focuses on risk and uncertainty. Almost every aspect of climate change—from the projection of emissions to impacts on climate and human responses—is marked by a degree of uncertainty and requires a strategy for managing risks; since AR4, a large number of studies has focused on how risk management might be managed where policies have effects at many different levels and on a diverse array of actors. Scholars have also been able to tap into a rich literature on how humans perceive (and respond to) different types of risks and opportunities. Chapter 3 introduces major social, economic, and ethical concepts. Responding to the dangers of unchecked climate change requires tradeoffs and thus demands clear metrics for identifying and weighing different priorities of individuals and societies. Chapter 3 examines the many different cost and benefit metrics that are used for this purpose along with varied ethical frameworks that are essential to any full assessment. Chapter 4 continues that analysis by focusing on the concept of 'sustainable development'. The varied definitions and practices surrounding this concept reflect the many distinct efforts by societies and the international community to manage tradeoffs and synergies involved with economic growth, protection of the environment, social equity, justice and other goals.

Second, Chapters 5–6 put the sources of emissions and the scale of the mitigation challenge into perspective. Chapter 5 evaluates the factors that determine patterns of anthropogenic emissions of GHGs and particulate pollutants that affect climate. Chapter 6 looks at the suite of computer models that simulate how these underlying driving forces may change over time. Those models make it possible to project future emission levels and assess the certainty of those projections; they also allow evaluation of whether and how changes in technology, economy, behaviour and other factors could lower emissions as needed to meet policy goals.

Third, Chapters 7–11 look in detail at the five sectors of economic activity that are responsible for nearly all emissions. These sectors include energy supply systems (Chapter 7), such as the systems that extract primary energy and convert it into useful forms such as electricity and refined petroleum products. While energy systems are ultimately responsible for the largest share of anthropogenic emissions of climate gases, most of those emissions ultimately come from other sectors, such as transportation, that make final use of energy carriers. Chapter 8 looks at transportation, including passenger and freight systems. Chapter 9 examines buildings and Chapter 10 is devoted to industry. Together, Chapters 7–10 cover the energy system as a whole. Chapter 11 focuses on agriculture, forestry, and other land use (AFOLU), the only sector examined in this study for which the majority of emissions are not rooted in the energy system. Chapter 11 includes an appendix that delves in more detail into the special issues related to bioenergy systems (Section 11.13).

Looking across Chapters 7–11 one major common theme is the consideration and quantification of 'co-benefits' and 'adverse side-effects' of mitigating climate change, i. e., effects that a policy or measure aimed at one objective might have on other objectives. Measures limiting emissions of GHGs or enhancing sinks often also yield other benefits such as lowering the harmful health effects of local air pollution or regional acidification when firms and individuals switch to less polluting combustion technologies and fuels. But fuel switching from coal to gas can have adverse side-effects on the jobs in the coal mining industry. Although difficult to quantify, these co-benefits and adverse side-effects often play a large role in evaluating the costs and benefits of mitigation policies (see also Sections 3.6.3, 4.2, 4.8 and 6.6).

Often, this approach of looking sector-by-sector (and within each sector at individual technologies, processes, and practices) is called 'bottom up'. That perspective, which is evident in Chapters 7–11 complements the 'top down' perspective of Chapters 5–6 in which emissions are analyzed by looking at the whole economy of a nation or the planet.

Fourth, Chapter 12 looks at spatial planning since many emissions are rooted in how humans live, such as the density of population and the infrastructure of cities. Matters of spatial planning are treated distinctly in this report because they are so fundamental to patterns of emissions and the design and implementation of policy options.

Fifth, Chapters 13–16 look at the design and implementation of policy options from a variety of perspectives. Chapter 13 concentrates on the special issues that arise with international cooperation. Since no nation accounts for more than about one-quarter of world emissions, and economies are increasingly linked through trade and competition, a large body of research has examined how national policies could be coordinated through international agreements like the UN Framework Convention on Climate Change and other mechanisms for cooperation. Chapter 14 continues that analysis by focusing on regional cooperation and development patterns.

Chapter 15 looks at what has been learned within countries about the design and implementation of policies. Nearly every chapter in this study looks at an array of mitigation policies, including policies that work through market forces as well as those that rely on other mechanisms such as direct regulation. Chapter 15 looks across that experience at what has been learned.

Chapter 16, finally, looks at issues related to investment and finance. The questions of who pays for mitigation and the mechanisms that can mobilize needed investment capital are rising in prominence in international and national discussions about mitigation. Chapter 16 examines one of the most rapidly growing areas of scholarship and explores the interaction between public institutions such as governments and private firms and individuals that will ultimately make most decisions that affect climate change mitigation. Among its themes is the central role that financial risk management plays in determining the level and allocation of investment financing.

1.6 Frequently Asked Questions

FAQ 1.1 What is climate change mitigation?

The Framework Convention on Climate Change (UNFCCC), in its Article 1, defines *climate change* as: "a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods". The UNFCCC thereby makes a distinction between climate change attributable to human activities altering the atmospheric composition, and climate variability attributable to natural causes. The IPCC, in contrast, defines climate change as "a change in the state of the climate that can be identified (e. g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer", making no such distinction.

Climate Change Mitigation is a "human intervention to reduce the sources or enhance the sinks of greenhouse gases" (GHG) (See Glossary (Annex I)). The ultimate goal of mitigation (per Article 2 of the UNFCCC) is preventing dangerous anthropogenic interference with the climate system within a time frame to allow ecosystems to adapt, to ensure food production is not threatened and to enable economic development to proceed in a sustainable manner.

FAQ 1.2 What causes GHG emissions?

Anthropogenic GHGs come from many sources of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases (HFCs, PFCs and SF_6). CO_2 makes the largest contribution to global GHG emissions; fluorinated gases (F-gases) contribute only a few per cent. The largest source of CO_2 is combustion of fossil fuels in energy conversion systems like boilers in electric power plants, engines in aircraft and automobiles, and in cooking and heating within homes and businesses. While most GHGs come from fossil fuel combustion, about one third comes from other activities like agriculture (mainly CH_4 and N_2O), deforestation (mainly CO_2), fossil fuel production (mainly CH_4) industrial processes (mainly CO_2, N_2O and F-gases) and municipal waste and wastewater (mainly CH_4). (See 1.3.1)

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