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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).

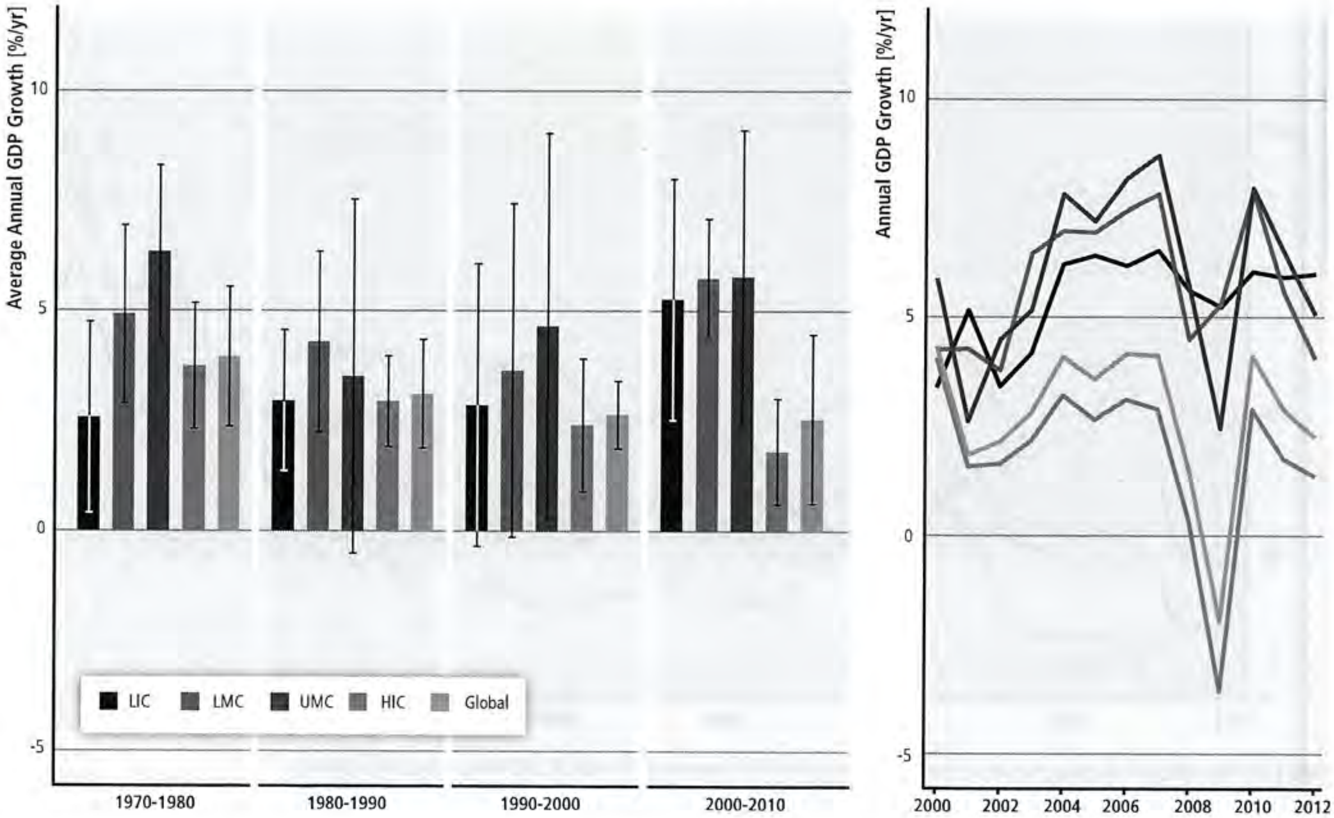

Figure 1.1 | Annual real growth rates of GDP by decade (left panel) and since 2000 (right panel) for four groups of countries as defined by the World Bank (World Bank, 2013): high-income, mature industrialized countries (HIC), upper-middle-income countries (UMC), lower-middle-income (LMC), and low-income 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

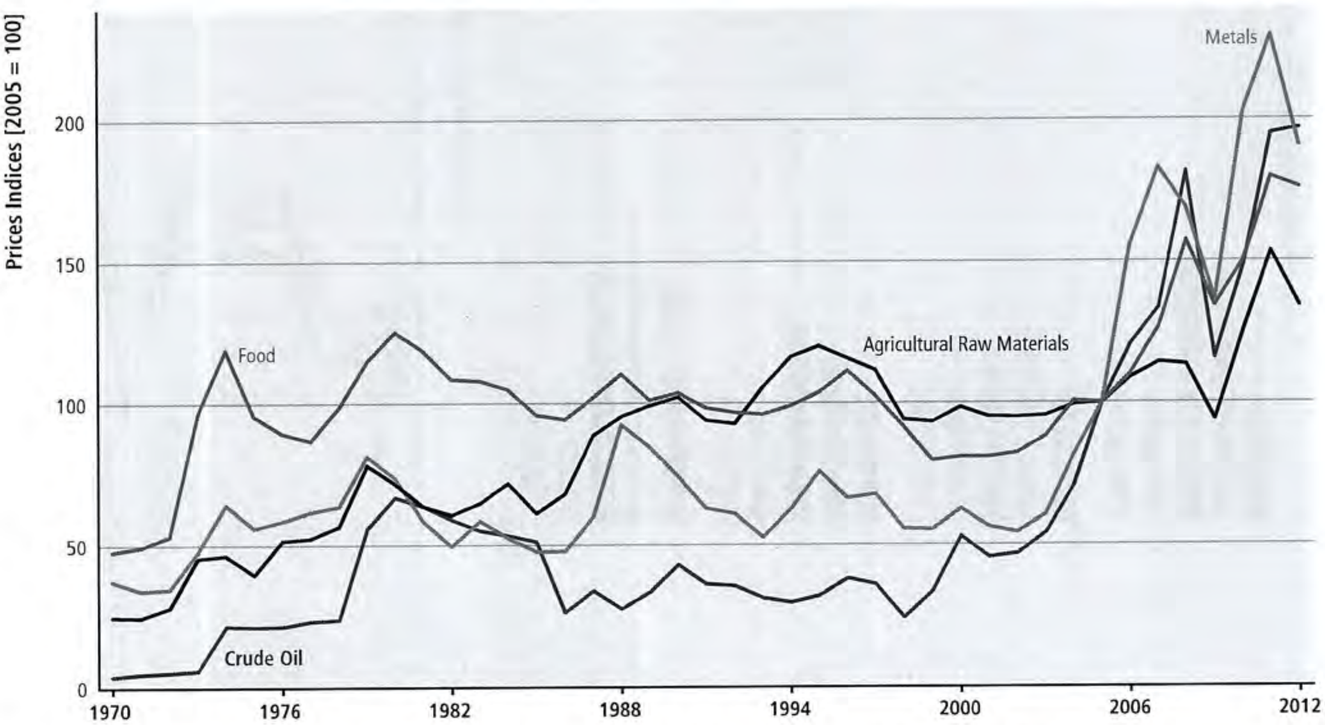

Figure 1.2 | Price indices for four major baskets of commodities: agricultural raw materials, food, crude oil, and metals. Source: IMF (2013a).

(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

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[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.

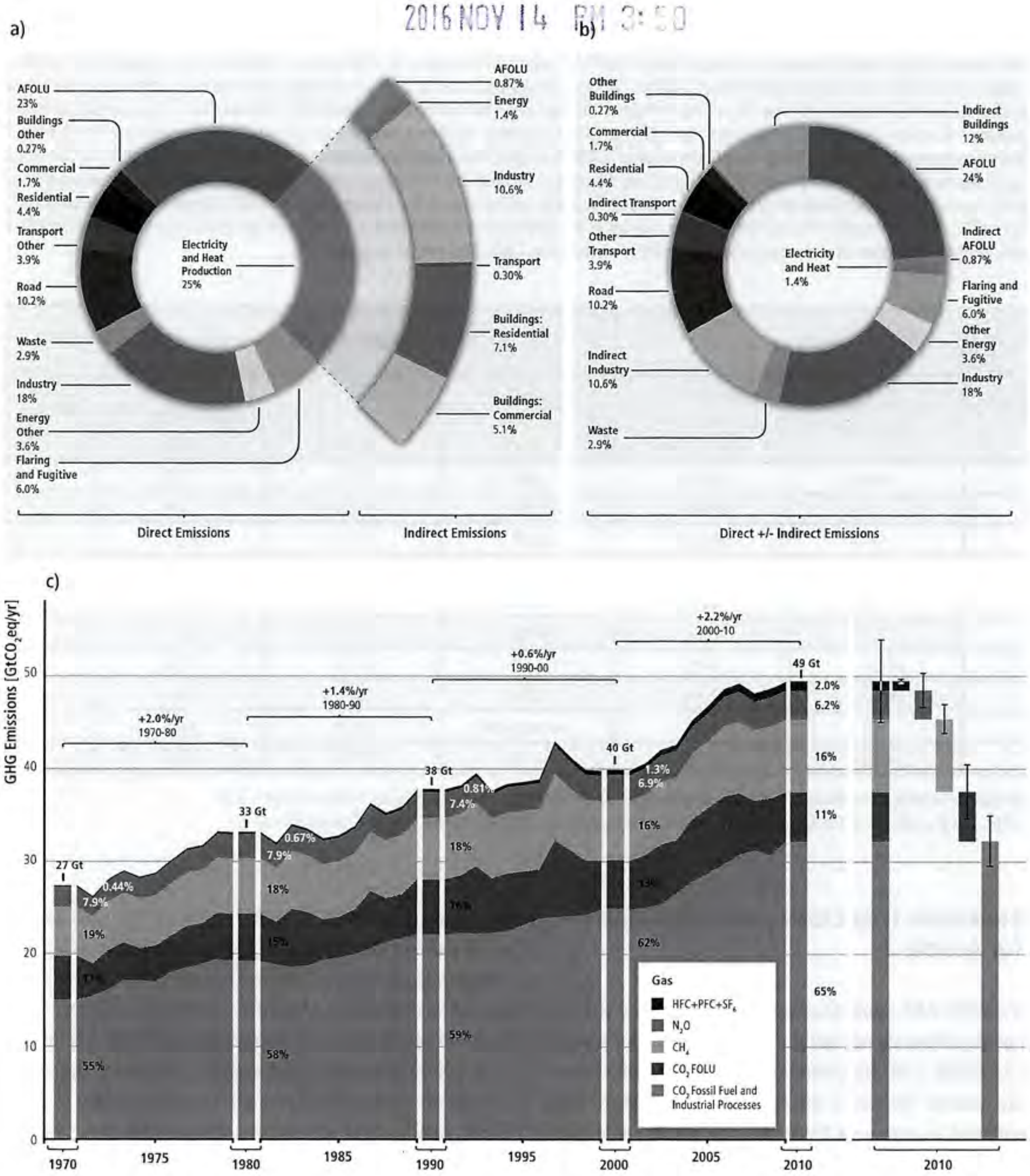


Figure 1.3 | Panel A (top left): Allocation of total GHG emissions in 2010 (49.5 $GtCO_2eq/yr$) across the five sectors examined in detail in this report (see Chapters 7–11). Pullout from panel A allocates indirect CO_2 emission shares from electricity and heat production to the sectors of final energy 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)	WGI (20 and 100 year from AR5 & 500 year from AR4)		
			100 years	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

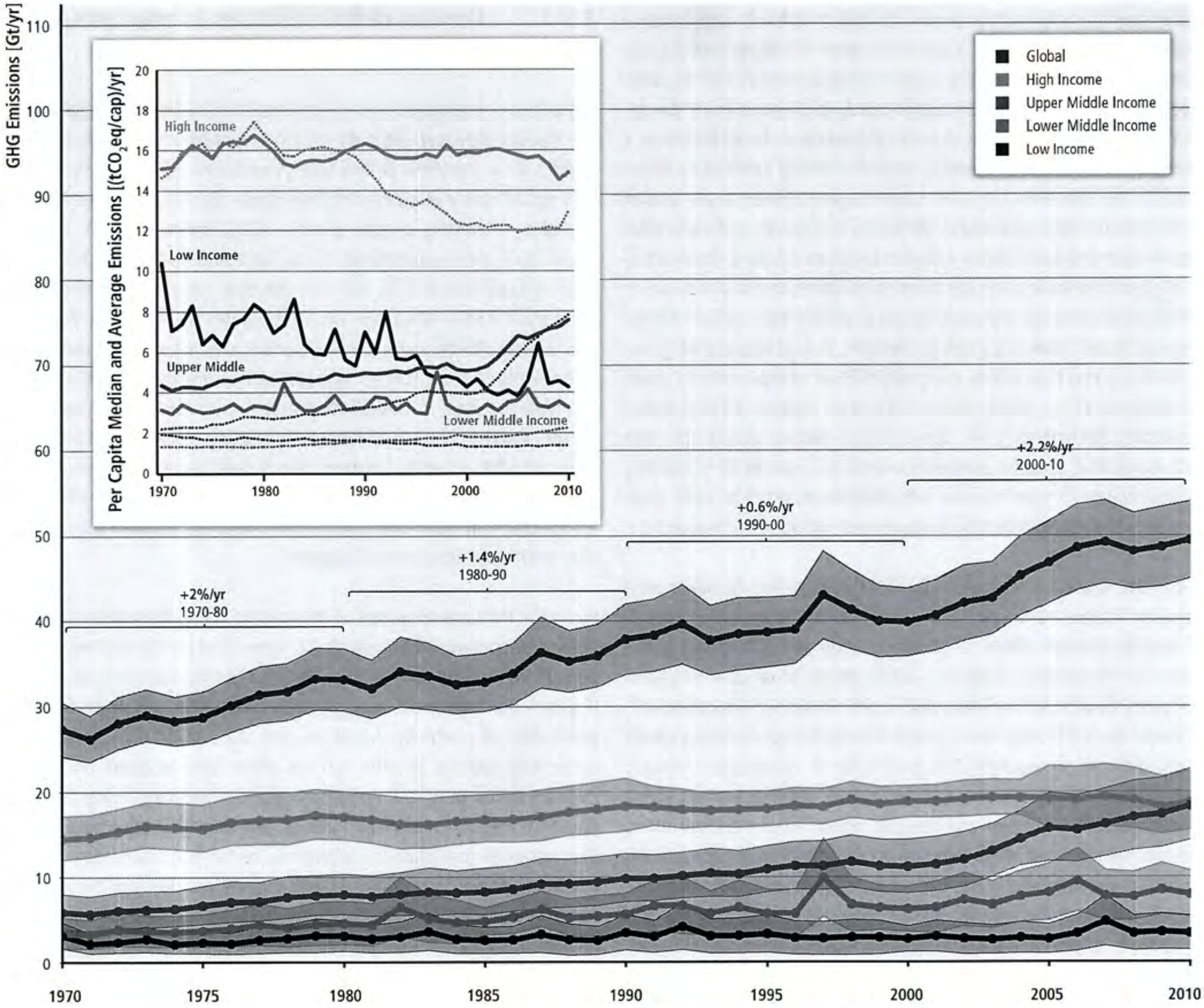


Figure 1.4 | Global growth in emissions of GHGs by economic region. Main figure shows world total (top line) and growth rates per decade, as well as the World Bank's four economic regions (see Figure 1.1 caption for more detail). Inset shows trends in annual per capita mean (solid lines) and median (dotted 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).

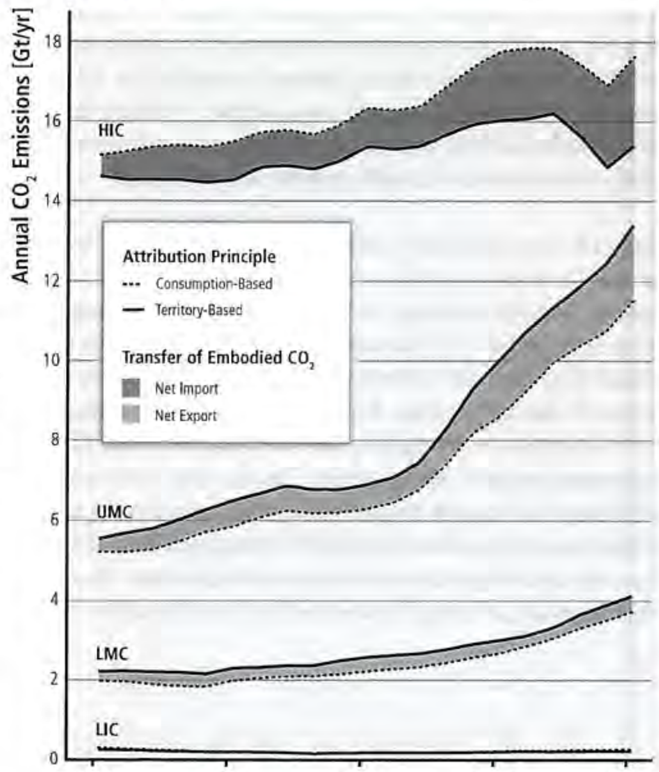


Figure 1.5 | CO_2 emissions from fossil fuel combustion for the four economic regions attributed on the basis of territory (solid line) and final consumption (dotted line) in gigatonnes of CO_2 per year (Gt/yr). The shaded areas are the net CO_2 trade balance (difference) between each of the four country 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.

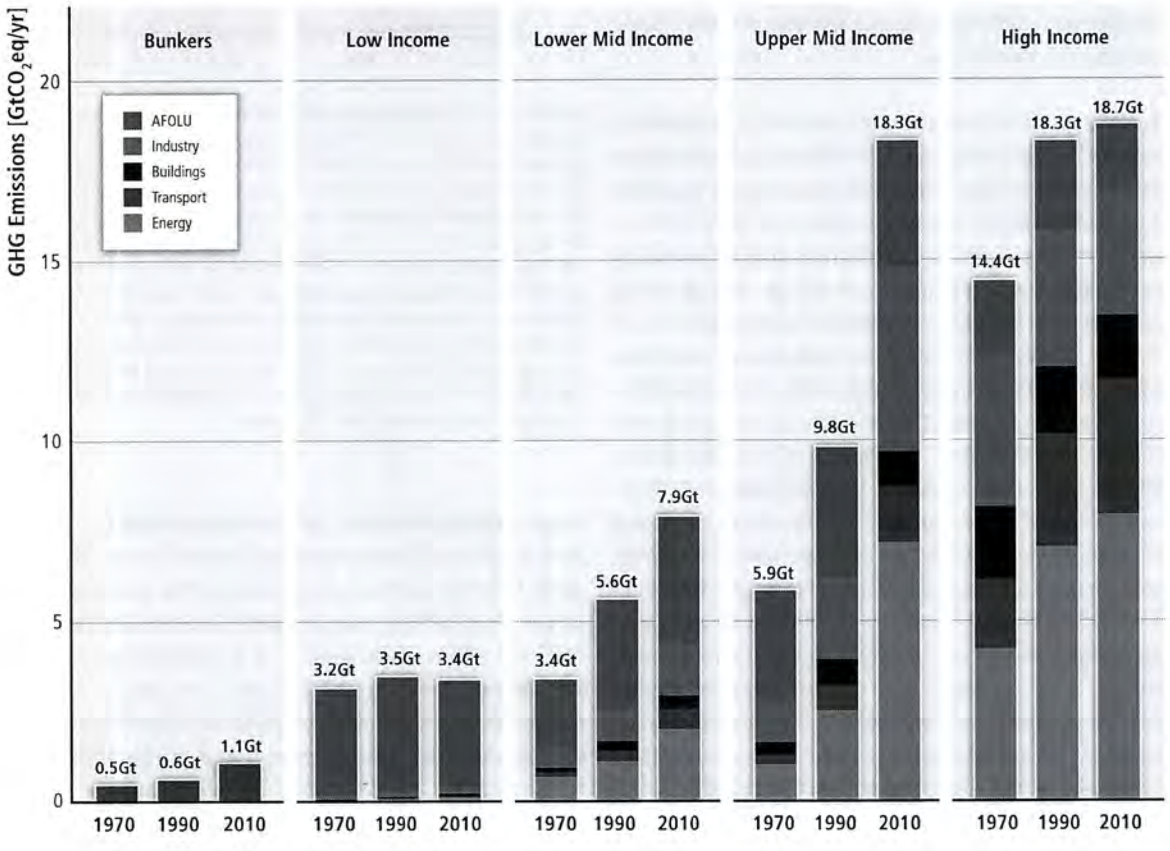


Figure 1.6 | Greenhouse gas emissions measured in gigatonnes of CO_2eq per year (Gt/yr) in 1970, 1990 and 2010 by five economic sectors (Energy supply, Transport, Buildings, Industry, as well as Agriculture, Forestry and Other Land Use (AFOLU) and four economic regions (see caption to Figure 1.1). 'Bunkers' 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.

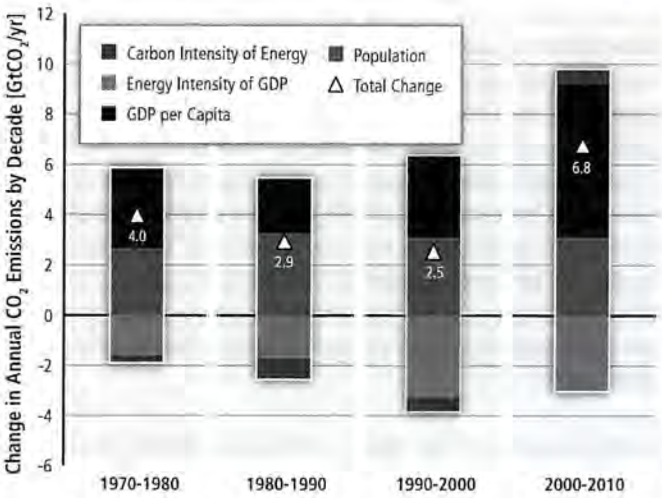


Figure 1.7 | Decomposition of the change in total annual CO_2 emissions from fossil fuel combustion by decade and four driving factors; population (light blue), GDP per capita (dark blue), energy intensity of GDP (yellow) and carbon intensity of energy (red orange). The bar segments show the changes 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).

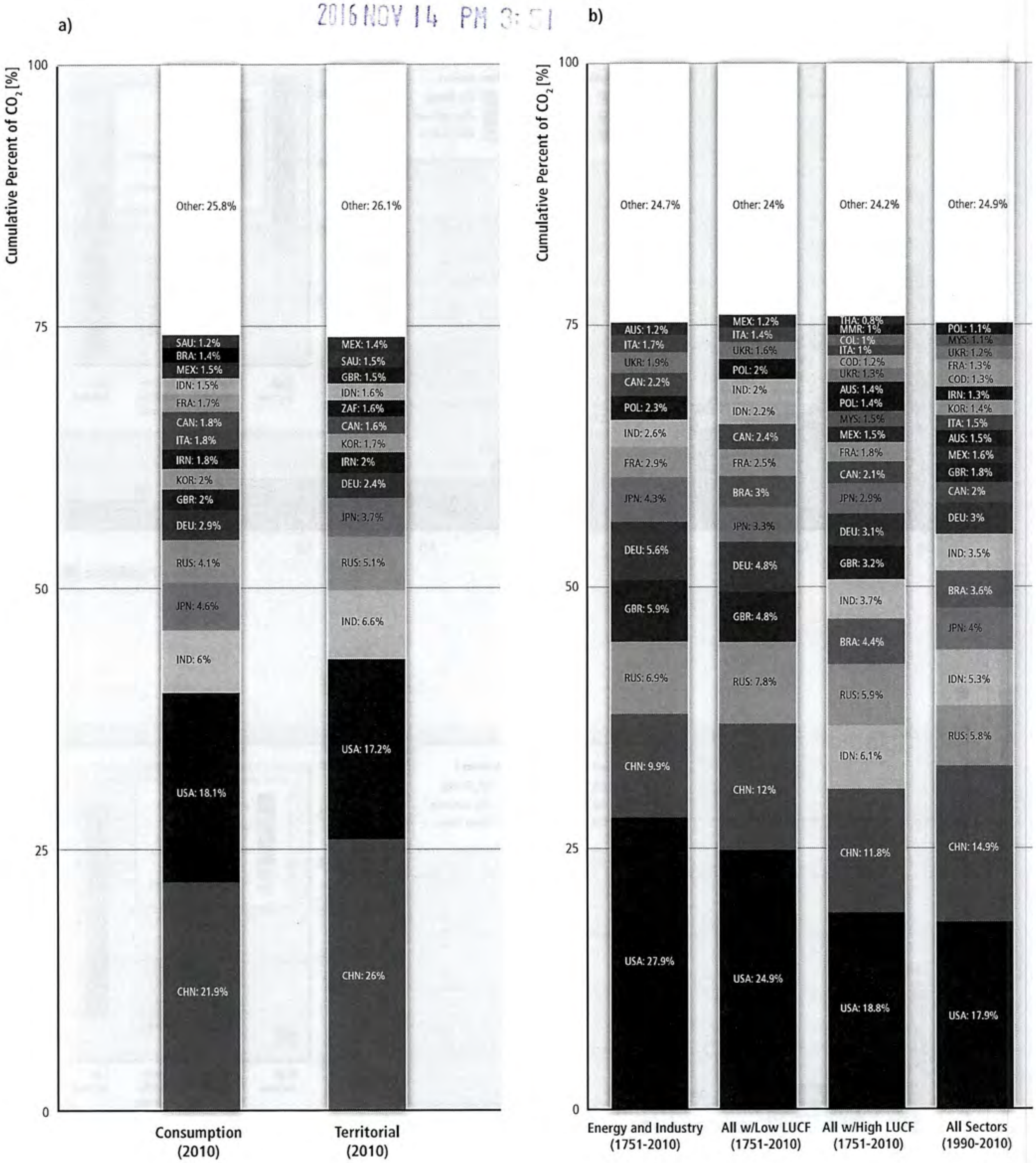
A few studies have extended the concepts of historical responsibility to include other gases as well (den Elzen et al., 2013; Smith et al., 2013). For simplicity, however, in panel B we report total cumulative emissions of just CO_2, the long-lived gas that accounts for the vast majority of long-term 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.

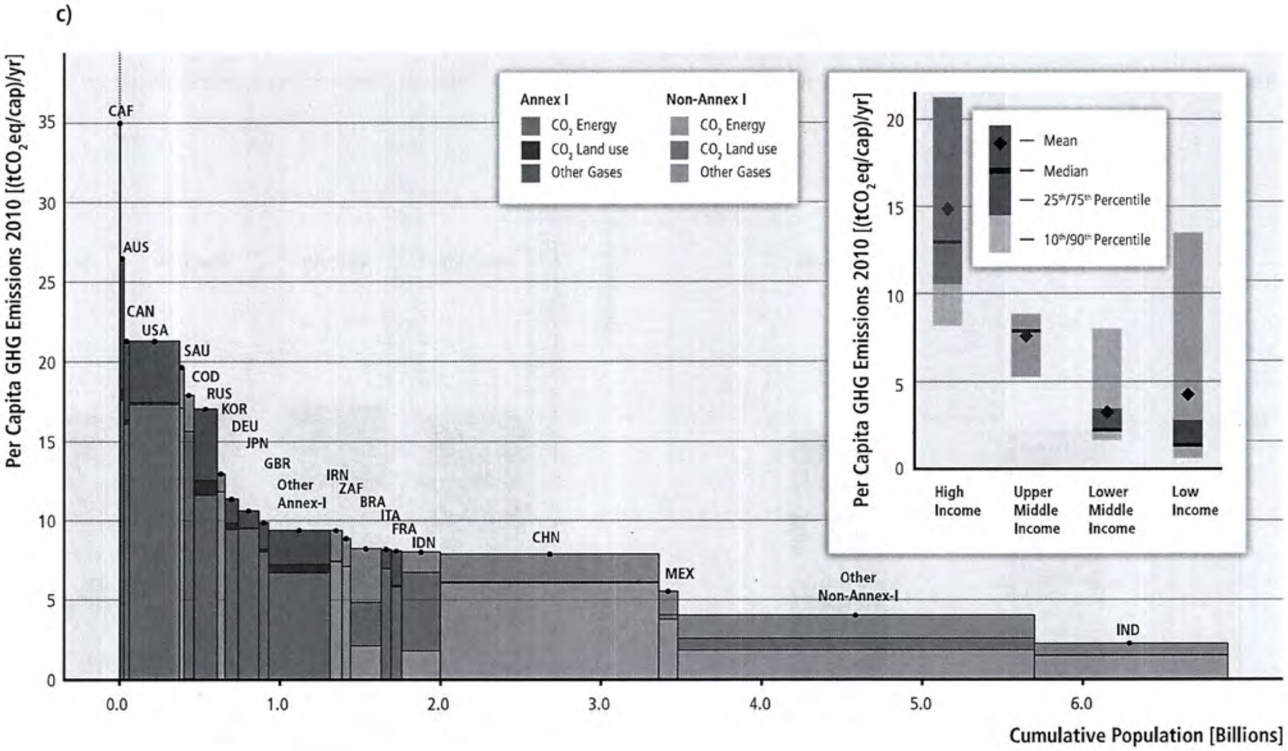
A fourth perspective looks at per-capita emissions, shown in panel C of Figure 1.8. This perspective draws attention to fundamental differences in the patterns of development of countries. This panel shows the variation in per-capita emissions for each of the four country groupings. The large variation 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.

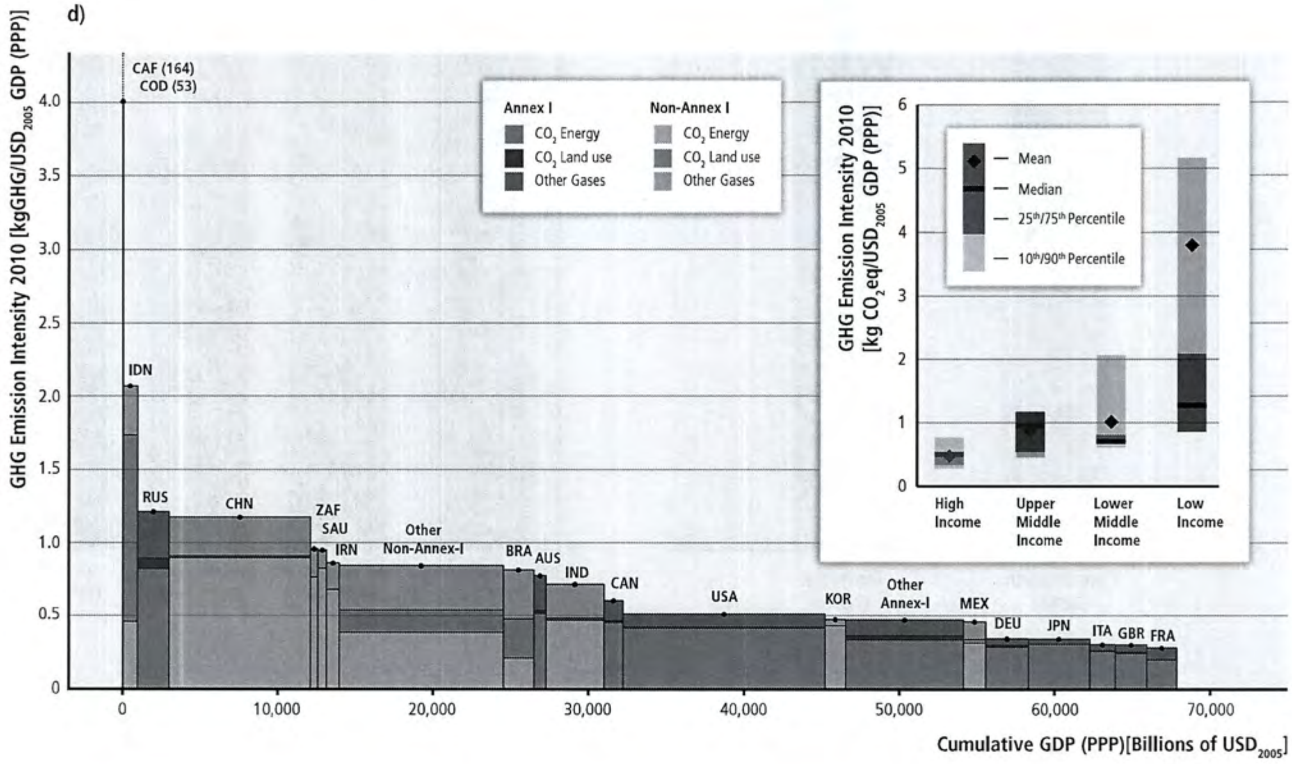
A fifth perspective is the carbon efficiency of different economies. Economies vary in how they convert inputs such as energy (and thus emissions associated with energy consumption) into economic value. This efficiency is commonly measured as the ratio of emission to unit economic output (CO_2/GDP) and 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 [%]
100
75
50
25
0
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)

⇒


c)
Per Capita GHG Emissions 2010 [(tCO2eq/cap)/yr]
0
5
10
15
20
25
30
35
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
Cumulative Population [Billions]
Annex I
CO2 Energy
CO2 Land use
Other Gases
Non-Annex I
CO2 Energy
CO2 Land use
Other Gases
Per Capita GHG Emissions 2010 [(tCO2eq/cap)/yr]
0
5
10
15
20
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)]
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
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
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
GHG Emission Intensity 2010 [kg CO2eq/USD2005 GDP (PPP)]
0
1
2
3
4
5
6
Mean
Median
25th/75th Percentile
10th/90th Percentile
High Income
Upper Middle Income
Lower Middle Income
Low Income

⇒

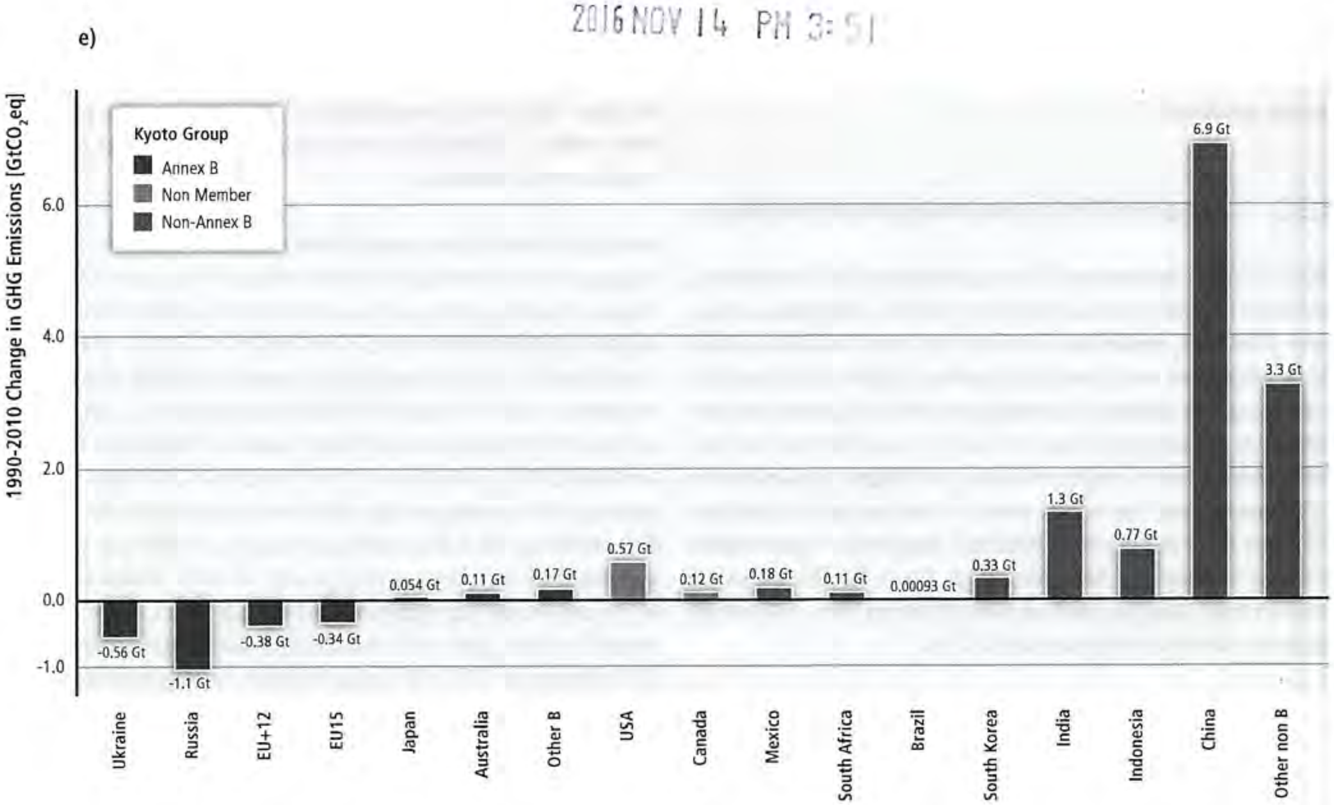


Figure 1.8 | Multiple perspectives on climate change mitigation. Panel A: 2010 emission, ranked in order for the top 75 % of global total. Left bar shows ranking with consumption-based statistics, and right bar shows territorial-based (see Figure 1.5 for more detail). Panel B: Cumulative emissions since 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 $GtCO_2$e 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.

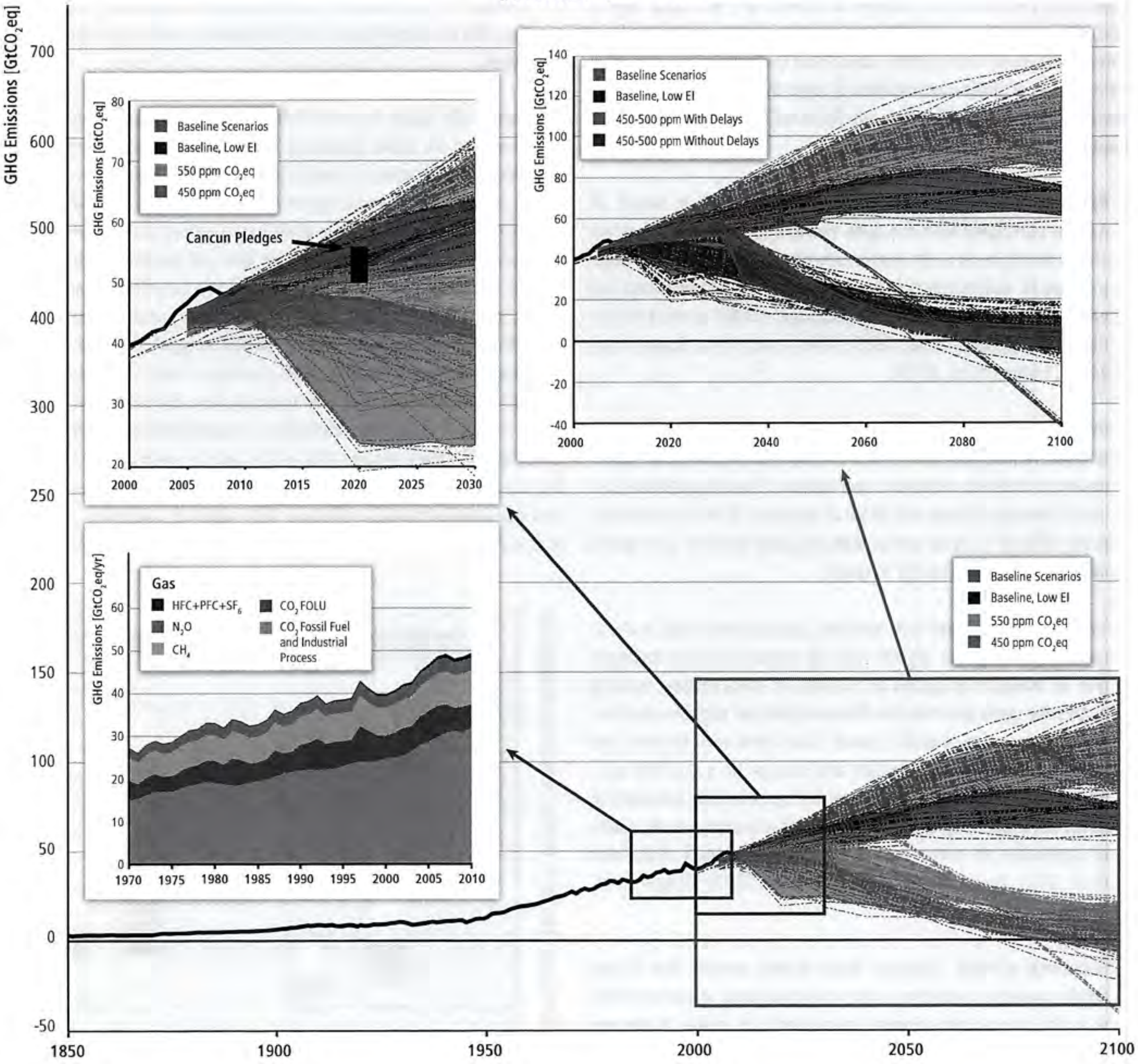


Figure 1.9 | The scale of the mitigation effort needed. Main figure shows the sweep of history from 1750 to 2010 (actual emission estimates) and published projections out to the future. Projections include baseline scenarios that do not assume new mitigation policies (grey shading), baseline scenarios 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$_2$eq (yellow) and 450 ppm CO$_2$eq (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$_2$eq to 500 ppm CO$_2$eq—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

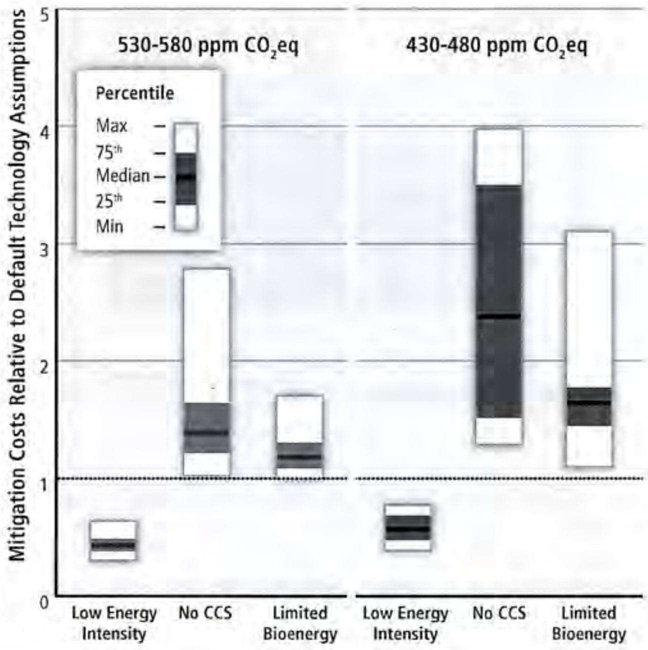


Figure 1.10 | The effects of real world assumptions on mitigation costs. Relative mitigation cost increase in case of technology portfolio variations compared to a scenario with default technology assumptions for stabilizing atmospheric GHG concentrations centered on 450 ppm (430–480 ppm, right) and 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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2

Integrated Risk and Uncertainty Assessment of Climate Change Response Policies

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Contents

Executive Summary

The scientific understanding of climate change and the impact it has on different levels of decision-making and policy options has increased since the publication of the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4). In addition, there is a growing recognition that decision makers often rely on intuitive thinking processes rather than undertaking a systematic analysis of options in a deliberative fashion. It is appropriate that climate change risk management strategies take into account both forms of thinking when considering policy choices where there is risk and uncertainty.

Consideration of risk perception and decision processes can improve risk communication, leading to more effective policies for dealing with climate change. By understanding the systematic biases that individuals utilize in dealing with climate change problems, one can more effectively communicate the nature of the climate change risk. An understanding of the simplified decision rules employed by decision makers in making choices may be helpful in designing policies that encourage the adoption of mitigation and adaptation measures. [Section 2.4]

Decision processes often include both deliberative and intuitive thinking. When making mitigation and adaptation choices, decision makers sometimes calculate the costs and benefits of their alternatives (deliberative thinking). They are also likely to utilize emotion- and rule-based responses that are conditioned by personal past experience, social context, and cultural factors (intuitive thinking). [2.4.2]

Laypersons tend to judge risks differently than experts. Laypersons' perceptions of climate change risks and uncertainties are often influenced by past experience, as well as by emotional processes that characterize intuitive thinking. This may lead them to overestimate or underestimate the risk. Experts engage in more deliberative thinking than laypersons by utilizing scientific data to estimate the likelihood and consequences of climate change. [2.4.6]

Cost-benefit analysis (CBA) and cost-effectiveness analysis (CEA) can enable decision makers to examine costs and benefits, but these methodologies also have their limitations. Both approaches highlight the importance of considering the likelihood of events over time and the importance of focusing on long-term horizons when evaluating climate change mitigation and adaptation policies. CBA enables governments and other collective decision-making units to compare the social costs and benefits of different alternatives. However, CBA cannot deal well with infinite (negative) expected utilities arising from low probability catastrophic events often referred to as 'fat tails'. CEA can generate cost estimates for stabilizing greenhouse gas (GHG) concentrations without having to take into account the uncertainties associated with cost estimates for climate change impacts. A limitation of CEA is that it takes the long-term stabilization as a given without considering the economic efficiency of the target level. [2.5.3, 2.5.4]

Formalized expert judgment and elicitation processes improve the characterization of uncertainty for designing climate change strategies (*high confidence*). Experts can quantify uncertainty through formal elicitation processes. Their judgments can characterize the uncertainties associated with a risk but not reduce them. The expert judgment process highlights the importance of undertaking more detailed analyses to design prudent climate policies. [2.5.6]

Individuals and organizations that link science with policy grapple with several different forms of uncertainty. These uncertainties include absence of prior agreement on framing of problems and ways to scientifically investigate them (paradigmatic uncertainty), lack of information or knowledge for characterizing phenomena (epistemic uncertainty), and incomplete or conflicting scientific findings (translational uncertainty). [2.6.2]

The social benefit from investments in mitigation tends to increase when uncertainty in the factors relating GHG emissions to climate change impacts are considered (*medium confidence*). If one sets a global mean temperature (GMT) target, then normative analyses that include uncertainty on the climate response to elevated GHG concentration, suggest that investments in mitigation measures should be accelerated. Under the assumption of nonlinear impacts of a GMT rise, inclusion of uncertainty along the causal chain from emissions to impacts suggests enhancing mitigation. [2.6.3]

The desirability of climate policies and instruments are affected by decision makers' responses to key uncertainties. At the national level, uncertainties in market behaviour and future regulatory actions have been shown to impact the performance of policy instruments designed to influence investment patterns. Both modelling and empirical studies have shown that uncertainty as to future regulatory and market conditions adversely affects the performance of emission allowance trading markets [2.6.5.1]. Other studies have shown that subsidy programmes (e.g., feed-in tariffs, tax credits) are relatively immune to market uncertainties, but that uncertainties with respect to the duration and level of the subsidy program can have adverse effects [2.6.5.2]. In both cases, the adverse effects of uncertainty include less investment in low-carbon infrastructure, increasing consumer prices, and reducing the pressure for technological development.

Decision makers in developing countries often face a particular set of challenges associated with implementing mitigation policies under risk and uncertainty (*medium confidence*). Managing risk and uncertainty in the context of climate policy is of particular importance to developing countries that are resource constrained and face other pressing development goals. In addition, institutional capacity in these countries may be less developed compared to advanced economies. Therefore, decision makers in these countries (governments and economic agents such as firms, farmers, households, to name a few) have less room for 'error' (uncertain outcomes and/or wrong or poorly implemented policies). The same applies to national, regional and local governments in developed countries who can ill afford to waste scarce resources through policy errors. [Box 2.1]

2.1 Introduction

This framing chapter considers ways in which risk and uncertainty can affect the process and outcome of strategic choices in responding to the threat of climate change.

'Uncertainty' denotes a cognitive state of incomplete knowledge that results from a lack of information and/or from disagreement about what is known or even knowable. It has many sources ranging from quantifiable errors in the data to ambiguously defined concepts or terminology to uncertain projections of human behaviour. The *Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (Mastrandrea et al., 2010) summarizes alternative ways of representing uncertainty. Probability density functions and parameter intervals are among the most common tools for characterizing uncertainty.

'Risk' refers to the potential for adverse effects on lives, livelihoods, health status, economic, social and cultural assets, services (including environmental), and infrastructure due to uncertain states of the world. To the extent that there is a detailed understanding of the characteristics of a specific event, experts will normally be in agreement regarding estimates of the likelihood of its occurrence and its resulting consequences. Risk can also be subjective in the sense that the likelihood and outcomes are based on the knowledge or perception that a person has about a given situation. There may also be risks associated with the outcomes of different climate policies, such as the harm arising from a change in regulations.

There is a growing recognition that today's policy choices are highly sensitive to uncertainties and risk associated with the climate system and the actions of other decision makers. The choice of climate policies can thus be viewed as an exercise in risk management (Kunreuther et al., 2013a). Figure 2.1 suggests a risk management framework that serves as the structure of the chapter.

After defining risk and uncertainty and their relevant metrics (Section 2.2), we consider how choices with respect to climate change policy options are sensitive to risk and uncertainty (Section 2.3). A taxonomy depicts the levels of decision making ranging from international agreements to actions undertaken by individuals in relation to climate change policy options under conditions of risk and uncertainty that range from long-term global temperature targets to lifestyle choices. The goals and values of the different stakeholders given their immediate and long-term agendas will also influence the relative attractiveness of different climate change policies in the face of risk and uncertainty.

Sections 2.4, 2.5 and 2.6 characterize descriptive and normative theories of decision-making and models of choice for dealing with risk and uncertainty and their implications for prescriptive analysis. *Descriptive* refers to theories of actual behaviour, based on experimental evidence and field studies that characterize the perception of risk and decision processes. *Normative* in the context of this chapter refers to theories of choice under risk and uncertainty based on abstract models and axioms that serve as benchmarks as to how decision makers should ideally make their choices. *Prescriptive* refers to ways of improving the decision process and making final choices (Kleindorfer et al., 1993).

A large empirical literature has revealed that individuals, small groups and organizations often do not make decisions in the analytic or rational way envisioned by normative models of choice in the economics and management science literature. People frequently perceive risk in ways that differ from expert judgments, posing challenges for risk communication and response. There is a tendency to focus on short time horizons, utilize simple heuristics in choosing between alternatives, and selectively attend to subsets of goals and objectives.

To illustrate, the voting public in some countries may have a wait-and-see attitude toward climate change, leading their governments to postpone mitigation measures designed to meet specified climate targets (Sterman, 2008; Dutt and Gonzalez, 2011). A coastal village may decide not to undertake measures for reducing future flood risks due to sea level rise (SLR), because their perceived likelihood that SLR will cause problems to their village is below the community council's level of concern.

Section 2.4 provides empirical evidence on behavioural responses to risk and uncertainty by examining the types of biases that influence individuals' perception of the likelihood of an event (e.g., availability, learning from personal experience), the role that emotional, social, and cultural factors play in influencing the perception of climate change risks and strategies for encouraging decision makers to undertake cost-effective measures to mitigate and adapt to the impacts of climate change.

A wide range of decision tools have been developed for evaluating alternative options and making choices in a systematic manner even when probabilities are difficult to characterize and/or outcomes are uncertain. The relevance of these tools for making more informed decisions depends on how the problem is formulated and framed, the nature of the institutional arrangements, and the interactions between stakeholders (Hammond et al., 1999; Schoemaker and Russo, 2001).

Governments debating the merits of a carbon tax may turn to cost-benefit analysis or cost-effectiveness analysis to justify their positions. They may need to take into account that firms who utilize formal approaches, such as decision analysis, may not reduce their emissions if they feel that they are unlikely to be penalized because the carbon tax will not be well enforced. Households and individuals may find the expected utility model or decision analysis to be useful tools for evaluating the costs and benefits of adopting energy efficient measures given the trajectory of future energy prices.

Section 2.5 delineates formal methodologies and decision aids for analysing risk and uncertainty when individuals, households, firms, communities and nations are making choices that impact their own well-being and those of others. These tools encompass variants of expected utility theory, decision analysis, cost-benefit analyses or cost-effectiveness analyses that are implemented in integrated assessment models (IAMs). Decision aids include adaptive management, robust decision making and uncertainty analysis techniques such as structured expert judgment and scenario analysis. The chapter highlights the importance of selecting different methodologies for addressing different problems.

Developing robust policy response strategies and instruments should take into account how the relevant stakeholders perceive risk and their behavioural responses to uncertain information and data (descriptive analysis). The policy design process also needs to consider the methodologies and decision aids for systematically addressing issues of risk and uncertainty (normative analysis) that suggest strategies for improving outcomes at the individual and societal level (prescriptive analysis).

Section 2.6 examines how the outcomes of particular options, in terms of their efficiency or equity, are sensitive to risks and uncertainties and affect policy choices. After examining the role of uncertainty in the science/policy interface, it examines the role of integrated assessment models (IAMs) from the perspective of the social planner operating at a global level and the structuring of international negotiations and paths to reach agreement. Integrated assessment models combined with an understanding of the negotiation process for reaching international agreements may prove useful to delegates for justifying the positions of their country at a global climate conference. The section also examines the role that uncertainty plays in the performance of different technologies now and in the future as well as how lifestyle decisions such as investing in energy efficient measures can be improved.

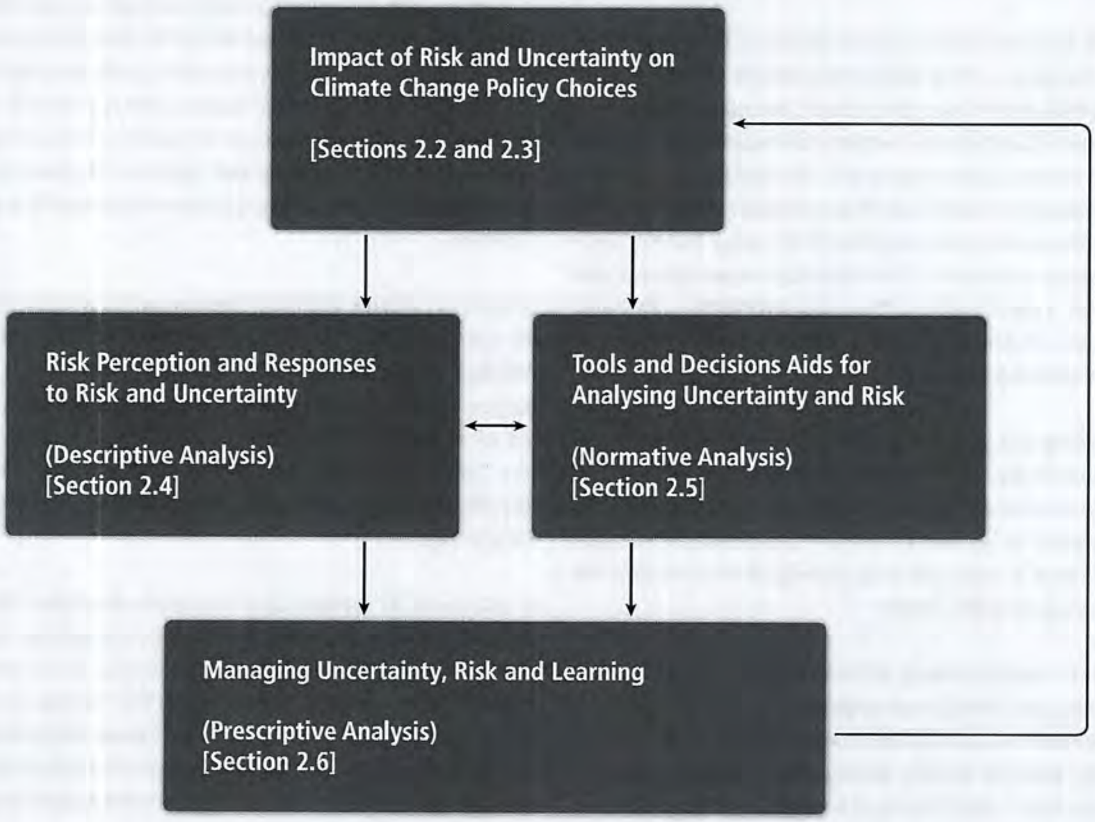

Figure 2.1 | A risk management framework. Numbers in brackets refer to sections where more information on these topics can be found.

The section concludes by examining the roles that risk and uncertainty play in support of or opposition to climate policies.

The way climate change is managed will have an impact on policy choices as shown by the feedback loop in Figure 2.1, suggesting that the risk management process for addressing climate change is iterative. The nature of this feedback can be illustrated by the following examples. Individuals may be willing to invest in solar panels if they are able to spread the upfront cost over time through a long-term loan. Firms may be willing to promote new energy technologies that provide social benefits with respect to climate change if they are given a grant to assist them in their efforts. National governments are more likely to implement carbon markets or international treaties if they perceive the short-term benefits of these measures to be greater than the perceived costs. Education and learning can play key roles in how climate change is managed through a reconsideration of policies for managing the risks and uncertainties associated with climate change.

2.2 Metrics of uncertainty and risk

The IPCC strives for a treatment of risk and uncertainty that is consistent across all three Working Groups based the *Guidance Note (GN) for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties* (Mastrandrea et al., 2010). This section summarizes key aspects of the GN that frames the discussion in this chapter.

The GN indicates that author teams should evaluate the associated evidence and agreement with respect to specific findings that involve risk and uncertainty. The amount of *evidence* available can range from small to large, and can vary in quality and consistency. The GN recommends reporting the degree of certainty and/or uncertainty of a given topic as a measure of the consensus or *agreement* across the scientific community. *Confidence* expresses the extent to which the IPCC authors do in fact support a key finding. If confidence is sufficiently high, the GN suggests specifying the key finding in terms of *probability*. The evaluation of evidence and degree of agreement of any key finding is labelled a *traceable account* in the GN.

The GN also recommends taking a risk-management perspective by stating that "sound decision making that anticipates, prepares for, and responds to climate change depends on information about the full range of possible consequences and associated probabilities." The GN also notes that, "low-probability outcomes can have significant impacts, particularly when characterized by large magnitude, long persistence, broad prevalence, and/or irreversibility." For this reason, the GN encourages the presentation of information on the extremes of the probability distributions of key variables, reporting quantitative estimates when possible and supplying qualitative assessments and evaluations when appropriate.

2.3 Risk and uncertainty in climate change

Since the publication of AR4, political scientists have documented the many choices of climate policy and the range of interested parties concerned with them (Moser, 2007; Andonova et al., 2009; Bulkeley, 2010; Betsill and Hoffmann, 2011; Cabré, 2011; Hoffmann, 2011; Meckling, 2011; Victor, 2011).

There continues to be a concern about global targets for mean surface temperature and GHG concentrations that are discussed in Chapter 6 of this report. This choice is normally made at the global level with some regions, countries, and sub-national political regions setting their own targets consistent with what they believe the global ones should be. Policymakers at all levels of decision making face a second-order set of choices as to how to achieve the desired targets. Choices in this vein that are assessed in Chapters 7–12 of this report, include transition pathways for various drivers of emissions, such as fossil fuels within the energy system, energy efficiency and energy-intensive behavioural patterns, issues associated with land-use and spatial planning, and/or the emissions of non- CO_2 greenhouse gases.

The drivers influencing climate change policy options are discussed in more detail in Chapters 13–16 of this report. These options include information provision, economic instruments (taxes, subsidies, fines), direct regulations and standards, and public investments. At the same time, individuals, groups and firms decide what actions to take on their own. These choices, some of which may be in response to governmental policy, include investments, lifestyle and behaviour.

Decisions for mitigating climate change are complemented by climate adaptation options and reflect existing environmental trends and drivers. The policy options are likely to be evaluated with a set of criteria that include economic impacts and costs, equity and distributional considerations, sustainable development, risks to individuals and society and co-benefits. Many of these issues are discussed in Chapters 3 and 4.

2.3.1 Uncertainties that matter for climate policy choices

The range and number of interested parties who are involved in climate policy choices have increased significantly in recent years. There has been a widening of the governance forums within which climate policies and international agreements are negotiated at the global level (Victor, 2011), across multiple networks within national governments (Andonova et al., 2009; Hoffmann, 2011), and at the local, regional and/or interest group level (Moser, 2007; Bulkeley, 2010). At the same time, the number of different policy instruments under active discussion has increased, from an initial focus on cap-and-trade and carbon tax instruments (Betsill and Hoffmann, 2011; Hoffmann, 2011), to feed-in tariffs or quotas for renewable energy (Wiser et al., 2005; Mendonça, 2007), investments in research and development (Sagar and van der Zwaan, 2006; De Coninck et al., 2008; Grubler and Riahi, 2010), and reform of intellectual property laws (Dechezleprêtre et al., 2011; Percival and Miller, 2011).

Choices are sensitive to the degree of uncertainty with respect to a set of parameters that are often of specific importance to particular climate policy decisions. Here, and as shown in Figure 2.2, we group these uncertainties into five broad classes, consistent with the approach taken in Patt and Weber (2014):

- *Climate responses to greenhouse gas (GHG) emissions, and their associated impacts.* The large number of key uncertainties with respect to the climate system are discussed in Working Group I (WGI). There are even greater uncertainties with respect to the impacts of changes in the climate system on humans and the ecological system as well as their costs to society. These impacts are assessed in WGII.
- *Stocks and flows of carbon and other GHGs.* The large uncertainties with respect to both historical and current GHG sources and sinks from energy use, industry, and land-use changes are assessed in Chapter 5. Knowledge gaps make it especially difficult to estimate how the flows of greenhouse gases will evolve in the future under conditions of elevated atmospheric CO_2 concentrations and their impact on climatic and ecological processes.
- *Technological systems.* The deployment of technologies is likely to be the main driver of GHG emissions and a major driver of climate vulnerability. Future deployment of new technologies will depend on how their price, availability, and reliability evolve over time as a result of technological learning. There are uncertainties as to how fast the learning will take place, what policies can accelerate learning and the effects of accelerated learning on deployment rates of new technologies. Technological deployment also depends on the degree of public acceptance, which in turn is typically sensitive to perceptions of health and safety risks.
- *Market behaviour and regulatory actions.* Public policies can create incentives for private sector actors to alter their investment behaviour, often in the presence of other overlapping regulations. The extent to which firms change their behaviour in response to the policy, however, often depends on their expectations about other highly uncertain market factors, such as fossil fuel prices. There are also uncertainties concerning the macro-economic effects of the aggregated behavioural changes. An additional factor influencing the importance of any proposed or existing policy-driven incentive is the likelihood with which regulations will be enacted and enforced over the lifetime of firms' investment cycles.
- *Individual and firm perceptions.* The choices undertaken by key decision makers with respect to mitigation and adaptation measures are impacted by their perceptions of risk and uncertainties, as well as their perceptions of the relevant costs and expected benefits over time. Their decisions may also be influenced by the actions undertaken by others.

Section 2.6 assesses the effects of uncertainties of these different parameters on a wide range of policy choices, drawing from both empirical studies and the modelling literature. The following three examples illustrate how uncertainties in one or more of the above factors can influence choices between alternative options.

Example 1: Designing a regional emissions trading system (ETS). Over the past decade, a number of political jurisdictions have designed and implemented ETSs, with the European ETS being the one most studied. In designing the European system, policymakers took as their starting point pre-defined emissions reduction targets. It was unclear whether these targets would be met, due to uncertainties with respect to national baseline emissions. The stocks and flows of greenhouse gas emissions were partly determined by the uncertainty of the performance of the technological systems that were deployed. Uncertainties in market behaviour could also influence target prices and the number of emissions permits allocated to different countries (Betsill and Hoffmann, 2011).

Example 2: Supporting scientific research into solar radiation management (SRM). SRM may help avert potentially catastrophic temperature increases, but may have other negative impacts with respect to global and regional climatic conditions (Rasch et al., 2008). Research could reduce the uncertainties as to these other consequences (Robock et al., 2010). The decision to invest in specific research activities requires an assessment as to what impact SRM will have on avoiding catastrophic temperature increases. Temperature change will be sensitive to the stocks and flows of greenhouse gases (GHG) and therefore to the responses by key decision makers to the impacts of GHG emissions. The decision to invest in specific research activities is likely to be influenced by the perceived uncertainty in the actions undertaken by individuals and firms (Blackstock and Long, 2010).

Example 3: Renting an apartment in the city versus buying a house in the suburbs. When families and households face this choice, it is likely to be driven by factors other than climate change concerns. The decision, however, can have major consequences on CO_2 emissions as well as on the impacts of climate change on future disasters such as damage from flooding due to sea level rise. Hence, governments may seek to influence these decisions as part of their portfolio of climate change policies through measures such as land-use regulations or the pricing of local transportation options. The final choice is thus likely to be sensitive to uncertainties in *market behaviour* as well *as actions undertaken by individuals and firms*.

To add structure and clarity to the many uncertainties that different actors face for different types of problems, we introduce a taxonomy shown in Figure 2.2 that focuses on levels of decision making (the rows) that range from international organizations to individuals and households, and climate policy options (the columns) that include long-term targets, transition pathways, policy instruments, resource allocation and lifestyle options. The circles that overlay the cells in Figure 2.2 highlight the principal uncertainties relevant to decision-making levels and climate policy choices that appear prominently in the literature associated with particular policies. These are reviewed in Section 2.6 of this chapter and in many of the following chapters of WGIII. The literature appraises the effects of a wide range of uncertainties, which we group according to the five types described above.

2.3.2 What is new on risk and uncertainty in AR5

Chapter 2 in WGIII AR4 on risk and uncertainty, which also served as a framing chapter, illuminated the relationship of risk and uncertainty to decision making and reviewed the literature on catastrophic or abrupt climate change and its irreversible nature. It examined three pillars for dealing with uncertainties: precaution, risk hedging, and crisis prevention and management. The report also summarized the debate in the economic literature about the limits of cost-benefit analysis in situations of uncertainty.

Since the publication of AR4, a growing number of studies have considered additional sources of risk and uncertainties, such as regulatory and technological risks, and examined the role they play in influencing climate policy. There is also growing awareness that risks in the extremes or tail of the distribution make it problematic to rely on historical averages. As the number of political jurisdictions implementing climate policies has increased, there are now empirical findings to supplement earlier model-based studies on the effects of such risks. At the local level, adaptation studies using scenario-based methods have been developed (ECLACS, 2011).

This chapter extends previous reports in four ways. First, rather than focusing solely at the global level, this chapter expands climate-related decisions to other levels of decision making as shown in Figure 2.2. Second, compared to AR4, where judgment and choice were primarily framed in rational-economic terms, this chapter reviews the psychological and behavioural literature on perceptions and responses to risk and uncertainty. Third, the chapter considers the pros and cons of alternative methodologies and decision aids from the point of view of practitioners. Finally, the chapter expands the scope of the challenges associated with developing risk management strategies in relation to

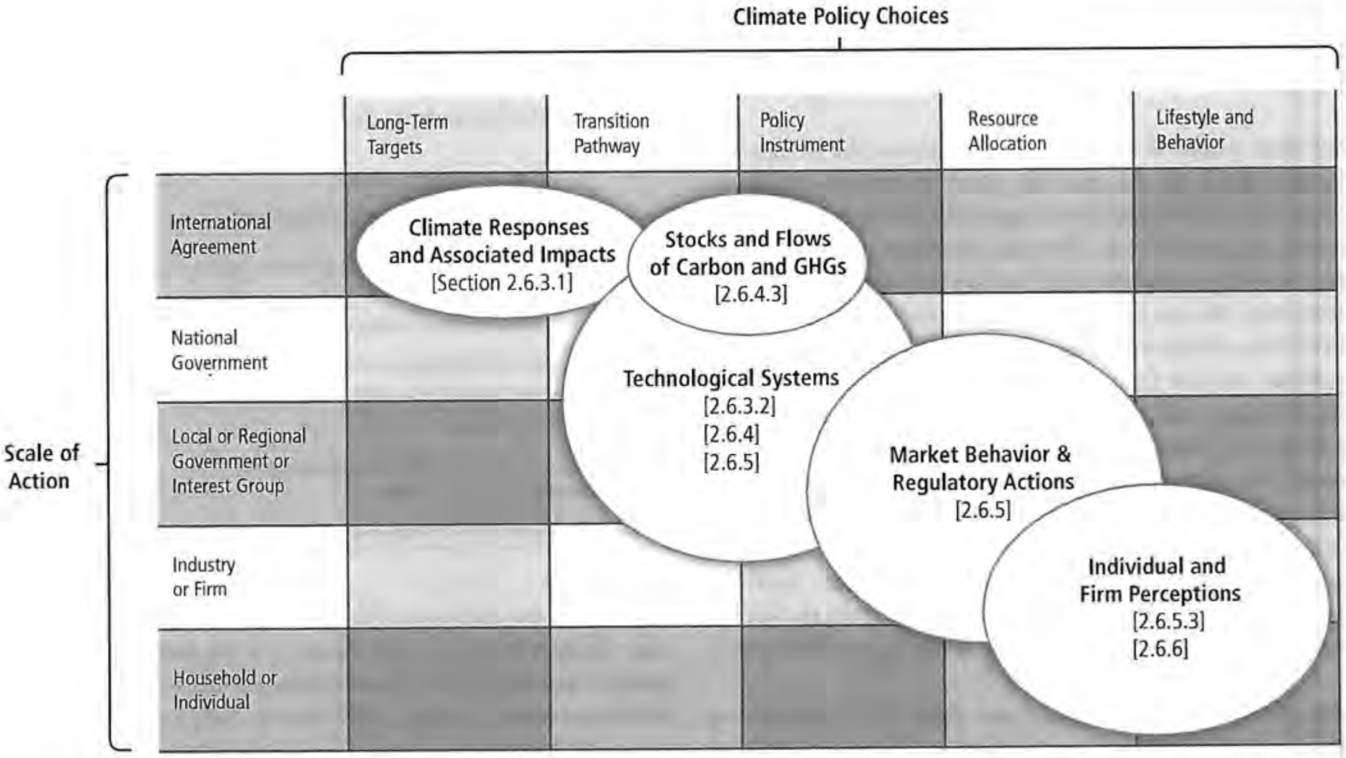

Figure 2.2 | Taxonomy of levels of decision making and climate policy choices. Circles show type and extent of uncertainty sources as they are covered by the literature. Numbers in brackets refer to sections where more information on these uncertainty sources can be found.

AR4 that requires reviewing a much larger body of published research. To illustrate this point, the chapter references more than 50 publications on decision making under uncertainty with respect to integrated assessment models (IAMs), the first time such a detailed examination of this literature has been undertaken.

2.4 Risk perception and responses to risk and uncertainty

2.4.1 Considerations for design of climate change risk reduction policies

When stakeholders are given information about mitigation and adaptation measures to reduce climate change risks, they make the following judgments and choices: How serious is the risk? Is any action required? Which options are ruled out because the costs seem prohibitive? Which option offers the greatest net expected benefits?

In designing such measures and in deciding how to present them to stakeholders, one needs to recognize both the strengths and limitations of decision makers at the different levels delineated in Figure 2.2. Decision makers often have insufficient or imperfect knowledge about climate risks, a deficit that can and needs to be addressed by better data and public education. However, cognitive and motivational barriers are equally or more important in this regard (Weber and Stern, 2011).

Normative models of choice described in Section 2.5 indicate how decisions under risk and uncertainty should be made to achieve efficiency and consistency, but these approaches do not characterize how choices are actually made. Since decision makers have limitations in their ability to process information and are boundedly rational (Simon, 1955), they often use simple heuristics and rules of thumb (Payne et al., 1988). Their choices are guided not only by external reality (objective outcomes and their likelihood) but also by the decision makers' internal states (e.g., needs and goals) and their mental representation of outcomes and likelihood, often shaped by previous experience. In other words, a descriptive model of choice needs to consider cognitive and motivational biases and decision rules as well as factors that are considered when engaging in deliberative thinking. Another complicating factor is that when groups or organizations make decisions, there is the potential for disagreement and conflict among individuals that may require interpersonal and organizational facilitation by a third party.

Mitigation and adaptation decisions are shaped also by existing economic and political institutional arrangements. Policy and market tools for addressing climate change, such as insurance, may not be feasible in developing countries that have no history of this type of protection; however, this option may be viewed as desirable in a country with an active insurance sector (see Box 2.1). Another important determinant of decisions is the status quo, because there is a tendency to give more weight to the negative impacts of undertaking change than the equivalent positive impacts (Johnson et al., 2007). For example, proposing a carbon tax to reduce GHG emissions may elicit much more concern from affected stakeholders as to how this measure will impact on their current activities than the expected climate change benefits from reducing carbon emissions. Choices are also affected by cultural differences in values and needs (Maslow, 1954), in beliefs about the existence and causes of climate change (Leiserowitz et al., 2008), and in the role of informal social networks for cushioning catastrophic losses (Weber and Hsee, 1998). By considering actual judgment and choice processes, policymakers can more accurately characterize the effectiveness and acceptability of alternative mitigation policies and new technologies. Descriptive models also provide insights into ways of framing mitigation or adaptation options so as to increase the likelihood that desirable climate policy choices are adopted. Descriptive models, with their broader assumptions about goals and processes, also allow for the design of behavioural interventions that capitalize on motivations such as equity and fairness.

2.4.2 Intuitive and deliberative judgment and choice

The characterization of judgment and choice that distinguishes intuitive processes from deliberative processes builds on a large body of cognitive psychology and behavioural decision research that can be traced to William James (1878) in psychology and to Friedrich Nietzsche (2008) and Martin Heidegger (1962) in philosophy. A recent summary has been provided by Kahneman (2003; 2011) as detailed in Table 2.1:

Table 2.1 | Intuitive and deliberative process characteristics.

Intuitive Thinking (System 1)
Operates automatically and quickly, with little or no effort and no voluntary control.
Uses simple and concrete associations, including emotional reactions or simple rules of conduct that have been acquired by personal experience with events and their consequences.
Deliberative Thinking (System 2)
Initiates and executes effortful and intentional abstract cognitive operations when these are seen as needed.
These cognitive operations include simple or complex computations or formal logic.

Even though the operations of these two types of processes do not map cleanly onto distinct brain regions, and the two systems often operate cooperatively and in parallel (Weber and Johnson, 2009), the distinction between Systems 1 and 2 helps to clarify the tension in the human mind between the automatic and largely involuntary processes of intuitive decisions, versus the effortful and more deliberate processes of analytic decisions (Kahneman, 2011).

Many of the simplified decision rules that characterize human judgment and choice under uncertainty utilize intuitive (System 1) processes. Simplification is achieved by utilizing the experiences, expectations, beliefs, and goals of the interested parties involved in the decision. Such shortcuts require much less time and effort than a more detailed analysis of the tradeoffs between options and often leads to reasonable outcomes. If one takes into account the constraints on time and attention and processing capacity of decision makers, these decisions may be the best we can do for many choices under uncertainty (Simon, 1955). Intuitive processes are utilized not only by the general public, but also by technical experts such as insurers and regulators (Kunreuther et al., 2013c) and by groups and organizations (Cyert and March, 1963; Cohen et al., 1972; Barreto and Patient, 2013).

Intuitive processes work well when decision makers have copious data on the outcomes of different decisions and recent experience is a meaningful guide for the future, as would be the case in stationary environments (Feltovich et al., 2006). These processes do not work well, however, for low-probability high-consequence events for which the decision maker has limited or no past experience (Weber, 2011). In such situations, reliance on intuitive processes for making decisions will most likely lead to maintaining the status quo and focusing on the recent past. This suggests that intuitive decisions may be problematic in dealing with climate change risks such as increased flooding and storm surge due to sea level rise, or a surge in fossil fuel prices as a result of an unexpected political conflict. These are risks for which there is limited or no personal experience or historical data and considerable disagreement and uncertainty among experts with respect to their risk assessments (Taleb, 2007).

The formal models and tools that characterize deliberative (System 2) thinking require stakeholders to make choices in a more abstract and systematic manner. A deliberative process focuses on potential short- and long-term consequences and their likelihoods, and evenly evaluates the options under consideration, not favouring the status quo. For the low-probability high-consequence situations for which decision makers have limited experience with outcomes, alternative decision frameworks that do not depend on precise specification of probabilities should be considered in designing risk management strategies for climate change (Charlesworth and Okereke, 2010; Kunreuther et al., 2013a).

The remainder of this section is organized as follows. Section 2.4.3 describes some important consequences of the intuitive processes utilized by individuals, groups, and organizations in making decisions. The predicted effectiveness of economic or technological climate change mitigation solutions typically presuppose rational deliberative thinking and evaluation without considering how perceptions and reactions to climate risks impose on these policy options. Section 2.4.4 discusses biases and heuristics that suggest that individuals learn in ways that differ significantly from deliberative Bayesian updating. Section 2.4.5 addresses how behaviour is affected by social amplification of risk and considers the different levels of decision making in Figure 2.2 by discussing the role of social norms, social comparisons, and social networks in the choice process. Section 2.4.6 characterizes the general public's perceptions of climate change risks and uncertainty and their implications for communicating relevant information.

Empirical evidence for the biases associated with climate change response decisions triggered by intuitive processes exists mostly at the level of the individual. As discussed in Sections 2.5 and 2.6, intuitive judgment and choice processes at other levels of decision making, such as those specified in Figure 2.2, need to be acknowledged and understood.

2.4.3 Consequences of intuitive decision making

The behaviour of individuals are captured by descriptive models of choice such as prospect theory (Kahneman and Tversky, 1979) for decisions under risk and uncertainty and the beta-delta model (Laibson, 1997) for characterizing how future costs and benefits are evaluated. While individual variation exists, the patterns of responding to potential outcomes over time and the probabilities of their occurrence have an empirical foundation based on controlled experiments and well-designed field studies examining the behaviour of technical experts and the general public (Loewenstein and Elster, 1992; Camerer, 2000).

2.4.3.1 Importance of the status quo

The tendency to maintain the current situation is a broadly observed phenomenon in climate change response contexts (e.g., inertia in switching to a non-carbon economy or in switching to cost-effective energy efficient products) (Swim et al., 2011). Sticking with the current state of affairs is the easy option, favoured by emotional responses in situations of uncertainty ("better the devil you know than the devil you don't"), by many proverbs or rules ("when in doubt, do nothing"), and observed biases in the accumulation of arguments for different choice options (Weber et al., 2007). Overriding the status quo requires commitment to change and effort (Fleming et al., 2010).

Loss aversion and reference points

Loss aversion is an important property that distinguishes prospect theory (Tversky and Kahneman, 1992) from expected utility theory (von Neumann and Morgenstern, 1944) by introducing a reference-dependent valuation of outcomes, with a steeper slope for perceived losses than for perceived gains. In other words, people experience more pain from a loss than they get pleasure from an equivalent gain. The status quo is often the relevant reference point that distinguishes outcomes perceived as losses from those perceived as gains. Given loss aversion, the potential negative consequences of moving away from the current state of affairs are weighted much more heavily than the potential gains, often leading the decision maker not to take action. This behaviour is referred to as the *status quo bias* (Samuelson and Zeckhauser, 1988).

Loss aversion explains a broad range of decisions in controlled laboratory experiments and real world choices that deviate from the predictions of rational models like expected utility theory (Camerer, 2000). Letson et al. (2009) show that adapting to seasonal and inter-annual climate variability in the Argentine Pampas by allocating land to different crops depends not only on existing institutional arrangements (e.g., whether the farmer is renting the land or owns it), but also on individual differences in farmers' degree of loss aversion and risk aversion. Greene et al. (2009) show that loss aversion combined with uncertainty about future cost savings can explain why consumers frequently appear to be unwilling to invest in energy-efficient technology such as a more expensive but more fuel-efficient car that has positive expected utility. Weber and Johnson (2009) distinguish between perceptions of risk, attitudes towards risk, and loss aversion that have different determinants, but are characterized by a single 'risk attitude' parameter in expected utility models. Distinguishing and measuring these psychologically distinct components of individual differences in risk taking (e.g., by using prospect theory and adaptive ways of eliciting its model parameters; Toubia et al., 2013) provides better targeted entry points for policy interventions.

Loss aversion influences the choices of experienced decision makers in high-stakes risky choice contexts, including professional financial markets traders (Haigh and List, 2005) and professional golfers (Pope and Schweitzer, 2011). Yet, other contexts fail to elicit loss aversion, as evidenced by the failure of much of the global general public to be alarmed by the prospect of climate change (Weber, 2006). In this and other contexts, loss aversion does not arise because decision makers are not emotionally involved (Loewenstein et al., 2001).

Use of framing and default options for the design of decision aids and interventions

Descriptive models not only help explain behaviours that deviate from the predictions of normative models of choice but also provide entry points for the design of decision aids and interventions collectively referred to as choice architecture, indicating that people's choices depend in part on the ways that possible outcomes of different options are framed and presented (Thaler and Sunstein, 2008). Prospect theory suggests that changing decision makers' reference points can impact on how they evaluate outcomes of different options and hence their final choice. Patt and Zeckhauser (2000) show, for example, how information about the status quo and other choice options can be presented differently to create an action bias with respect to addressing the climate change problem. More generally, choice architecture often involves changing the description of choice options and the context of a decision to overcome the pitfalls of intuitive (System 1) processes without requiring decision makers to switch to effortful (System 2) thinking (Thaler and Sunstein, 2008).

One important choice architecture tool comes in the form of behavioural defaults, that is, recommended options that will be implemented if no active decision is made (Johnson and Goldstein, 2013). Default options serve as a reference point so that decision makers normally stick with this option due to loss aversion (Johnson et al., 2007; Weber et al., 2007). 'Green' energy defaults have been found to be very effective in lab studies involving choices between different lighting technologies (Dinner et al., 2011), suggesting that environmentally friendly and cost-effective energy efficient technology will find greater deployment if it were to show up as the default option in building codes and other regulatory contexts. Green defaults are desirable policy options because they guide decision makers towards individual and social welfare maximizing options without reducing choice autonomy. In a field study, German utility customers adopted green energy defaults, a passive choice that persisted over time and was not changed by price feedback (Pichert and Katsikopoulos, 2008). Moser (2010) provides other ways to frame climate change information and response options in ways consistent with the communication goal and characteristics of the audience.

2.4.3.2 Focus on the short term and the here-and-now

Finite attention and processing capacity imply that unaided intuitive choices are restricted in their scope. This makes individuals susceptible to different types of myopia or short-sightedness with respect to their decisions on whether to invest in measures they would consider cost-effective if they engaged in deliberative thinking (Weber and Johnson, 2009; Kunreuther et al., 2013b).

Present bias and quasi-hyperbolic time discounting

Normative models suggest that future costs and benefits should be evaluated using an exponential discount function, that is, a constant discount rate per time period (i.e., exponentially), where the discount rate should reflect the decision maker's opportunity cost of money (for more details see Section 3.6.2). In reality, people discount future costs or benefits much more sharply and at a non-constant rate (i.e., hyperbolically), so that delaying an immediate receipt of a benefit is viewed much more negatively than if a similar delay occurs at a future point in time (Loewenstein and Elster, 1992). Laibson (1997) characterized this pattern by a quasi-hyperbolic discount function, with two parameters: (1) present bias, i.e., a discount applied to all non-immediate outcomes regardless how far into the future they occur, and (2) a rational discounting parameter. The model retains much of the analytical tractability of exponential discounting, while capturing the key qualitative feature of hyperbolic discounting.

Failure to invest in protective measures

In the management of climate-related natural hazards such as flooding, an extensive empirical literature reveals that adoption rates of protective measures by the general public are much lower than if individuals had engaged in deliberative thinking by making relevant tradeoffs between expected costs and benefits. Thus, few people living in flood prone areas in the United States voluntarily purchase flood insurance, even when it is offered at highly subsidized premiums under the National Flood Insurance Program (NFIP) (Kunreuther et al., 1978). In the context of climate change mitigation, many efficient responses like investments in household energy efficiency are not adopted because decision makers focus unduly on the upfront costs of these measures (due to hyperbolic discounting amplified by loss aversion) and weight the future benefits of these investments less than predicted by normative models (see Sections 2.6.4.3 and 3.10). The failure of consumers to buy fuel-efficient cars because of their higher upfront costs (Section 8.3.5) is another example of this behaviour.

At a country or community level, the upfront costs of mitigating CO_2 emissions or of building seawalls to reduce the effects of sea level rise loom large due to loss aversion, while the uncertain and future benefits of such actions are more heavily discounted than predicted by normative models. Such accounting of present and future costs and benefits on the part of consumers and policymakers might make it difficult for them to justify these investments today and arrive at long-term sustainable decisions (Weber, 2013).

Focus on short-term goals

Krantz and Kunreuther (2007) emphasize the importance of goals and plans as a basis for making decisions. In the context of climate change, protective or mitigating actions often require sacrificing short-term goals that are highly weighted in people's choices in order to meet more abstract, distant goals that are typically given very low weight. A strong focus on short-term goals (e.g., immediate survival) may have been helpful as humans evolved, but may have negative consequences in the current environment where risks and challenges are more complex and solutions to problems such as climate change require a focus on long time horizons. Weber et al. (2007) succeeded in drastically reducing people's discounting of future rewards by prompting them to first generate arguments for deferring consumption, contrary to their natural inclination to focus initially on rationales for immediate consumption. To deal with uncertainty about future objective circumstances as well as subjective evaluations, one can adopt multiple points of view (Jones and Preston, 2011) or multiple frames of reference (De Boer et al., 2010); a generalization of the IPCC's scenario approach to an uncertain climate future is discussed in Chapter 6.

Mental accounting as a protection against short-term focus

People often mentally set up separate 'accounts' for different classes of expenditures and do not treat money as fungible between these accounts (Thaler, 1999). Mental accounts for different expenditures serve as effective budgeting and self-control devices for decision makers with limited processing capacity and self-control. A focus on short-term needs and goals can easily deplete financial resources, leaving not enough for long(er)-term goals. Placing a limit on short-term spending prevents this from happening. But such a heuristic also has a downside by unduly limiting people's willingness to invest in climate change mitigation or adaptation measures (e.g., flood proofing or solar panels) that exceed their allocated budget for this account, regardless of future benefits. Such constraints (real or mental) often lead to the use of lexicographic (rather than compensatory) choice processes, where option sets are created or eliminated sequentially, based on a series of criteria of decreasing importance (Payne et al., 1988).

Mental accounting at a nonfinancial level may also be responsible for rebound effects of a more psychological nature, in addition to the economically based rebound effects discussed in Section 8.3.5. Rebound effects describe the increase in energy usage that sometimes follows improvements in household, vehicle, or appliance efficiency. For example, households who weatherize their homes tend to increase their thermostat settings during the winter afterwards, resulting in a decrease in energy savings relative to what is technologically achievable (Hirst et al., 1985). While rebound effects on average equal only 10–30% of the achievable savings, and therefore do not cancel out the benefits of efficiency upgrades (Ehrhardt-Martinez and Laitner, 2010), they are significant and may result from fixed mental accounts that people have for environmentally responsible behaviour. Having fulfilled their self-imposed quota by a particular action allows decision makers to move on to other goals, a behaviour also sometimes referred to as the single-action bias (Weber, 2006).

2.4.3.3 Aversion to risk, uncertainty, and ambiguity

Most people are averse to risk and to uncertainty and ambiguity when making choices. More familiar options tend to be seen as less risky, all other things being equal, and thus more likely to be selected (Figner and Weber, 2011).

Certainty effect or uncertainty aversion

Prospect theory formalizes a regularity related to people's perceptions of certain versus probabilistic prospects. People overweight outcomes they consider certain, relative to outcomes that are merely probable—a phenomenon labelled the *certainty effect* (Kahneman and Tversky, 1979). This frequently observed behaviour can explain why the certain upfront costs of adaptation or mitigation actions are viewed as unattractive when compared to the uncertain future benefits of undertaking such actions (Kunreuther et al., 2013b).

Ambiguity aversion

Given the high degree of uncertainty or ambiguity in most forecasts of future climate change impacts and the effects of different mitigation or adaptation strategies, it is important to consider not only decision makers' risk attitudes, but also attitudes towards ambiguous outcomes. The Ellsberg paradox (Ellsberg, 1961) revealed that, in addition to being risk averse, most decision makers are also ambiguity averse, that is, they prefer choice options with well-specified probabilities over options where the probabilities are uncertain. Heath and Tversky (1991) demonstrated, however, that ambiguity aversion is not present when decision makers believe they have expertise in the domain of choice. For example, in contrast to the many members of the general public who consider themselves to be experts in sports or the stock market, relatively few people believe themselves to be highly competent in environmentally relevant technical domains such as the tradeoffs between hybrid electric versus conventional gasoline engines in cars, so they are likely to be ambiguity averse. Farmers who feel less competent with respect to their understanding of new technology are more ambiguity averse and less likely to adopt farming innovations (in Peru; Engle-Warnick and Laszlo, 2006; and in the USA; Barham et al., 2014). With respect to the likelihood of extreme events, such as natural disasters, insurers feel they do not have special expertise in estimating the likelihood of these events so they also tend to be ambiguity averse and set premiums that are considerably higher than if they had more certainty with respect to the likelihood of their occurrence (Kunreuther et al., 1993; Cabantous et al., 2011).

2.4.4 Learning

The ability to change expectations and behaviour in response to new information is an important survival skill, especially in uncertain and non-stationary environments. Bayesian updating characterizes learning when one engages in deliberative thinking. Individuals who engage in intuitive thinking are also highly responsive to new and especially recent feedback and information, but treat the data differently than that implied by Bayesian updating (Weber et al., 2004).

Availability bias and the role of salience

People's intuitive assessment of the likelihood of an uncertain event is often based on the ease with which instances of its occurrence can be brought to mind, a mechanism called *availability* by Tversky and Kahneman (1973). Sunstein (2006) discusses the use of the availability heuristics in response to climate change risks and how it differs among groups, cultures, and nations. Availability is strongly influenced by recent personal experience and can lead to an underestimation of low-probability events (e.g., typhoons, floods, or droughts) before they occur, and their overestimation after an extreme event has occurred. The resulting availability bias can explain why individuals first purchase insurance after a disaster has occurred and cancel their policies several years later, as observed for earthquake (Kunreuther et al., 1978) and flood insurance (Michel-Kerjan et al., 2012). It is likely that most of these individuals had not suffered any losses during this period and considered the insurance to be a poor investment. It is difficult to convince insured individuals that the best return on their policy is no return at all. They should celebrate not having suffered a loss (Kunreuther et al., 2013c).

Linear thinking

A majority of people perceive climate in a linear fashion that reflects two common biases (Sterman and Sweeney, 2007; Cronin et al., 2009; Dutt and Gonzalez, 2011). First, people often rely on the *correlation heuristic*, which means that people wrongly infer that an accumulation (CO_2 concentration) follows the same path as the inflow (CO_2 emissions). This implies that cutting emissions will quickly reduce the concentration and damages from climate change (Sterman and Sweeney, 2007). According to Dutt (2011) people who rely on this heuristic likely demonstrate wait-and-see behaviour on policies that mitigate climate change because they significantly underestimate the delay between reductions in CO_2 emissions and in the CO_2 concentration. Sterman and Sweeny (2007) show that people's wait-and-see behaviour on mitigation policies is also related to a second bias whereby people incorrectly infer that atmospheric CO_2 concentration can be stabilized even when emissions exceeds absorption.

Linear thinking also leads people to draw incorrect conclusions from nonlinear metrics, like the miles-per-gallon (mpg) ratings of vehicles' gasoline consumption in North America (Larrick and Soll, 2008). When given a choice between upgrading to a 15-mpg car from a 12-mpg car, or to a 50-mpg car from a 29-mpg car, most people choose the latter option. However, for 100 miles driven under both options, it is easily shown that the first upgrade option saves more fuel (1.6 gallons for every 100 miles driven) than the second upgrade option (1.4 gallons for every 100 miles driven).

Effects of personal experience

Learning from personal experience is well predicted by reinforcement learning models (Weber et al., 2004). Such models describe and predict why the general public is less concerned about low-probability high-impact climate risks than climate scientists would suggest is warranted by the evidence (Gonzalez and Dutt, 2011). These learning models also capture the volatility of the public's concern about climate change over time, for example in reaction to the personal experience of local weather abnormalities (an abnormal cold spell or heat wave) that have been shown to influence belief in climate change (Li et al., 2011).

Most people do not differentiate very carefully between weather, climate (average weather over time), and climate variability (variations in weather over time). People confound climate and weather in part because they have personal experience with weather and weather abnormalities but little experience with climate change, an abstract statistical concept. They thus utilize weather events in making judgments about climate change (Whitmarsh, 2008). This confusion has been observed in countries as diverse as the United States (Bostrom et al., 1994; Cullen, 2010) and Ethiopia (BBC World Service Trust, 2009).

Personal experience can differ between individuals as a function of their location, history, and/or socio-economic circumstances (Figner and Weber, 2011). Greater familiarity with climate risks, unless accompanied by alarming negative consequences, could actually lead to a reduction rather than an increase in the perceptions of its riskiness (Kloeckner, 2011). On the other hand, people's experience can make climate a more salient issue. For example, changes in the timing and extent of freezing and melting (and associated effects on sea ice, flora, and fauna) have been experienced since the 1990s in the American and Canadian Arctic and especially indigenous communities (Laidler, 2006), leading to increased concern with climate change because traditional prediction mechanisms no longer can explain these phenomena (Turner and Clifton, 2009).

People's expectations of change (or stability) in climate variables also affect their ability to detect trends in probabilistic environments. For instance, farmers in Illinois were asked to recall growing season temperature or precipitation statistics for seven preceding years. Farmers who believed that their region was affected by climate change recalled precipitation and temperature trends consistent with this expectation, whereas farmers who believed in a constant climate, recalled precipitations and temperatures consistent with that belief (Weber, 1997). Recognizing that beliefs shape perception and memory provides insight into why climate change expectations and concerns vary between segments of the US population with different political ideologies (Leiserowitz et al., 2008).

The evidence is mixed when we examine whether individuals learn from past experience with respect to investing in adaptation or mitigation measures that are likely to be cost-effective. Even after the devastating 2004 and 2005 hurricane seasons in the United States, a large number of residents in high-risk areas had still not invested in relatively inexpensive loss-reduction measures, nor had they undertaken emergency preparedness measures (Goodnough, 2006). Surveys conducted in Alaska and Florida, regions where residents have been exposed more regularly to physical evidence of climate change, show greater concern and willingness to take action (ACI, 2004; Leiserowitz and Broad, 2008; Mozumder et al., 2011).

A recent study assessed perceptions and beliefs about climate change of a representative sample of the Britain public (some of whom had experienced recent flooding in their local area). It also asked whether they would reduce personal energy use to reduce greenhouse gas emission (Spence et al., 2011). Concern about climate change and willingness to take action was greater in the group of residents who had experienced recent flooding. Even though the flooding was only a single and local data point, this group also reported less uncertainty about whether climate change was really happening than those who did not experience flooding recently, illustrating the strong influence of personal experience. Other studies fail to find a direct effect of personal experience with flooding generating concern about climate risks (Whitmarsh, 2008).

Some researchers find that personal experience with ill health from air pollution affects perceptions of and behavioural responses to climate risks (Bord et al., 2000; Whitmarsh, 2008), with the negative effects from air pollution creating stronger pro-environmental values. Myers et al. (2012) looked at the role of experiential learning versus motivated reasoning among highly engaged individuals and those less engaged in the issue of climate change. Low-engaged individuals were more likely to be influenced by their perceived personal experience of climate change than by their prior beliefs, while those highly engaged in the issue (on both sides of the climate issue) were more likely to interpret their perceived personal experience in a manner that strengthens their pre-existing beliefs.

Indigenous climate change knowledge contributions from Africa (Orlove et al., 2010), the Arctic (Gearheard et al., 2009), Australia (Green et al., 2010), or the Pacific Islands (Lefale, 2010), derive from accumulated and transmitted experience and focus mostly on predicting seasonal or interannual climate variability. Indigenous knowledge can supplement scientific knowledge in geographic areas with a paucity of data (Green and Raygorodetsky, 2010) and can guide knowledge generation that reduces uncertainty in areas that matter for human responses (ACI, 2004). Traditional ecological knowledge is embedded in value-institutions and belief systems related to historical modes of experimentation and is transferred from generation to generation (Pierotti, 2011).

Underweighting of probabilities and threshold models of choice

The probability weighting function of prospect theory indicates that low probabilities tend to be overweighted relative to their objective probability unless they are perceived as being so low that they are ignored because they are below the decision maker's threshold level of concern. Prior to a disaster, people often perceive the likelihood of catastrophic events occurring as below their threshold level of concern, a form of intuitive thinking in the sense that one doesn't have to reflect on the consequences of a catastrophic event (Camerer and Kunreuther, 1989). The need to take steps today to deal with future climate change presents a challenge to individuals who are myopic. They are likely to deal with this challenge by using a threshold model that does not require any action for risks below this level. The problem is compounded by the inability of individuals to distinguish between low likelihoods that differ by one or even two orders of magnitude (e.g., between 1 in 100 and 1 in 10,000) (Kunreuther et al., 2001).

2.4.5 Linkages between different levels of decision making

Social amplification of risk

Hazards interact with psychological, social, institutional, and cultural processes in ways that may amplify or attenuate public responses to the risk or risk event by generating emotional responses and other biases associated with intuitive thinking. Amplification may occur when scientists, news media, cultural groups, interpersonal networks, and other forms of communication provide risk information. The amplified risk leads to behavioural responses, which, in turn, may result in secondary impacts such as the stigmatization of a place that has experienced an adverse event (Kasperson et al., 1988; Flynn et al., 2001). The general public's overall concern about climate change is influenced, in part, by the amount of media coverage the issue receives as well as the personal and collective experience of extreme weather in a given place (Leiserowitz et al., 2012; Brulle et al., 2012).

Social norms and social comparisons

Individuals' choices are often influenced by other people's behaviour, especially under conditions of uncertainty. Adherence to formal rules (e.g., standard operating procedures or best practices in organizations) or informal rules of conduct is an important way in which we intuitively decide between different courses of action (Weber and Lindemann, 2007). "When in doubt, copy what the majority is doing" is not a bad rule to follow in many situations, as choices adopted by others are assumed to be beneficial and safe (Weber, 2013). In fact, such social imitation can lead to social norms. Section 3.10.2 describes the effects of social norms in greater detail. Goldstein et al. (2008) demonstrate the effectiveness of providing descriptive norms ("this is what most people do") versus injunctive norms ("this is what you should be doing") to reduce energy use in US hotels. The application of social norms to encourage investment in energy efficient products and technology is discussed in Section 2.6.5.3.

Social comparisons are another effective way to evaluate and learn about the quality of obtained outcomes (Weber, 2004). It helps, for example, to compare one's own energy consumption to that of neighbours in similar-sized apartments or houses to see how effective efforts at energy conservation have been. Such non-price interventions can substantially change consumer behaviour, with effects equivalent to that of a short-run electricity price increase of 11 % to 20 % (Alcott, 2011). Social comparisons, imitation, and norms may be necessary to bring about lifestyle changes that are identified in Chapter 9 as reducing GHG emissions from the current levels (Sanquist et al., 2012).

Social learning and cultural transmission

Section 9.3.10 suggests that indigenous building practices in many parts of the world provide important lessons for affordable low-energy housing design and that developed countries can learn from traditional building practices, transmitted over generations, the social-scale equivalent of 'intuitive' processing and learning at the individual level.

Risk protection by formal (e.g., insurance) and informal institutions (e.g., social networks)

Depending on their cultural and institutional context, people can protect themselves against worst-case and/or potentially catastrophic economic outcomes either by purchasing insurance (Kunreuther et al., 2013c) or by developing social networks that will help bail them out or assist them in the recovery process (Weber and Hsee, 1998). Individualist cultures favour formal insurance contracts, whereas collectivist societies make more use of informal mutual insurance via social networks. This distinction between risk protection by either formal or informal means exists at the individual level and also at the firm level, e.g., the chaebols in Korea or the keiretsus in Japan (Gilson and Roe, 1993).

Impact of uncertainty on coordination and competition

Adaptation and especially mitigation responses require coordination and cooperation between individuals, groups, or countries for many of the choices associated with climate change. The possible outcomes often can be viewed as a game between players who are concerned with their own payoffs but who may still be mindful of social goals and objectives. In this sense they can be viewed in the context of a prisoners' dilemma (PD) or social dilemma. Recent experimental research on two-person PD games reveals that individuals are more likely to be cooperative when payoffs are deterministic than when the outcomes are probabilistic. A key factor explaining this difference is that in a deterministic PD game, the losses of both persons will always be greater when they both do not cooperate than when they do. When outcomes are probabilistic there is some chance that the losses will be smaller when both parties do not cooperate than when they do, even though the expected losses to both players will be greater if they both decide not to cooperate than if they both cooperate (Kunreuther et al., 2009).

In a related set of experiments, Gong et al. (2009) found that groups are less cooperative than individuals in a two-person deterministic PD game; however, in a stochastic PD game, where defection increased uncertainty for both players, groups became more cooperative than they were in a deterministic PD game and more cooperative than individuals in the stochastic PD game. These findings have relevance to behaviour with respect to climate change where future outcomes of specific policies are uncertain. Consider decisions made by groups of individuals, such as when delegations from countries are negotiating at the Conference of Parties (COP) to make commitments for reducing GHG emissions where the impacts on climate change are uncertain. These findings suggest that there is likely to be more cooperation between governmental delegations than if each country was represented by a single decision maker.

Cooperation also plays a crucial role in international climate agreements. There is a growing body of experimental literature that looks at individuals' cooperation when there is uncertainty associated with others adopting climate change mitigation measures. Tavoni et al. (2011) found that communication across individuals improves the likelihood of cooperation. Milinski et al. (2008) observed that the higher the risky losses associated with the failure to cooperate in the provision of a public good, the higher the likelihood of cooperation. If the target for reducing CO_2 is uncertain, Barrett and Dannenberg (2012) show in an experimental setting that cooperation is less likely than if the target is well specified.

2.4.6 Perceptions of climate change risk and uncertainty

Empirical social science research shows that the perceptions of climate change risks and uncertainties depend not only on external reality but also on the observers' internal states, needs, and the cognitive and emotional processes that characterize intuitive thinking. Psychological research has documented the prevalence of affective processes in the intuitive assessment of risk, depicting them as essentially effort-free inputs that orient and motivate adaptive behaviour, especially under conditions of uncertainty that are informed and shaped by personal experience over time (Finucane et al., 2000; Loewenstein et al., 2001; Peters et al., 2006).

Box 2.1 | Challenges facing developing countries

One of the key findings on developing countries is that non-state actors such as tribes, clans, castes, or guilds may be of substantial influence on how climate policy choices are made and diffused rather than having the locus of decision making at the level of the individual or governmental unit. For instance, a farming tribe/caste may address the climate risks and uncertainties faced by their community and opt for a system of crop rotation to retain soil fertility or shift cultivation to preserve the nutritious state of farmlands. Research in developing countries in Africa has shown that people may understand probabilistic information better when it is presented in a group where members have a chance to discuss it (Patt et al., 2005; Roncoli, 2006). This underscores why the risks and uncertainty associated with climate change has shifted governmental responsibility to non-state actors (Rayner, 2007).

In this context, methodologies and decision aids used in individual-centred western societies for making choices that rely on uncertain probabilities and uncertain outcomes may not apply to developing countries. Furthermore, methodologies, such as expected utility theory, assume an individual decision maker whereas in developing countries, decisions are often made by clans or tribes. In addition, tools such as cost-benefit analysis, cost-effectiveness analysis and robust decision making may not always be relevant for developing countries since decisions are often based on social norms, traditions, and customs

The adverse effects of climate change on food, water, security, and incidences of temperature-influenced diseases (Shah and Lele, 2011), are further fuelled by a general lack of awareness about climate change in developing countries (UNDP, 2007); consequently, policymakers in these countries support a wait-and-see attitude toward climate change (Dutt, 2011). Resource allocation and investment constraints may also lead policy-makers to postpone policy decisions to deal with climate change, as is the case with respect to integration of future energy systems in small island states (UNFCCC, 2007). The delay may prevent opportunities for learning and increase future vulnerabilities. It may also lock in countries into infrastructure and technologies that may be difficult to alter.

The tension between short- and long-term priorities in low income countries is often accentuated by uncertainties in political culture and regulatory policies (Rayner, 1993). This may lead to policies that are flawed in design and/or implementation or those that have unintended negative consequences. For example, subsidies for clean fuels such as liquefied petroleum gas (LPG) in a country like India often do not reach their intended beneficiaries (the poor), and at the same time add a large burden to the exchequer (Government of India, Ministry of Finance, 2012; IISD, 2012).

Other institutional and governance factors impede effective climate change risk management in developing countries. These include lack of experience with insurance (Patt et al., 2010), dearth of data, and analytical capacity. A more transparent and effective civil service would also be helpful, for instance in stimulating investments in renewable energy generation capacities (Komendantova et al., 2012). Financial constraints suggest the importance of international assistance and private sector contribution to implement adaptation and mitigation strategies for dealing with climate change in developing countries.

Two important psychological risk dimensions have been shown to influence people's intuitive perceptions of health and safety risks across numerous studies in multiple countries (Slovic, 1987). The first factor, 'dread risk', captures emotional reactions to hazards like nuclear reactor accidents, or nerve gas accidents, that is, things that make people anxious because of a perceived lack of control over exposure to the risks and because consequences may be catastrophic. The second factor, 'unknown risk', refers to the degree to which a risk (e.g., DNA technology) is perceived as new, with unforeseeable consequences and with exposures not easily detectable.

Perceptions of the risks associated with a given event or hazard are also strongly influenced by personal experience and can therefore differ between individuals as a function of their location, history, and/or socio-economic circumstances (see Box 2.1) (Figner and Weber, 2011). Whereas personal exposure to adverse consequences increases fear and perceptions of risk, familiarity with a risk can lower perceptions of its riskiness unless it is accompanied by alarming negative consequences (Kloeckner, 2011). Seeing climate change only as a simple and gradual change from current to future average temperatures and precipitation may make it seem controllable—the non-immediacy of the danger seems to provide time to plan and execute protective responses (Weber, 2006). These factors suggest that laypersons differ in their perception of climate risks more than experts who engage in deliberative thinking and estimate the likelihood and consequences of climate change utilizing scientific data.

Impact of uncertainties in communicating risk

If the uncertainties associated with climate change and its future impact on the physical and social system are not communicated accurately, the general public may misperceive them (Corner and Hahn, 2009). Krosnick et al. (2006) found that perceptions of the seriousness of global warming as a national issue in the United States depended on the degree of certainty of respondents as to whether global warming is occurring and will have negative consequences coupled with their belief that humans are causing the problem and have the ability to solve it. Accurately communicating the degree of uncertainty in both climate risks and policy responses is therefore a critically important challenge for climate scientists and policymakers (Pidgeon and Fischhoff, 2011).

Roser-Renouf et al. (2011), building upon the work of Krosnick et al. (2006), apply social cognitive theory to develop a model of climate advocacy to increase the attention given to climate change in the spirit of social amplification of risk. They found that campaigns looking to increase the number of citizens contacting elected officials to advocate climate policy action should focus on increasing the belief that global warming is real, human-caused, a serious risk, and solvable. These four key elements, coupled with the understanding that there is strong scientific agreement on global warming (Ding et al., 2011), are likely to build issue involvement and support for action to reduce the impacts of climate change.

The significant time lags within the climate system and a focus on short-term outcomes lead many people to believe global warming will have only moderately negative impacts. This view is reinforced because adverse consequences are currently experienced only in some regions of the world or are not easily attributed to climate change. For example, despite the fact that "climate change currently contributes to the global burden of disease and premature deaths" (IPCC, 2007) relatively few people make the connection between climate change and human health risks.

One challenge is how to facilitate correct inferences about the role of climate change as a function of extreme event frequency and severity. Many parts of the world have seen increases in the frequency and magnitude of heat waves and heavy precipitation events (IPCC, 2012). In the United States, a large majority of Americans believe that climate change exacerbated extreme weather events (Leiserowitz et al., 2012). That said, the perception that the impact of climate change is neither immediate nor local persists (Leiserowitz et al., 2008), leading many to think it rational to advocate a wait-and-see approach to emissions reductions (Sterman, 2008; Dutt and Gonzalez, 2013).

Differences in education and numeracy

Individual and group differences in education and training and the resulting different cognitive and affective processes have additional implications for risk communication. It may help to supplement the use of words to characterize the likelihood of an outcome recommended by the current IPCC Guidance Note (GN) with numeric probability ranges (Budescu et al., 2009). Patt and Dessai (2005) show that in the IPCC Third Assessment Report (TAR), words that characterized numerical probabilities were interpreted by decision makers in inconsistent and often context-specific ways, a phenomenon with a long history in cognitive psychology (Wallsten et al., 1986; Weber and Hilton, 1990). These context-specific interpretations of probability words are deeply rooted, as evidenced by the fact that the likelihood of using the intended interpretation of TAR probability words did not differ with level of expertise (attendees of a UN COP conference versus students) or as a function of whether respondents had read the TAR instructions that specify how the probability words characterized numerical probabilities (Patt and Dessai, 2005).

Numeracy, the ability to reason with numbers and other mathematical concepts, is a particularly important individual and group difference in this context as it has implications for the presentation of likelihood information using either numbers (for example, 90 %) or words (for example, "very likely" or "likely") or different graphs or diagrams (Peters et al., 2006; Mastrandrea et al., 2011). Using personal experience with climate variables has been shown to be effective in communicating the impact of probabilities (e.g., of below-, about-, and above-normal rainfall in an El Niño year) to decision makers with low levels of numeracy, for example subsistence farmers in Zimbabwe (Patt et al., 2005).

2.5 Tools and decision aids for analysing uncertainty and risk

This section examines how more formal approaches can assist decision makers in engaging in more deliberative thinking with respect to climate change policies when faced with the risks and uncertainties characterized in Section 2.3.

2.5.1 Expected utility theory

Expected utility [E(U)] theory (Ramsey, 1926; von Neumann and Morgenstern, 1944; Savage, 1954); remains the standard approach for providing normative guidelines against which other theories of individual decision making under risk and uncertainty are benchmarked. According to the E(U) model, the solution to a decision problem under uncertainty is reached by the following four steps:

1. Define a set of possible decision alternatives.
2. Quantify uncertainties on possible states of the world.
3. Value possible outcomes of the decision alternatives as utilities.
4. Choose the alternative with the highest expected utility.

This section clarifies the applicability of expected utility theory to the climate change problem, highlighting its potentials and limitations.

2.5.1.1 Elements of the theory

E(U) theory is based on a set of axioms that are claimed to have normative rather than descriptive validity. Based on these axioms, a person's subjective probability and utility function can be determined by observing preferences in structured choice situations. These axioms have been debated, strengthened, and relaxed by economists, psychologists, and other social scientists over the years. The axioms have been challenged by controlled laboratory experiments and field studies discussed in Section 2.4 but they remain the basis for parsing decision problems and recommending options that maximize expected utility.

2.5.1.2 How can expected utility improve decision making?

E(U) theory provides guidelines for individual choice, such as a farmer deciding what crops to plant or an entrepreneur deciding whether to invest in wind technology. These decision makers would apply E(U) theory by following the four steps above. The perceptions and responses to risk and uncertainty discussed in Section 2.5 provide a rationale for undertaking deliberative thinking before making final choices. More specifically, a structured approach, such as the E(U) model, can reduce the impact of probabilistic biases and simplified decision rules that characterize intuitive thinking. At the same time, the limitations of E(U) must be clearly understood, as the procedures for determining an optimal choice do not capture the full range of information about outcomes and their risks and uncertainties.

Subjective versus objective probability

In the standard E(U) model, each individual has his/her own subjective probability estimates. When there is uncertainty on the scientific evidence, experts' probability estimates may diverge from each other, sometimes significantly. With respect to climate change, observed relative frequencies are always preferred when suitable sets of observations are accessible. When these data are not available, one may want to utilize structured expert judgment for quantifying uncertainty (see Section 2.5.7).

Individual versus social choice

In applying E(U) theory to problems of social choice, a number of issues arise. Condorcet's voting paradox shows that groups of rational individuals deciding by majority rule do not exhibit rational preferences. Using a social utility or social welfare function to determine an optimal course of action for society requires some method of measuring society's preferences. In the absence of these data the social choice problem is not a simple exercise of maximizing expected utility. In this case, a plurality of approaches involving different aggregations of individual utilities and probabilities may best aid decision makers. The basis and use of the social welfare function are discussed in Section 3.4.6.

Normative versus descriptive

As noted above, the rationality axioms of E(U) are claimed to have normative as opposed to descriptive validity. The paradoxes of Allais (1953) and Ellsberg (1961) reveal choice behaviour incompatible with E(U); whether this requires modifications of the normative theory is a subject of debate. McCrimmon (1968) found that business executives willingly corrected violations of the axioms when they were made aware of them. Other authors (Kahneman and Tversky, 1979; Schmeidler, 1989; Quiggin, 1993; Wakker, 2010) account for such paradoxical choice behaviour by transforming the probabilities of outcomes into decision weight probabilities that play the role of likelihood in computing optimal choices but do not obey the laws of probability. However, Wakker (2010, p. 350) notes that decision weighting fails to describe some empirically observed behavioural patterns.

2.5.2 Decision analysis

2.5.2.1 Elements of the theory

Decision analysis is a formal approach for choosing between alternatives under conditions of risk and uncertainty. The foundations of decision analysis are provided by the axioms of expected utility theory. The methodology for choosing between alternatives consists of the following elements that are described in more detail in Keeney (1993):

1. Structure the decision problem by generating alternatives and specifying values and objectives or criteria that are important to the decision maker.
2. Assess the possible impacts of different alternatives by determining the set of possible consequences and the probability of each occurring.
3. Determine preferences of the relevant decision maker by developing an objective function that considers attitudes toward risk and aggregates the weighted objectives.
4. Evaluate and compare alternatives by computing the expected utility associated with each alternative. The alternative with the highest expected utility is the most preferred one.

To illustrate the application of decision analysis, consider a homeowner that is considering whether to invest in energy efficient technology as part of their lifestyle options as depicted in Figure 2.2:

1. The person focuses on two alternatives: (A1) Maintain the status quo, and (A2) Invest in solar panels, and has two objectives: (O1) Minimize cost, and (O2) Assist in reducing global warming.
2. The homeowner would then determine the impacts of A1 and A2 on the objectives O1 and O2 given the risks and uncertainties associated with the impact of climate change on energy usage as well as the price of energy.
3. The homeowner would then consider his or her attitude toward risks and then combine O1 and O2 into a multiattribute utility function.
4. The homeowner would then compare the expected utility of A1 and A2, choosing the one that had the highest expected utility.

2.5.2.2 How can decision analysis improve decision making?

Decision analysis enables one to undertake sensitivity analyses with respect to the uncertainties associated with the various consequences and to different value structures. Suppose alternative A1 had the highest expected utility. The homeowner could determine when the decision to invest in solar panels would be preferred to maintaining the status quo by asking questions such as:

- What would the minimum annual savings in energy expenses have to be over the next 10 years to justify investing in solar panels?
- What is the fewest number of years one would have to reside in the house to justify investing in solar panels?
- What impact will different levels of global warming have on the expected costs of energy over the next 10 years for the homeowner to want to invest in solar panels?
- How will changing the relative weights placed on minimizing cost (O1) and assisting in reducing global warming (O2) affect the expected utility of A1 and A2?

2.5.3 Cost-benefit analysis

2.5.3.1 Elements of the theory

Cost-benefit analysis (CBA) compares the costs and benefits of different alternatives with the broad purpose of facilitating more efficient allocation of society's resources. When applied to government decisions, CBA can indicate the alternative that has the highest social net present value based on a discount rate, normally constant over time, that converts future benefits and costs to their present values (Boardman et al., 2005; see also the extensive discussion in Section 3.6). Social, rather than private, costs and benefits are compared, including those affecting future generations (Brent, 2006). In this regard, benefits across individuals are assumed to be additive. Distributional issues may be addressed by putting different weights on specific groups to reflect their relative importance. Under conditions of risk and uncertainty, one determines expected costs and benefits by weighting outcomes by their likelihoods of occurrence. In this sense, the analysis is similar to expected utility theory and decision analysis discussed in Sections 2.5.1 and 2.5.2.

CBA can be extremely useful when dealing with well-defined problems that involve a limited number of actors who make choices among different mitigation or adaptation options. For example, a region could examine the benefits and costs over the next fifty years of building levees to reduce the likelihood and consequences of flooding given projected sea level rise due to climate change.

CBA can also provide a framework for defining a range of global long-term targets on which to base negotiations across countries (see for example Stern, 2007). However, CBA faces major challenges when defining the optimal level of global mitigation actions for the following three reasons: (1) the need to determine and aggregate individual welfare, (2) the presence of distributional and intertemporal issues, and (3) the difficulty in assigning probabilities to uncertain climate change impacts. The limits of CBA in the context of climate change are discussed at length in Sections 3.6 and 3.9. The discussion that follows focuses on challenges posed by risk and uncertainty.

2.5.3.2 How can CBA improve decision making?

Cost-benefit analysis assumes that the decision maker(s) will eventually choose between well-specified alternatives. To illustrate this point, consider a region that is considering measures that coastal villages in hazard-prone areas can undertake to reduce future flood risks that are expected to increase in part due to sea level rise. The different options range from building a levee (at the community level) to providing low interest loans to encourage residents and businesses in the community to invest in adaptation measures to reduce future damage to their property (at the level of an individual or household).

Some heuristics and resulting biases discussed in the context of expected utility theory also apply to cost-benefit analysis under uncertainty. For example, the key decision maker, the mayor, may utilize a threshold model of choice by assuming that the region will not be subject to flooding because there have been no floods or hurricanes during the past 25 years. By relying solely on intuitive processes there would be no way to correct this behaviour until the next disaster occurred, at which time the mayor would belatedly want to protect the community. The mayor and his advisors may also focus on short-time horizons, and hence do not wish to incur the high upfront costs associated with building flood protection measures such as dams or levees. They are unconvinced that that such an investment will bring significant enough benefits over the first few years when these city officials are likely to be held accountable for the expenditures associated with a decision to go forward on the project.

Cost-benefit analysis can highlight the importance of considering the likelihood of events over time and the need to discount impacts exponentially rather than hyperbolically, so that future time periods are given more weight in the decision process. In addition, CBA can highlight the tradeoffs between efficient resource allocation and distributional issues as a function of the relative weights assigned to different stakeholders (e.g., low income and well-to-do households in flood prone areas).

2.5.3.3 Advantages and limitations of CBA

The main advantage of CBA in the context of climate change is that it is internally coherent and based on the axioms of expected utility theory.

As the prices used to aggregate costs and benefits are the outcomes of market activity, CBA is, at least in principle, a tool reflecting people's preferences. Although this is one of the main arguments in favour of CBA (Tol, 2003), this line of reasoning can also be the basis for recommending that this approach not be employed for making choices if market prices are unavailable. Indeed, many impacts associated with climate change are not valued in any market and are therefore hard to measure in monetary terms. Omitting these impacts distorts the cost-benefit relationship.

Several ethical and methodological critiques have been put forward with respect to the application of CBA to climate policy (Charlesworth and Okereke, 2010; Caney, 2011). For example, the uncertainty surrounding the potential impacts of climate change, including possible irreversible and catastrophic effects on ecosystems, and their asymmetric distribution around the planet, suggests CBA may be inappropriate for assessing optimal responses to climate change in these circumstances.

A strong and recurrent argument against CBA (Azar and Lindgren, 2003; Tol, 2003; Weitzman, 2009, 2011) relates to its failure in dealing with infinite (negative) expected utilities arising from low-probability catastrophic events often referred to as 'fat tails'. In these situations, CBA is unable to produce meaningful results, and thus more robust techniques are required. The debate concerning whether fat tails are indeed relevant to the problem at hand is still unsettled (see for example Pindyck, 2011). Box 3.9 in Chapter 3 addresses the fat tail problem and suggests the importance of understanding the impacts associated with low probability, high impact climate change scenarios in evaluating alternative mitigation strategies.

One way to address the fat tail problem would be to focus on the potential catastrophic consequences of low-probability, high-impact events in developing GHG emissions targets and to specify a threshold probability and a threshold loss. One can then remove events from consideration that are below these critical values in determining what mitigation and/or adaptation to adopt as part of a risk management strategy for dealing with climate change (Kunreuther et al., 2013c). Insurers and reinsurers specify these thresholds and use them to determine the amount of coverage that they are willing to offer against a particular risk. They then diversify their portfolio of policies so the annual probability of a major loss is below a pre-specified threshold level of concern (e.g., 1 in 1000) (Kunreuther et al., 2013c). This approach is in the spirit of a classic paper by Roy (1952) on safety-first behaviour and can be interpreted as an application of probabilistic cost-effectiveness analysis (i.e., chance constrained programming) discussed in the next section. It was applied in a somewhat different manner to environmental policy by Ciriacy-Wantrup (1971) who contended that "*a safe minimum standard* is frequently a valid and relevant criterion for conservation policy."

One could also view uncertainty or risk associated with different options as one of the many criteria on which alternatives should be evaluated. Multi-criteria analysis (MCA) is sometimes proposed to overcome some of the limitations of CBA (see more on its basic features in Chapter 3 and for applications in Chapter 6). MCA implies that the different criteria or attributes should not be aggregated by converting all of them into monetary units. MCA techniques commonly apply numerical analysis in two stages:

- *Scoring:* for each option and criterion, the expected consequences of each option are assigned a numerical score on a strength of preference scale. More (less) preferred options score higher (lower) on the scale. In practice, scales often extend from 0 to 100, where 0 is assigned to a real or hypothetical least preferred option, and 100 is assigned to a real or hypothetical most preferred option. All options considered in the MCA would then fall between 0 and 100.
- *Weighting:* numerical weights are assigned to define their relative performance on a chosen scale that will often range from 0 (no importance) to 1 (highest importance) (Dodgson et al., 2009).

2.5.4 Cost-effectiveness analysis

2.5.4.1 Elements of the theory

Cost-effectiveness analysis (CEA) is a tool based on constrained optimization for comparing policies designed to meet a pre-specified target. The target can be defined through CBA, by applying a specific guideline such as the precautionary principle (see Section 2.5.5), or by specifying a threshold level of concern or environmental standard in the spirit of the safety-first models discussed above. The target could be chosen without the need to formally specify impacts and their respective probabilities. It could also be based on an ethical principle such as minimizing the worst outcome, in the spirit of a Rawlsian fair agreement, or as a result of political and societal negotiation processes.

Cost-effectiveness analysis does not evaluate benefits in monetary terms. Rather, it attempts to find the least-cost option that achieves a desired quantifiable outcome. In one sense CEA can be seen as a special case of CBA in that the technique replaces the criterion of choosing a climate policy based on expected costs and benefits with the objective of selecting the option that minimizes the cost of meeting an exogenous target (e.g., equilibrium temperature, concentration, or emission trajectory).

Like CBA, CEA can be generalized to include uncertainty. One solution concept requires the externally set target to be specified with certainty. The option chosen is the one that minimizes expected costs. Since temperature targets cannot be met with certainty (den Elzen and van Vuuren, 2007; Held et al., 2009), a variation of this solution concept requires that the likelihood that an exogenous target (e.g., equilibrium temperature) will be exceeded is below a pre-defined threshold probability. This solution procedure, equivalent to chance constrained programming (CCP) (Charnes and Cooper, 1959), enables one to use stochastic programming to examine the impacts of uncertainty with respect to the cost of meeting a pre-specified target. Chance constrained programming is a conceptually valid decision-analytic framework for examining the likelihood of attaining climate targets when the probability distributions characterizing the decision maker's state of knowledge is held constant over time (Held et al., 2009).

2.5.4.2 How can CEA improve decision making?

To illustrate how CEA can be useful, consider a national government that wants to set a target for reducing greenhouse gas (GHG) emissions in preparation for a meeting of delegates from different countries at the Conference of Parties (COP). It knows there is uncertainty as to whether specific policy measures will achieve the desired objectives. The uncertainties may be related to the outcomes of the forthcoming negotiation process at the COP and/or to the uncertain impacts of proposed technological innovations in reducing GHG emissions. Cost-effectiveness analysis could enable the government to assess alternative mitigation strategies (or energy investment policies) for reducing GHG emissions in the face of these uncertainties by specifying a threshold probability that aggregate GHG emissions will not be greater than a pre-specified target level.

2.5.4.3 Advantages and limitations of CEA over CBA

Cost-effectiveness analysis has an advantage over CBA in tackling the climate problem in that it does not require formalized knowledge about global warming impact functions (Pindyck, 2013). The focus of CEA is on more tangible elements, such as energy alternatives, where scientific understanding is more established (Stern, 2007). Still, CEA does require scientific input on potential risks associated with climate change. National and international political processes specify temperature targets and threshold probabilities that incorporate the preferences of different actors guided by data from the scientific community. The corresponding drawback of CEA is that the choice of the target is specified without considering its impact on economic efficiency. Once costs to society are assessed and a range of temperature targets is considered, one can assess people's preferences by considering the potential benefits and costs associated with different targets. However, if costs of a desirable action turn out to be regarded as too high, then CEA may not provide sufficient information to support taking action now. In this case additional knowledge on the mitigation benefit side would be required.

An important application of CEA in the context of climate change is evaluating alternative transition pathways that do not violate a predefined temperature target. Since a specific temperature target cannot be attained with certainty, formulating probabilistic targets as a CCP problem is an appropriate solution technique to use. However, introducing anticipated future learning so that probability distributions change over time can lead to infeasible solutions (Eisner et al., 1971). Since this is a problem with respect to specifying temperature targets, Schmidt et al. (2011) proposed an approach that that combines CEA and CBA. The properties of this hybrid model (labelled 'cost risk analysis') require further investigation. At this time, CEA through the use of CCP represents an informative concept for deriving mitigation costs for the case where there is no learning over time. With learning, society would be no worse off than the proposed CEA solution.

2.5.5 The precautionary principle and robust decision making

2.5.5.1 Elements of the theory

In the 1970s and 1980s, the precautionary principle was proposed for dealing with serious uncertain risks to the natural environment and to public health (Vlek, 2010). In its strongest form the precautionary principle implies that if an action or policy is suspected of having a risk that causes harm to the public or to the environment, precautionary measures should be taken even if some cause and effect relationships are not established. The burden of proof that the activity is not harmful falls on the proponent of the activity rather than on the public. A consensus statement to this effect was issued at the Wingspread Conference on the Precautionary Principle on 26 January 1998.

The precautionary principle allows policymakers to ban products or substances in situations where there is the possibility of their causing harm and/or where extensive scientific knowledge on their risks is lacking. These actions can be relaxed only if further scientific findings emerge that provide sound evidence that no harm will result. An influential statement of the precautionary principle with respect to climate change is principle 15 of the 1992 Rio Declaration on Environment and Development: "where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."

Robust decision making (RDM) is a particular set of methods developed over the last decade to address the precautionary principle in a systematic manner. RDM uses ranges or, more formally, sets of plausible probability distributions to describe uncertainty and to evaluate how well different policies perform with respect to different outcomes arising from these probability distributions. RDM provides decision makers with tradeoff curves that allow them to debate how much expected performance they are willing to sacrifice in order to improve outcomes in worst case scenarios. RDM thus captures the spirit of the precautionary principle in a way that illuminates the risks and benefits of different policies. Lempert et al. (2006) and Hall et al. (2012) review the application of robust approaches to decision making with respect to mitigating or adapting to climate change.

The tolerable windows approach can also be regarded as a 'robust method'. Temperature targets are specified and the bundle of decision paths compatible with the targets is characterized. Mathematically, the tolerable windows approach incorporates the features of CEA or CCP without optimization. The selection of the relevant targets and the paths to achieving it are left to those making the decision. (See Bruckner and Zickfeld (2008) for an introduction and an overview to peer-reviewed literature on the tolerable windows approach.)

2.5.6 Adaptive management

Adaptive management is an approach to governance that that grew out of the field of conservation ecology in the 1970s and incorporates mechanisms for reducing uncertainty over time (Holling, 1978; Walters and Hilborn, 1978). Paraphrasing the IPCC Special Report on Extreme Events (SREX) (IPCC, 2012), adaptive management represents structured processes for improving decision making and policy over time, by incorporating lessons learned. From the theoretical literature, two strands of adaptive management have been developed for improving decision making under uncertainty: passive and active.

Passive adaptive management (PAM) involves carefully designing monitoring systems, at the relevant spatial scales, so as to be able to track the performance of policy interventions and improve them over time in response to what has been learned. Active adaptive management (AAM) extends PAM by designing the interventions themselves as controlled experiments, so as to generate new knowledge. For example, if a number of political jurisdictions were seeking to implement support mechanisms for technology deployment, in an AAM approach they would deliberately design separate mechanisms that are likely to differ across jurisdictions. By introducing such variance into the management regime, however, one would collectively learn more about how industry and investors respond to a range of interventions. All jurisdictions could then use this knowledge in a later round of policymaking, reflecting the public goods character of institutional knowledge.

With respect to the application of PAM, Nilsson (2005) reports on a case study of Sweden, in which policymakers engaged in repetitive ex post analyses of national climate policy, and then responded to the lessons learned by modifying their goals and strategies. There are many documented cases of PAM applications in the area of climate change adaptation (Lawler et al., 2008; Berkes et al., 2000; Berkes and Jolly, 2001; Joyce et al., 2009; Armitage, 2011). The information gathering and reporting requirements of the UNFCCC are also in the spirit of PAM with respect to policy design, as are the diversity of approaches implemented for renewable energy support across the states and provinces of North America and the countries in Europe. The combination of the variance in action with data gathered about the consequences of these actions by government agencies has allowed for robust analysis on the relative effectiveness of different instruments (Blok, 2006; Mendonça, 2007; Butler and Neuhoff, 2008).

Individuals relying on intuitive thinking are unlikely to undertake experimentation that leads to new knowledge, as discussed in Section 2.4.3.1. In theory, adaptive management ought to correct this problem by making the goal of learning through experimentation an explicit policy goal. Lee (1993) illustrates this point by presenting a paradigmatic case of AAM designed to increase salmon stocks in the Columbia River watershed in the western United States and Canada. In this case, there was the opportunity to introduce a number of different management regimes on the individual river tributaries, and to reduce uncertainty about salmon population dynamics. As Lee (1993) documented, policymakers on the Columbia River were ultimately not able to carry through with AAM: local constituencies, valuing their own immediate interests over long-term learning in the entire region, played a crucial role in blocking it. One could imagine such political and institutional issues hindering the application of AAM at a global scale with respect to climate change policies.

To date, there are no cases in the literature specifically documenting climate change policies explicitly incorporating AAM. However, there are a number of examples where policy interventions implicitly follow AAM principles. One of these is promotion of energy research and development (R&D). In this case the government invests in a large number of potential new technologies, with the expectation that some technologies will not prove practical, while others will be successful and be supported by funding in the form of incentives such as subsidies (Fischer and Newell, 2008).

2.5.7 Uncertainty analysis techniques

Uncertainty analysis consists of both qualitative and quantitative methodologies (see Box 2.2 for more details). A Qualitative Uncertainty Analysis (QLUA) helps improve the choice process of decision makers by providing data in a form that individuals can easily understand. QLUA normally does not require complex calculations so that it can be useful in helping to overcome judgmental biases that characterize intuitive thinking. QLUA assembles arguments and evidence and provides a verbal assessment of plausibility, frequently incorporated in a Weight of Evidence (WoE) narrative.

A Quantitative Uncertainty Analysis (QNUA) assigns a joint distribution to uncertain parameters of a specific model used to characterize different phenomena. Quantitative Uncertainty Analysis was pioneered in the nuclear sector in 1975 to determine the risks associated with nuclear power plants (Rasmussen, 1975). The development of QNUA and its prospects for applications to climate change are reviewed by Cooke (2012).

2.5.7.1 Structured expert judgment

Structured expert judgment designates methods in which experts quantify their uncertainties to build probabilistic input for complex

Box 2.2 | Quantifying uncertainty

Natural language is not adequate for propagating and communicating uncertainty. To illustrate, consider the U.S. National Research Council 2010 report Advancing the Science of Climate Change (America's Climate Choices: Panel on Advancing the Science of Climate Change; National Research Council, 2010). Using the AR4 calibrated uncertainty language, the NRC is highly confident that (1) the Earth is warming and that (2) most of the recent warming is due to human activities.

What does the second statement mean? Does it mean the NRC is highly confident that the Earth is warming *and* the recent warming is anthropogenic or that, given the Earth is warming, are they highly confident humans cause this warming? The latter seems most natural, as the warming is asserted in the first statement. In that case the 'high confidence' applies to a conditional statement. The probability of both statements being true is the probability of the condition (Earth is warming) multiplied by the probability of this warming being caused by humans, given that warming is taking place. If both statements enjoy high confidence, then in the calibrated language of AR4 where high confidence implies a probability of 0.8, the statement that both are true would only be "more likely than not" (0.8 x 0.8 = 0.64).

Qualitative uncertainty analysis easily leads the unwary to erroneous conclusions. Interval analysis is a semi-qualitative method in which ranges are assigned to uncertain variables without distributions and can mask the complexities of propagation, as attested by the following statement in an early handbook on risk analysis: "The simplest quantitative measure of variability in a parameter or a measurable quantity is given by an assessed range of the values the parameter or quantity can take. This measure may be adequate for certain purposes (e.g., as input to a sensitivity analysis), but in general it is not a complete representation of the analyst's knowledge or state of confidence and generally will lead to an unrealistic range of results if such measures are propagated through an analysis", (U.S. NRC, 1983, Chapter 12, p.12).

The sum of 10 independent variables each ranging between zero and ten, can assume any value between zero and 100. The upper (lower) bound can be attained only if ALL variables take their maximal (minimal) values, whereas values near 50 can arise through many combinations. Simply stating the interval [0, 100] conceals the fact that very high (low) values are much more exceptional than central values. These same concepts are widely represented throughout the uncertainty analysis literature. According to Morgan and Henrion (1990): "Uncertainty analysis is the computation of the total uncertainty induced in the output by quantified uncertainty in the inputs and models [...] Failure to engage in systematic sensitivity and uncertainty analysis leaves both analysts and users unable to judge the adequacy of the analysis and the conclusions reached", (Morgan and Henrion, 1990, p. 39).

decision problems (Morgan and Henrion, 1990; Cooke, 1991; O'Hagan et al., 2006). A wide variety of activities fall under the heading of expert judgment that includes blue ribbon panels, Delphi surveys, and decision conferencing.

Elements

Structured expert judgment such as science-based uncertainty quantification was pioneered in the Rasmussen Report on risks of nuclear power plants (Rasmussen, 1975). The methodology was further elaborated in successive studies and involves protocols for expert selection and training, elicitation procedures and performance-based combinations that are described in more detail in Goossens et al. (2000). In large studies, multiple expert panels provide inputs to computer models with no practical alternative for combining expert judgments except to use equal weighting. Hora (2004) has shown that equal weight combinations of statistically accurate ('well calibrated') experts loses statistical accuracy. Combinations based on experts' statistical accuracy have consistently given more accurate and informative results (see for example Cooke and Goossens, 2008; Aspinall, 2010).

How can this tool improve decision making under uncertainty?

Structured expert judgment can provide insights into the nature of the uncertainties associated with a specific risk and the importance of undertaking more detailed analyses to design meaningful strategies and policies for dealing with climate change in the spirit of deliberative thinking. In addition to climate change (Morgan and Keith, 1995; Zickfeld et al., 2010), structured expert judgment has migrated into many fields such as volcanology (Aspinall, 1996, 2010), dam/dyke safety (Aspinall, 2010), seismicity (Klügel, 2008), civil aviation (Ale et al., 2009), ecology (Martin et al., 2012; Rothlisberger et al., 2012), toxicology (Tyshenko et al., 2011), security (Ryan et al., 2012), and epidemiology (Tuomisto et al., 2008).

The general conclusions emerging from experience with structured expert judgments to date are: (1) formalizing the expert judgment process and adhering to a strict protocol adds substantial value to understanding the importance of characterizing uncertainty; (2) experts differ greatly in their ability to provide statistically accurate and informative quantifications of uncertainty; and (3) if expert judgments must be combined to support complex decision problems, the combination method should be subjected to the following quality controls: statistical accuracy and informativeness (Aspinall, 2010).

As attested by a number of governmental guidelines, structured expert judgment is increasingly accepted as quality science that is applicable when other methods are unavailable (U.S. Environmental Protection Agency, 2005). Some expert surveys of economists concerned with climate change examine damages (Nordhaus, 1994) and appropriate discount rates (Weitzman, 2001). Structured expert judgments of climate scientists were recently used to quantify uncertainty in the ice sheet contribution to sea level rise, revealing that experts' uncertainty regarding the 2100 contribution to sea level rise from ice sheets increased between 2010 and 2012 (Bamber and Aspinall, 2013).

Damages or benefits to ecosystems from invasions of non-indigenous species are difficult to quantify and monetize on the basis of historical data. However ecologists, biologists and conservation economists have substantial knowledge regarding the possible impacts of invasive species. Recent studies applied structured expert judgment with a performance-based combination and validation to quantify the costs and benefits of the invasive species introduced since 1959 into the U.S. Great Lakes by opening the St. Lawrence Seaway (Rothlisberger et al., 2009, 2012). Lessons from studies such as these reveal that experts may have applicable knowledge that can be captured in a structured elicitation when historical data have large uncertainties associated with them.

Advantages and limitations of structured expert judgment

Expert judgment studies do not reduce uncertainty; they merely quantify it. If the uncertainties are large, as indeed they often are, then decision makers cannot expect science to relieve them of the burden of deciding under conditions of ambiguity. Since its inception, structured expert judgment has been met with scepticism in some quarters; it is, after all, just opinions and not hard facts. Its steady growth and widening acceptance over 35 years correlates with the growth of complex decision support models. The use of structured expert judgment must never justify a diminution of effort in collecting hard data.

2.5.7.2 Scenario analysis and ensembles

Scenario analysis develops a set of possible futures based on extrapolating current trends and varying key parameters, without sampling in a systematic manner from an uncertainty distribution. Utilizing sufficiently long time horizons ensures that structural changes in the system are considered. The futurist Herman Kahn and colleagues at the RAND Corporation are usually credited with inventing scenario analysis (Kahn and Wiener, 1967). In the climate change arena, scenarios are currently presented as different emission pathways or Representative Concentration Pathways (RCPs). Predicting the effects of such pathways involves modelling the Earth's response to changes in GHG concentrations from natural and anthropogenic sources. Different climate models will yield different projections for the same emissions scenario. Model Intercomparison studies generate sets of projections termed 'ensembles' (van Vuuren et al., 2011).

Elements of the theory

Currently, RCPs are carefully constructed on the bases of plausible storylines while insuring (1) they are based on a representative set of peer-reviewed scientific publications by independent groups, (2) they provide climate and atmospheric models as inputs, (3) they are harmonized to agree on a common base year, and (4) they extend to the year 2100. The four RCP scenarios, shown in Figure 2.3 relative to the range of baseline scenarios in the literature, roughly span the entire scenario literature, which includes control scenarios reaching 430 ppm CO_2eq or lower by 2100. The scenarios underlying the RCPs were originally developed by four independent integrated assessment models, each with their own carbon cycle. To provide the climate community with four harmonized scenarios, they were run through the same carbon cycle/climate model (Meinshausen et al., 2011). Note that a representative set is not a random sample from the scenarios as they do not represent independent samples from some underlying uncertainty distribution over unknown parameters.

Ensembles of model runs generated by different models, called multi-model ensembles or super-ensembles, convey the scatter of the climate response and natural internal climate variability around reference scenarios as sampled by a set of models, but cannot be interpreted probabilistically without an assessment of model biases, model interdependence, and how the ensemble was constructed (see WGI AR5 Section 12.2; Knutti et al., 2010). In many cases the assessed uncertainty is larger than the raw model spread, as illustrated in Figure 2.4. The shaded areas (+/-1 standard deviation) around the time series do not imply that 68 % are certain to fall in the shaded areas, but the modelers' assessed uncertainty (likely ranges, vertical bars on the right) are larger. These larger ranges reflect uncertainty in the carbon cycle and the full range of climate sensitivity (WGI AR4 Section 10.5.4.6 and Box 10.3; Knutti et al., 2008) but do not reflect other possible sources of uncertainty (e.g., ice sheet dynamics, permafrost, or changes in future solar and volcanic forcings). Moreover, many of these models have common ancestors and share parameterizations or code (Knutti et al., 2013) creating dependences between different model runs. Probability statements on global surface warming require estimating the models' bias and interdependence (see WGI AR5 Sections 12.2 and 12.4.1.2). WGI AR5 assigns likelihood statements (calibrated language) to global temperature ranges for the RCP scenarios (WGI AR5 Table SPM.2) but does not provide probability density functions (PDFs), as there is no established formal method to generate PDFs based on results from different published studies.

Advantages and limitation of scenario and ensemble analyses

Scenario and ensemble analyses are an essential step in scoping the range of effects of human actions and climate change. If the scenarios span the range of possible outcomes, they may be seen as providing support for uncertainty distributions in a formal uncertainty analysis. If specific assumptions are imposed when generating the scenarios, then

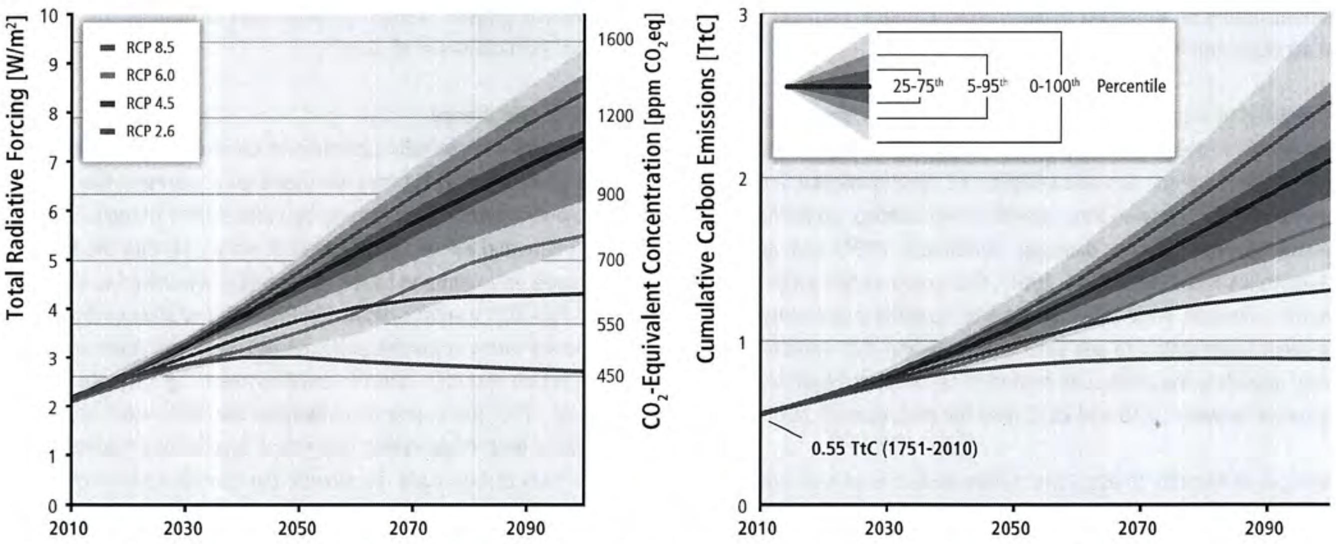

Figure 2.3 | Total radiative forcing (left panel) and cumulative carbon emissions since 1751 (right panel) in baseline scenario literature compared to RCP scenarios. Forcing was estimated ex-post from models with full coverage using the median output from the MAGICC results. Secondary axis in the left panel expresses forcing in CO_2eq concentrations. Scenarios are depicted as ranges with median emboldened; shading reflects interquartile range (darkest), 5th–95th percentile range (lighter), and full extremes (lightest). Source: Figure 6.6 from WGIII AR5.

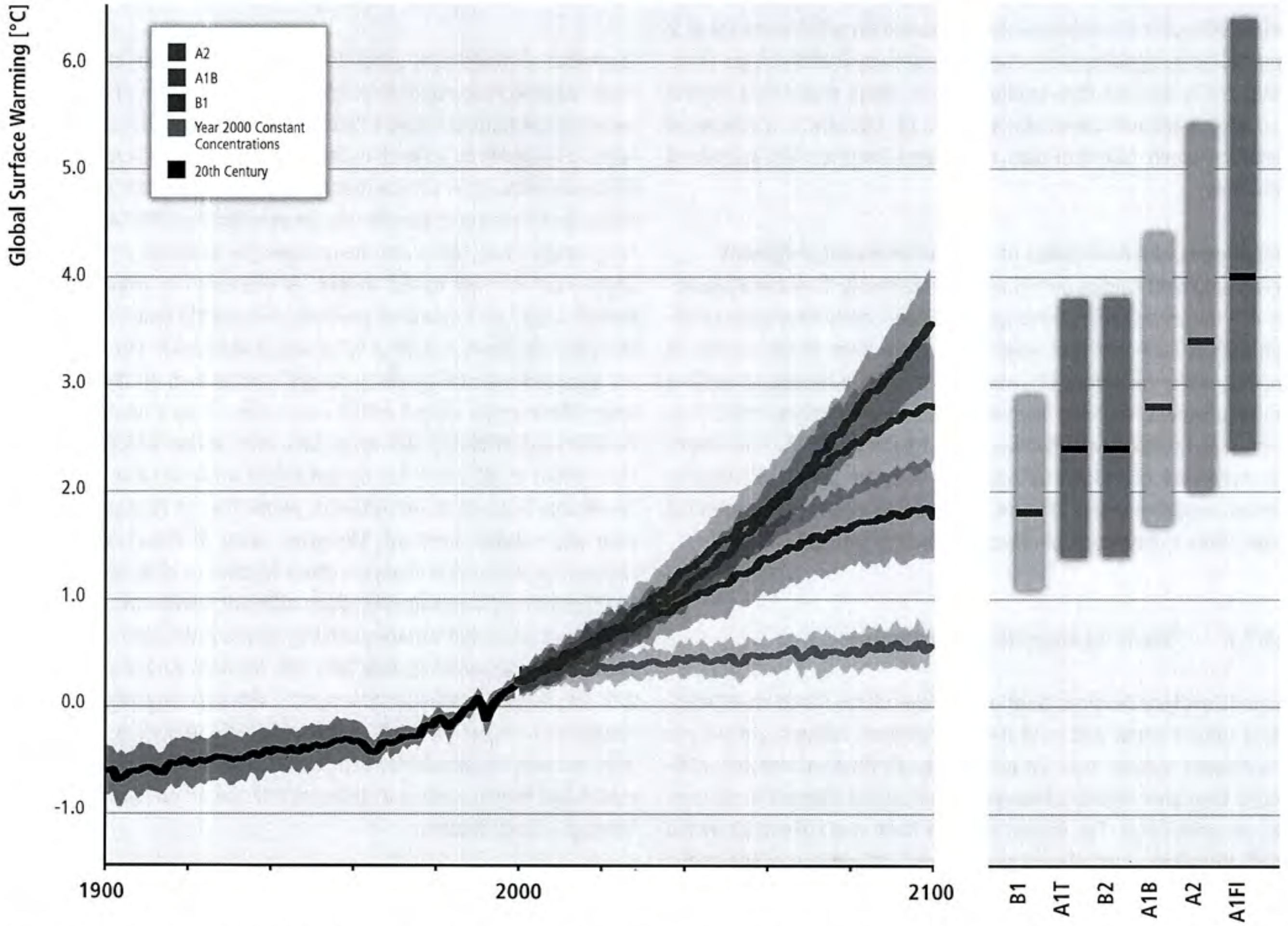

Figure 2.4 | Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six families of emissions scenarios discussed in the IPCC's Fourth Assessment Report (AR4). The assessment of the best estimate and likely ranges in the grey bars includes the Atmosphere-Ocean General Circulation Models (AOGCMs) in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints. Based on: Figure SPM.5 from WGI AR5.

the support is conditional on these assumptions (see Section 6.2.3). The advantage of scenario/ensemble analyses is that they can be performed without quantifying the uncertainty of the underlying unknown parameters. On the downside, it is easy to read more into these analyses than is justified. Analysts often forget that scenarios are illustrative possible futures along a continuum. They tend to use one of those scenarios in a deterministic fashion without recognizing that they have a low probability of occurrence and are only one of many possible outcomes. The use of probabilistic language in describing the swaths of scenarios (such as standard deviations in Figure 2.4) may also encourage the misunderstandings that these represent science-based ranges of confidence.

The study of representative scenarios based on probabilistic forecasts have been shown to facilitate strategic planning by professional groups such as military commanders, oil company managers, and policymakers (Schoemaker, 1995; Bradfield et al., 2005). Recent work on ice sheet modelling (Little et al., 2013) points in this direction. Using modelling assumptions and prior distributions on model coefficients, Monte Carlo simulations are used to produce probabilistic predictions. Expert informed modelling is methodologically intermediate between structured expert judgment (Bamber and Aspinall, 2013) and non-probabilistic scenario sweeps. Structured expert judgment leaves the modelling assumptions to the experts who quantify their uncertainty on future observables.

2.6 Managing uncertainty, risk and learning

2.6.1 Guidelines for developing policies

This section assesses how the risks and uncertainties associated with climate change can affect choices with respect to policy responses, strategies, and instruments. At the time of the AR4, there was some modelling-based literature on how uncertainties affected policy design, but very few empirical studies. In the intervening years, international negotiations failed to establish clear national emissions reductions targets, but established a set of normative principles, such as limiting global warming to 2 °C. These are now reflected in international, national, and subnational planning processes and have affected the risks and uncertainties that matter for new climate policy development. Greater attention and effort has been given to finding synergies between climate policy and other policy objectives, so that it is now important to consider multiple benefits of a single policy instrument. For example, efforts to protect tropical rainforests (McDermott et al., 2011), rural livelihoods (Lawlor et al., 2010), biodiversity (Jinnah, 2011), public health (Stevenson, 2010), fisheries (Axelrod, 2011), arable land (Conliffe, 2011), energy security (Battaglini et al., 2009), and job creation (Barry et al., 2008) have been framed as issues that should be considered when evaluating climate policies.

The treatment here complements the examination of policies and instruments in later chapters of this report, such as Chapter 6 (which assesses the results of IAMs) and Chapters 13–15 (which assess policy instruments at a range of scales). Those later chapters provide greater details on the overall tradeoffs to be made in designing policies. The focus here is on the special effects of various uncertainties and risks on those tradeoffs.

- Section 2.6.2 discusses how institutions that link science with policy grapple with several different forms of uncertainty so that they meet both scientific and political standards of accountability.
- Section 2.6.3 presents the results of integrated assessment models (IAMs) that address the choice of a climate change temperature target or the optimal transition pathway to achieve a particular target. IAMs normally focus on a social planner operating at the global level.
- Section 2.6.4 summarizes the findings from modelling and empirical studies that examine the processes and architecture of international treaties.
- Section 2.6.5 presents the results of modelling studies and the few empirical analyses that examine the choice of particular policy instruments at the sovereign state level for reducing GHG emissions. It also examines how the adoption of energy efficiency products and technologies can be promoted at the firm and household levels. Special attention is given to how uncertainties affect the performance and effectiveness of these policy instruments.
- Section 2.6.6 discusses empirical studies of people's support or opposition with respect to changes in investment patterns and livelihood or lifestyles that climate policies will bring about. These studies show people's sensitivity to the impact that climate change will have on their personal health or safety and their perceptions of the health and safety risks associated with the new technologies addressing the climate change problem.

Linking intuitive thinking and deliberative thinking processes for dealing with uncertainties associated with climate change and climate policy should increase the likelihood that instruments and robust policies will be implemented. In this sense, the concepts presented in this section should be viewed as a starting point for integrating descriptive models with normative models of choice for developing risk management strategies.

2.6.2 Uncertainty and the science/policy interface

Science/policy interfaces are defined as social processes which encompass relationships between scientists and other actors in the policy process, and which allow for exchanges, co-evolution, and joint construction of knowledge with the aim of enriching decision making (Van den Hove, 2007). Analysts have called attention to several different forms of uncertainty affecting the science/policy relationship that can be summarized as follows:

- *Paradigmatic uncertainty* results from the absence of prior agreement on the framing of problems, on methods for scientifically investigating them, and on how to combine knowledge from disparate research traditions. Such uncertainties are especially common in cross-disciplinary, application-oriented research and assessment for meeting policy objectives (Gibbons, 1994; Nowotny et al., 2001).
- *Epistemic uncertainty* results from lack of information or knowledge for characterizing phenomena. Stirling (2007) further distinguishes between uncertainty (insufficient knowledge to assess probabilities), ambiguity (insufficient knowledge about possible outcomes), and ignorance (insufficient knowledge of likely outcomes and their probabilities). Others have noted that producing more knowledge may exacerbate uncertainty, especially when actors disagree about how to frame a problem for scientific investigation (Beck, 1992; Gross, 2010).
- *Translational uncertainty* results from scientific findings that are incomplete or conflicting, so that they can be invoked to support divergent policy positions (Sarewitz, 2010). In such circumstances, protracted controversy often occurs, as each side challenges the methodological foundations of the other's claims in a process called 'experimenters' regress' (Collins, 1985).

Institutions that link science to policy must grapple with all of the above forms of uncertainty, often simultaneously. Because their work cuts across conventional lines between science and politics, these institutions have been called 'boundary organizations' (Guston, 2001) and their function has been termed 'hybrid management' (Miller, 2001). Straddling multiple worlds, science-policy institutions are required to meet both scientific and political standards of accountability. Whereas achieving scientific consensus frequently calls for bounding and closing down disagreements, achieving political legitimacy requires opening up areas of conflict in order to give voice to divergent perspectives.

The task of resolving conflicts in policy-relevant science is generally entrusted to multidisciplinary expert bodies. These organizations are best suited to addressing the paradigmatic uncertainties that arise when problems are novel or when synthesis is required across fields with different standards of good scientific practice. Bridging epistemic and translational uncertainties, however, imposes added demands. For expert advisory bodies to be viewed as legitimate they must represent all relevant viewpoints in a politically acceptable manner (Jasanoff, 1990; 2005a). What counts as acceptable varies to some degree across national decision-making cultures. Each culture may place different weights on experts' personal integrity, the reliability of their disciplinary judgments, and their ability to forge agreement across competing values (Jasanoff, 2005b, pp. 209–224).

To achieve legitimacy, institutions charged with linking science to policy must also open themselves up to public input at one or more stages in their deliberations. This process of "extended peer review" (Funtowicz and Ravetz, 1992) is regarded as necessary, though insufficient, for the production of "socially robust knowledge", that is, knowledge that can withstand public scrutiny and scepticism (Gibbons, 1994). Procedures that are sufficient to produce public trust in one political context may not work in others because national political cultures are characterized by different "civic epistemologies", i.e., culturally specific modes of generating and publicly testing policy-relevant knowledge (Jasanoff, 2005a).

International and global scientific assessment bodies confront additional problems of legitimacy because they operate outside long-established national decision-making cultures and are accountable to publics subscribing to different civic epistemologies (Jasanoff, 2010). The temptation for such bodies has been to seek refuge in the linear model in the hope that the strength of their internal scientific consensus will be sufficient to win wide political buy-in. The recent research on linking science to policy suggests otherwise.

2.6.3 Optimal or efficient stabilization pathways (social planner perspective)

Integrated assessment models (IAMs) vary widely in their underlying structure and decision-making processes. IAMs designed for cost-benefit analysis typically simulate the choices of an idealized 'social planner', who by definition is someone who makes decisions on behalf of society, in order to achieve the highest social welfare by weighting the benefits and cost of mitigation measures. In contrast, many IAMs designed for cost-effectiveness analysis (CEA) specify the social planner's objective as identifying the transformation pathway that achieves a pre-defined climate goal at the lowest discounted aggregated costs to society. In both cases, the analyses do not consider distributional effects of policies on different income groups, but instead focus on the effect on total macroeconomic costs. Hence, with these types of IAMs, negotiators that are part of the political process are able to rank the relative desirability of alternative policies to the extent that they share the definition of social welfare embedded in the model (e.g., discounted aggregate cost minimization), and believe that those implementing the policy will do so cooperatively.

Chapter 6 describes in more detail important structural characteristics of a set of IAMs used to generate transformation pathways. The modelling analyses highlighted in Chapter 6 utilize the scenario approach to represent uncertainty. In this section we instead focus on IAM results where uncertainty is an integral part of the decision-analytic framework.

Climate policy assessment should be considered in the light of uncertainties associated with climate or damage response functions, the costs of mitigation technology and the uncertainty in climate change policy instruments. A key question these analyses address is how uncertainty with respect to the above factors alters the optimal social planner's short-term reactions to climate change. A subset also asks whether adjusting behaviour to uncertainty and designing more flexible policies and technology solutions would induce a significant welfare gain.

Table 2.2 provides an overview of the existing literature on IAMs that examine mitigation actions. The rows classify the literature on the basis of the type of uncertainty: *upstream*, associated with emission baseline drivers, such as economic and population growth; *downstream continuous*, associated with climate feedbacks and damages; *downstream strongly nonlinear*, associated with the possibility of thresholds and irreversibilities; *policy responses*, associated with the uncertain adoption of policy tools; and *multiple sources*, when more than one of the sources above are considered simultaneously. The three columns categorize the literature according to the ways introducing uncertainty influence the findings. The theoretical economic literature shows that the effect of including uncertainty in decision making on near-term mitigation is ambiguous (for an overview see e.g., Lange and Treich, 2008; De Zeeuw and Zemel, 2012). However, for most studies that assume *downstream strongly nonlinear* uncertainties under a social welfare maximization or *downstream* uncertainties in combination with a temperature target, including uncertainty in the analysis leads to an optimal or efficient level of mitigation that is greater and/or accelerated than under conditions of certainty.

The literature on IAMs incorporating uncertainty uses either Monte Carlo simulations or fully stochastic programming techniques. Monte Carlo studies provide insights regarding the order-of-magnitude effect of multiple model parameter uncertainties for model output (Nordhaus and Popp, 1997; Tol, 1999; Webster et al., 2002; Hope, 2008, p. 200; Ackerman et al., 2010; Dietz, 2011; Pycroft et al., 2011). In this sense they can be interpreted as a preparatory step towards a full-fledged decision analysis under uncertainty.

Table 2.2 | Overview of literature on integrated assessment models examining mitigation actions. (cea) indicates: analysis based on a probabilistic generalization of CEA. Papers that appear several times report different scenarios or assumptions. The few studies highlighted by "*" use non-probabilistic decision criteria under uncertainty (e.g., minimax regret or maximin).[1]

Type of Uncertainty Considered	**Effect on Mitigation Action**		
	Accelerates/Increases Mitigation Action	*Delays/Decreases Mitigation Action*	*Ambiguous Effect*
Upstream (emission drivers)	Reilly et al., 1987; Webster et al., 2002; O'Neill and Sanderson, 2008; Rozenberg et al., 2010		O'Neill and Sanderson, 2008
Downstream (climate and damages)—mildly nonlinear damages	Chichilnisky and Heal, 1993; Peck and Teisberg, 1994; Ha-Duong and Treich, 2004; Syri et al., 2008; Athanassoglou and Xepapadeas, 2011; Kaufman, 2012; Ackerman et al., 2013	Kolstad, 1994, 1996a; Baranzini et al., 2003	Clarke and Reed, 1994; Kolstad, 1996b; Tsur and Zemel, 1996; Gollier et al., 2000; Fisher and Narain, 2003; Ha-Duong and Treich, 2004; Baker et al., 2006; Lange and Treich, 2008; Lorenz et al., 2012b; Ulph and Ulph, 1997; Ackerman et al., 2013
Downstream (climate and damages)—strongly nonlinear event or temperature target	Ha-Duong, 1998; Gjerde et al., 1999; O'Neill and Oppenheimer, 2002; Baranzini et al., 2003; Dumas and Ha-Duong, 2005; Syri et al., 2008(cea); Johansson et al., 2008(cea); Hope, 2008; Webster, 2008; Tsur and Zemel, 2009; Schmidt et al., 2011(cea); Funke and Paetz, 2011; Iverson and Perrings, 2012*; Lorenz et al., 2012b; de Zeeuw and Zemel, 2012	Peck and Teisberg, 1995	Gollier and Treich, 2003
Uncertainty on Policy Response	Ha-Duong et al., 1997; Blanford, 2009; Bosetti and Tavoni, 2009; Bosetti et al., 2009; Durand-Lasserve et al., 2010(cea)	Baudry, 2000; Baker and Shittu, 2006(cea)[2]	Farzin and Kort, 2000(cea)
Multiple Sources of Uncertainty	Nordhaus and Popp, 1997; Grubb, 1997; Pizer, 1999; Tol, 1999; Obersteiner et al., 2001; Yohe et al., 2004; Keller et al., 2004; Baker and Shittu, 2008; Baker and Adu-Bonnah, 2008; Bahn et al., 2008; Held et al., 2009; Hope, 2009; Labriet et al., 2012(cea), 2010; Hof et al., 2010* ; Funke and Paetz, 2011*	Scott et al., 1999	Manne and Richels, 1991; Baker and Shittu, 2008(4); Baker and Adu-Bonnah, 2008[3]

Notes:

[1] In some studies the 'baseline case' is a decision analysis based on a reduced form of uncertainty.

[2] The impact on R&D investments depend on technology; the most common result is, however, that uncertainty decreases the optimal level of R&D investments.

[3] In the sense of: increasing damage uncertainty would lead to higher investments in less risky programmes, but the effect depends on the type of technology.

Table 2.2 also characterizes the effect of the inclusion of uncertainty on early-period mitigation efforts. A decision analysis is generally compared to a baseline-case represented by a deterministic study utilizing average values of uncertain parameters. (In some studies, the baseline case is a decision analysis based on a reduced form of uncertainty.)

It should be noted that, although IAMs mimic decision makers who utilize deliberative processes, in reality social planners might resort to intuitive thinking to simplify their decision processes, leading to biases and inferior choices. To date there is no research that considers such behaviour by decision makers and how it affects the projections of IAMs. We discuss the need for such studies in Section 2.7 on gaps in knowledge and data.

2.6.3.1 Analyses predominantly addressing climate or damage response uncertainty

Although studies differ in their approaches, the case against accelerated or increased mitigation action is the possibility that irreversible sunk cost investments in abatement options outweigh the irreversible effects of climate change. This has been an infrequent finding, with the exception of those studies that have not included catastrophic/threshold damage and give no consideration to the non-climate related benefits of these investments, such as enhancing energy security or local pollution benefits. Indeed, the one set of papers that finds a need for increased or accelerated mitigation action is ambiguous when the social welfare optimum is examined under *downstream continuous/mildly nonlinear damages* uncertainty. Lorenz et al. (2012a) show that this is due primarily to the fact that damage nonlinearities are often compensated by other nonlinearities such as a concave (i.e., sublinear) concentration-temperature relation.

Studies that cluster in the first column (accelerated or increased mitigation action) assumed strongly non-linear damage functions or temperature targets (3rd row). Cost-effectiveness analysis has been applied to reflect targets when the models have been generalized to include uncertainty. In this regard, Held et al. (2009), utilizing chance constrained programming (CCP) (see Section 2.5.4.1), examine uncertainty in climate and technology response properties. As their reference case they calculated the mitigation effort needed to achieve a 2 °C temperature target, assuming average values for all uncertain parameters. Given uncertainty, however, it is clear that any given mitigation effort will exceed the target with some probability; for the reference case this is approximately 50 %. As the required probability for meeting the target increases, a greater level of mitigation effort is required. (An analogous argument holds for tipping-point derived targets. See McInerney and Keller, 2008). If the required probability is 66.6 % rather than 50 %, investments in mitigation technologies need to occur in earlier decades.

The effects on investment in mitigation also depend on whether uncertainty is expected to be reduced. Is a reduction of uncertainty on climate sensitivity and related climate response properties realistic? In an early paper, Kelly and Kolstad (1999) evaluated the amount of time needed to significantly reduce uncertainty about the parameters influencing climate sensitivity by observing global warming. They found the required time to be 90 to 160 years. Leach (2007) conducted a similar analysis that allowed two rather than one independent sources of downstream uncertainty. In that case, the time required to resolve the climate sensitivity parameters is likely to be even longer. These kind of studies assumed that our basic understanding of atmospheric chemistry and physics would remain unchanged over time. If one were to relax this constraint, then one could imagine that learning would progress more rapidly.

Another set of papers examines the 'anticipation effect', namely what it means if we believe we will learn in the future, rather than that our knowledge will remain constant. Lange and Treich (2008) showed that the sign and magnitude of mitigation depend on the particular numerical model and type of uncertainty when introducing the anticipation effect. Using CBA, for example, Lorenz et al. (2012b), Peck and Teisberg (1993), Webster et al. (2008), and Yohe and Wallace (1996) showed the anticipation effect to be negligible when assuming continuous and only weakly non-linear damages. However, Lorenz (2012b) showed slightly less immediate mitigation (compared to no-learning) if one anticipates learning within a given, narrow, time window with respect to threshold-type impacts. Such a mild reduction of early mitigation in response to anticipation was also reported in Keller et al. (2004) in accordance with Ulph and Ulph (1997).

When CEA is used to represent temperature targets in combination with climate response uncertainty, it is difficult to evaluate learning effects (see the discussion in Section 2.5.4.3). One way to allow for numerical solutions in this case is to assume an upper limit on the distribution of climate sensitivity to examine the effect of learning in the presence of a climate target. Under this assumption, more mitigation is called for (Bahn et al., 2008; Syri et al., 2008; Fouquet and Johansson, 2008; Webster, 2008).

A further set of papers considers the impossibility of specifying a precise probability density function for characterizing climate sensitivity as suggested by many climate scientists. This implies that these probabilities are difficult to estimate and decisions have to be made under conditions of ambiguity. Funke and Paetz (2011) account for model structure uncertainty by employing a robust control approach based on a maximin principle. When considering uncertainty on the ecological side of the balance, they conclude that model uncertainty implies a need for more aggressive near-term emissions reductions. Athanassoglou and Xepapadeas (2011) extend this approach to include adaptation. Iverson and Perrings (2012) apply combinations of maximin and/or minimax decision criteria, examining the effects of widening the range of climate sensitivity. Hof et al. (2010), contrast a CBA with a minimax regret approach and find that the minimax regret approach leads to more stringent and robust climate targets for relatively low discount rates if both high climate sensitivity and high damage estimates are assumed. What remains unresearched is the possibility of using non-probabilistic methods to evaluate the effects of an unbounded, or 'fat-tails', distribution for climate responses and climate impacts.

Finally, a potentially path-breaking development in economics is the effort of Ackerman et al. (2013), Crost and Traeger (2013), and Kaufman (2012) to disentangle risk aversion (a static effect) from consumption smoothing (an intertemporal effect) (for a conceptual discussion see Ha-Duong and Treich, 2004) in an Integrated Assessment Model. Compared to the results of a standard discounted expected utility model that relates risk aversion to consumption smoothing, Ackerman (2013) as well as Crost and Traeger (2013) find optimal mitigation to be twice as great. Since these are the first papers on this topic, it is too early to tell whether their results represent a robust result that captures society's risk preferences.

2.6.3.2 Analyses predominantly addressing policy response uncertainty

There are two strands of research in the area of policy response uncertainty. The first has focused on examining how the extent and timing of mitigation investments are affected by the uncertainty on the effectiveness of Research, Development, and Demonstration (RD&D) and/or the future cost of technologies for reducing the impact of climate change. An example of this would be optimal investment in energy technologies that a social planner should undertake, knowing that there might be a nuclear power ban in the near future. Another strand of research looks at how uncertainty concerning future climate policy instruments in combination with climate and/or damage uncertainty affects a mitigation strategy. An example would be the optimal technological mix in the power sector to hedge future climate regulatory uncertainty.

With respect to the first strand, the main challenge is to quantify uncertainty related to the future costs and/or availability of mitigation technologies. Indeed, there does not appear to be a single stochastic process that underlies all (RD&D) programmes' effectiveness or innovation processes. Thus elicitation of expert judgment on the probabilistic improvements in technology performance and cost becomes a crucial input for numerical analysis. A literature is emerging that uses expert elicitation to investigate the uncertain effects of RD&D investments on the prospect of success of mitigation technologies (see for example Baker et al., 2008; Curtright et al., 2008; Chan et al., 2010; Baker and Keisler, 2011). In future years, this new body of research will allow the emergence of a literature studying the probabilistic relationship between R&D and the future cost of energy technologies in IAMs.

The few existing papers reported in Table 2.2 under the Policy Response uncertainty column (see Blanford, 2009; Bosetti and Tavoni, 2009) point to increased investments in energy RD&D and in early deployment of carbon-free energy technologies in response to uncertainty. An interesting analysis has been performed in Goeschl and Perino (2009), where the potential for technological 'boomerangs' is considered. Indeed, while studies cited above consider an innovation failure an R&D project that does not deliver a clean technology at a competitive cost, Goeschl and Perino (2009) define R&D failure when it brings about a new, environmentally harmful, technology. Under such characterization they find that short-term R&D investments are negatively affected.

Turning to the second strand of literature reported in the Policy Response or in the Multiple Uncertainty columns of Table 2.2 (see Ha-Duong et al., 1997; Baker and Shittu, 2006; Durand-Lasserve et al., 2010), most analyses imply increased mitigation in the short term when there is uncertainty about future climate policy due to the asymmetry of future states of nature. In the event of the realization of the 'no climate policy' state, investment in carbon-free capital has low or zero value. Conversely, if a 'stringent climate policy' state of nature is realized, it will be necessary to rapidly ramp up mitigation to reduce the amount of carbon in the atmosphere. This cost is consistently higher, thus implying higher mitigation prior to the realization of the uncertain policy state.

2.6.4 International negotiations and agreements

Social planner studies, as reviewed in the previous sub-sections, consider the appropriate magnitude and pace of aggregate global emissions reduction. These issues have been the subject of negotiations about long-term strategic issues at the international level along with the structuring of national commitments and the design of mechanisms for compliance, monitoring, and enforcement.

2.6.4.1 Treaty formation

A vast literature looks at international treaties in general and how they might be affected by uncertainties. Cooper (1989) examined two centuries of international agreements that aimed to control the spread of communicable diseases and concludes that it is only when uncertainty is largely resolved that countries will enter into agreements. Young (1994), on the other hand, suggests that it may be easier to enter into agreements when parties are uncertain over their individual net benefits from an agreement than when that uncertainty has been resolved. Coalition theory predicts that for international negotiations related to a global externality such as climate change, stable coalitions will generally be small and/or ineffective (Barrett, 1994). Recently, De Canio and Fremstad (2013) show how the recognition of the seriousness of a climate catastrophe on the part of leading governments—which increases the incentives for reaching an agreement—could transform a prisoner's dilemma game into a coordination game leading to an increased likelihood of reaching an international agreement to limit emissions.

Relatively little research has been undertaken on how uncertainty affects the stability of multilateral environmental agreements (MEAs) and when uncertainty and learning has the potential to unravel agreements. Kolstad (2007), using a game theoretic model, looks specifically at environmental agreements. He finds that systematic uncertainty decreases the size of the largest stable coalition of an MEA. Kolstad and Ulph (2011) show that partial or complete learning has a negative impact on the formation of an MEA because as outcomes become more certain, some countries also learn the MEA will reduce their own welfare benefits, which deters them from joining the coalition. Baker (2005), using a model of the impacts of uncertainty and learning in a non-cooperative game, shows that the level of correlation of damages across countries is a crucial determinant of outcome.

Barrett (2013) has investigated the role of catastrophic, low probability events on the likelihood of cooperation with respect to a global climate agreement. By comparing a cooperative agreement with the Nash equilibrium it is possible to assess a country's incentives for participating in such an agreement. Looking at stratospheric ozone as an analogy for climate, Heal and Kunreuther (2013) observed that the signing of the Montreal Protocol by the United States led many other countries to follow suit. The authors in turn suggest how it could be applied to foster an international treaty on greenhouse gas emissions by tipping a non-cooperative game from an inefficient to an efficient equilibrium.

Several analyses, including Victor (2011) and Hafner-Burton et al. (2012), contend that the likelihood of a successful comprehensive international agreement for climate change is low because of the sensitivity of negotiations to uncertain factors, such as the precise alignment and actions of participants. Keohane and Victor (2011), in turn, suggest that the chances of a positive outcome would be higher in the case of numerous, more limited agreements. Developing countries have been unlikely to agree to binding targets in the context of international agreements due in part to the interests of developed countries dominating the negotiation process. For the situation to change, the developing countries would have to enhance their negotiating power in international climate change discussions by highlighting their concerns (Rayner and Malone, 2001).

The above analyses all assume that the agents are deliberative thinkers, each of whom has the same information on the likelihood and consequences of climate change. Section 2.7 indicates the need for future research that examines the impact of intuitive thinking on behaviour on international negotiations and processes for improving the chances of reaching an agreement on treaties.

2.6.4.2 Strength and form of national commitments

Buys et al. (2009) construct a model to predict national level support for a strong global treaty based on both the climatic and economic risks that parties to the treaty face domestically; however Buys et al. do not test the model empirically. Their model distinguishes between vulnerabilities to climate impacts and climate policy restrictions with respect to carbon emissions and implies that countries would be most supportive of strong national commitments when they are highly vulnerable to climate impacts and their emitting sectors are not greatly affected by stringent policy measures.

Victor (2011) analyzes the structure of the commitments themselves, or what Hafner-Burton et al. (2012) call rational design choices. Victor suggests that while policymakers have considerable control over the carbon intensity of their economies, they have much less control over the underlying economic growth of their country. As a result, there is greater uncertainty on the magnitude of emissions reductions, which depends on both factors, than on the reductions in carbon intensity. Victor suggests that this could account for the reluctance by many countries to make binding commitments with respect to emissions reductions. Consistent with this reasoning, Thompson (2010) examined negotiations within the UNFCCC and found that greater uncertainty with respect to national emissions was associated with a decrease in support for a national commitment to a global treaty.

Webster et al. (2010) examined whether uncertainty with respect to national emissions increases the potential for individual countries to hedge by joining an international trade agreement. They found that hedging had a minor impact compared to the other effects of international trade, namely burden sharing and wealth transfer. These findings may have relevance for structuring a carbon market to reduce emissions by taking advantage of disparities in marginal abatement costs across different countries. In theory, the right to trade emission permits or credits could lessen the uncertainties associated with any given country's compliance costs compared to the case where no trading were possible. Under a trading scheme, if a country discovered its own compliance costs to be exceptionally high, for example, it could purchase credits on the market.

2.6.4.3 Design of measurement, verification regimes, and treaty compliance

A particularly important issue in climate treaty formation and compliance is uncertainty with respect to actual emissions from industry and land use. Measurement, reporting, and verification (MRV) regimes have the potential to set incentives for participation in a treaty and still be stringent, robust, and credible with respect to compliance. The effects of strategies for managing GHG emissions are uncertain because the magnitude of the emissions of carbon dioxide and other GHG gases, such as methane, often cannot be detected given the error bounds associated with the measurement process. This is especially the case in the agriculture, forestry, and other land-use (AFOLU) sectors.

In the near term, an MRV regime that met the highest standards could require stock and flow data for carbon and other GHGs. These data are currently available only in wealthy countries, thus precluding developing countries from participating (Oliveira et al., 2007). By contrast, there are design options for MRV regimes that are less accurate, but which still provide data on the drivers of emissions so that the developing countries could be part of the system. By being more inclusive, these options could be a more effective way to actually reduce aggregate emissions, at least in the near term (Bucki et al., 2012). In the longer term, robust and harmonized estimation of GHG flows—emissions and their removal—in agriculture and forestry requires investment in monitoring and reporting capacity, especially in developing countries (Böttcher et al., 2009; Romijn et al., 2012). Reflecting this need for an evolving MRV regime to match data availability, the 2006 Guidelines for National Greenhouse Gas Inventories, prepared by an IPCC working group, suggested three hierarchical tiers of data for emission and carbon stock change factors with increasing levels of data requirements and analytical complexity. Tier 1 uses IPCC default values of high uncertainty; Tier 2 uses country-specific data; and Tier 3 uses higher spatial resolution, models, and inventories. In 2008, only Brazil, India and Mexico had the capacity to use Tier 2 and no developing country was able to use tier 3 (Hardcastle and Baird, 2008). Romijn et al. (2012) focused on 52 tropical countries and found that four of them had a very small capacity gap regarding the monitoring of their forests through inventories, while the remaining 48 had limited or no ability to undertake this monitoring process.

In order to overcome the gaps and uncertainties associated with lower tier approaches, different principles can be applied to form pools (Böttcher et al., 2008). For example, a higher level of aggregation by including soil, litter and harvested products in addition to a biomass pool as part of the MRV regime decreases relative uncertainty: the losses in one pool (e.g., biomass) are likely to be offset by gains in other pools (e.g., harvested products) (Böttcher et al., 2008). Researchers have suggested that the exclusion of a pool (e.g., soil) in an MRV regime should be allowed only if there is adequate documentation that the exclusion provides a more conservative estimate of emissions (Grassi et al., 2008). They also suggest that an international framework needs to create incentives for investments. In this respect, overcoming initialization costs and unequal access to monitoring technologies would be crucial for implementation of an integrated monitoring system, and fostering international cooperation (Böttcher et al., 2009).

2.6.5 Choice and design of policy instruments

Whether motivated primarily by a binding multilateral climate treaty or by some other set of factors, there is a growing set of policy instruments that countries have implemented or are considering to deal with climate change. Typically, these instruments will influence the decisions of firms and private individuals, so that policymakers try to anticipate how these agents will react to them.

Some policy instruments operate by mandating particular kinds of behaviour, such as the installation of pollution control technology or limits on emissions from particular sources. There is an extensive literature in political science demonstrating that the effects of these instruments are fairly predictable (Shapiro and McGarity, 1991) and are insensitive to market or regulatory uncertainties, simply because they prescribe particular technologies or practices which must be strictly adhered to. There is a literature in economics, however, suggesting that their very inflexibility makes them inefficient (Malueg, 1990; Jaffe and Stavins, 1995).

In the presence of substantial technological uncertainty, no matter what policy instrument is employed, interventions that shift investment behaviour from currently low cost to currently high cost technologies run the risk of increasing short-term costs and energy security concerns for consumers (Del Rio and Gual, 2007; Frondel et al., 2008, 2010). In some cases, long-term costs may be higher or lower, depending on how different technologies evolve over time (Williges et al., 2010; Reichenbach and Requate, 2012). This section is structured by considering two broad classes of interventions for targeting the energy supply: interventions that focus on emissions, by placing a market price or tax on CO_2 or other greenhouse gases; and interventions that promote Research, Development, Deployment, and Diffusion (RDD&D) of particular technologies. In both types of interventions, policy choices can be sensitive to uncertainties in technology costs, markets, and the state of regulation in other jurisdictions and over time. In the case of technology-oriented policy, choices are also sensitive to the risks that particular technologies present. We then describe instruments for reducing energy demand by focusing on lifestyle choice and energy efficient products and technologies. Finally, we briefly contrast the effects of uncertainties in the realm of climate change adaptation with climate change mitigation, recognizing that more detail on adaptation can be found in the WGII AR5.

2.6.5.1 Instruments creating market penalties for GHG emissions

Market-based instruments increase the cost of energy derived from fossil fuels, potentially leading firms involved in the production and conversion of energy to invest in low carbon technologies. Considerable research prior to AR4 identified the differences between two such instruments—carbon taxes and cap-and-trade regimes—with respect to uncertainty. Since AR4, research has examined the effects of regulatory risk and market uncertainty on one instrument or the other by addressing the following question: how is the mitigation investment decision affected by uncertainty with respect to whether and to what extent a market instrument and well-enforced regulations will be in place in the future?

Much of this research has focused on uncertainty with respect to carbon prices under a cap-and-trade system. A number of factors influence the relationship between the size of the cap and the market price that includes fossil fuel prices, consumer demand for energy, and economic growth more generally. Each of these factors can lead to volatility in carbon market prices (Alberola et al., 2008; Carraro et al., 2009; Chevallier, 2009). Vasa and Michaelowa (2011) assessed the impact of policy uncertainty on carbon markets and found that the possibility of easily creating and destroying carbon markets leads to extreme short-term rent-seeking behaviour and high volatility in market prices. Experience so far with the most developed carbon market—the European Emissions Trading System (ETS)—reveals high volatility marked by not-infrequent decreases of the price of carbon to very low values (Feng et al., 2011).

Numerous modelling studies have shown that regulatory uncertainty reduces the effectiveness of market-based instruments. More specifically, a current or expected carbon price induces a decrease in investment into lower carbon infrastructure and hence less technological learning, when there is uncertainty as to future market conditions, compared to the case where future conditions are known (Yang et al., 2008; Fuss et al., 2009; Oda and Akimoto, 2011). In order to compensate and maintain a prescribed level of change in the presence of uncertainty, carbon prices would need to be higher. Estimates of the additional macroeconomic costs range from 16–37 % (Blyth et al., 2007) to as much as 50 % (Reinelt and Keith, 2007), depending on the particular type of investment under consideration. The precise instrument design details can affect investment behaviour. Patiño-Echeverri et al. (2007, 2009), for example, found that less frequent but larger regulatory policy changes had less of a negative interactive effect with uncertainty, while Zhao (2003) found a greater impact of uncertainty on the performance of a carbon tax than on a cap-and-trade system. Fan et al. (2010) added to this analysis by examining the sensitivity of these results to increasing risk aversion, under two alternative carbon market designs: one in which carbon allowances were auctioned by the government to firms, and a second in which existing firms received free allowances due to a grandfathering rule.

Under an auctioned system for carbon allowances, increasing risk aversion leads to greater investments in low carbon technologies. In contrast, under a grandfathered market design, increasing risk aversion combined with uncertainty pushes investment behaviour closer to what it would be in the absence of the carbon market: more investment in coal. The intuition behind this finding is that the grandfathered scheme would create a situation of windfall profits (since the freely allocated permits have a value to the firms receiving them), and risk-averse investors would be more influenced by the other, less desirable state of the world, the absence of carbon markets. Fan et al., (2012) replicated these results using a broader range of technological choices than in their earlier paper. Whereas these latter two papers used a game-theoretic model, Fuss et al., (2012) employed a real options theory model to arrive at qualitatively the same conclusions.

One option for reducing carbon price volatility is to set a cap or floor for that price to stabilize investment expectations (Jacoby and Ellerman, 2004; Philibert, 2009). Wood and Jotzo (2011) found that setting a price floor increased the effectiveness of the carbon price in stimulating investments in low carbon technologies, given a particular expectation of macroeconomic drivers (e.g., economic growth and fossil fuel prices that influence the degree to which a carbon cap is a constraint on emissions). Szolgayova et al., (2008), using a real options model to examined the value of waiting for information, found the cap stabilized expectations. In the process, the cap lessened the effectiveness of an expected carbon price at altering investment behaviour, as many investments in low carbon technologies are undertaken only because of the possibility of very high carbon prices in the future. In another study assuming rational actor behaviour, Burtraw et al. (2010) found that a symmetric safety valve that sets both a floor and a ceiling price outperforms a single-sided safety valve in terms of both emissions reduction and economic efficiency. Murray et al. (2009) suggested that a reserve allowance for permits outperforms a simple safety valve in this regard.

Empirical research on the influence of uncertainty on carbon market performance has been constrained by the small number of functioning markets, thus making it difficult to infer the effects of differences in market design. The few studies to date suggest that the details of market design can influence the perception of uncertainty, and in turn the performance of the market. More specifically, investment behaviour into the Clean Development Mechanism (CDM) has been influenced by uncertainties in terms of what types of projects are eligible (Castro and Michaelowa, 2011), as well as the actual number of Certified Emissions Reductions (CERs) that can be acquired from a given project (Richardson, 2008).

Looking at the European Union's Emission Trading System (ETS), researchers have observed that expected carbon prices do affect investment behaviour, but primarily for investments with very short amortization periods. High uncertainty with respect to the longer-term market price of carbon has limited the ETS from having an impact on longer-term investments such as R&D or new power plant construction (Hoffmann, 2007). Blyth and Bunn (2011) found that uncertainty for post-2012 targets was a major driver of ETS prices, with an effect of suppressing those prices. The literature suggests that prices have not been high enough to drive renewable energy investment in the absence of feed-in tariffs (Blanco and Rodrigues, 2008). Barbose et al. (2008) examined a region—the western United States—where no ETS was functioning but many believed that it would, and found that most utilities did consider the possibility of carbon prices in the range of USD 4 to USD 22 a ton. At the same time, the researchers could not determine whether this projection of carbon prices would have an actual effect on utilities' decisions, were an actual ETS in place, because they were unable to document the analysis underlying the utilities' investment decisions.

2.6.5.2 Instruments promoting technological RDD&D

Several researchers suggest that future pathways for RDD&D will be the determining factor for emissions reductions (Prins and Rayner, 2007; Lilliestam et al., 2012). Policy instruments can provide an incentive for firms not only to alter their investment portfolio towards low carbon technologies, but also to devote resources towards innovation (Baker et al., 2008). Because instruments differ in terms of how they influence behaviour, such as whether or not they create an immediate incentive or one that accrues over the lifetime of the investment, their relative effectiveness can be sensitive to relevant market uncertainties.

The literature reviewed in the previous section reveals that in the presence of substantial regulatory uncertainty, market-based instruments do a poor job of promoting RDD&D. This has given rise to policy proposals to supplement a pure-market system with another instrument—such as a cap, floor, or escape valve—to reduce price volatility and stabilize expectations. By contrast, combining a market-based instrument with specific technology support can lead to greater volatility in the carbon price, even when there is very little uncertainty about which technologies will be assisted in the coming years (Blyth et al., 2009).

Several empirical studies with a focus on risk and uncertainty have compared the effectiveness of market instruments with other instruments such as feed-in tariffs or renewable quota systems, in stimulating low carbon investments and R&D. Butler and Neuhoff (2008) compared the feed-in tariff in Germany with the quota system in the United Kingdom, and found the German system outperformed the UK system on two dimensions: stimulating overall investment quantity, and reducing costs to consumers. The primary driver was the effectiveness of the feed-in tariff in reducing risks associated with future revenues from the project investment, therefore making it possible to lower the cost of project financing. Other researchers replicate this finding using other case studies (Mitchell et al., 2006; Fouquet and Johansson, 2008). Lüthi and Wüstenhagen (2012) surveyed investors with access to a number of markets, and found that they steered their new projects to those markets with feed-in tariff systems, as it was more likely than other policy instruments to reduce their risks. Lüthi (2010) compared policy effectiveness across a number of jurisdictions with feed-in tariffs, and found that above a certain level of return, risk-related factors did more to influence investment than return-related factors.

Looking at the early stages in the technology development process, Bürer and Wüstenhagen (2009) surveyed 'green' tech venture capitalists in the United States and Europe using a stated preference approach to identify which policy instrument or instruments would reduce the perceived risks of investment in a particular technology. They identified a strong preference in both continents, but particularly Europe, for feed-in tariffs over cap-and-trade and renewable quota systems, because of the lower risks to return on investment associated with the former policy instrument. Moreover, venture capital investors typically look for short- to medium-term returns on their investment, for which the presence of feed-in tariffs has the greatest positive effect.

Held et al. (2006) identified patterns of success across a wide variety of policy instruments to stimulate investment in renewable energy technologies in Europe. They found that long-term regulatory consistency was vital for new technology development. Other studies have shown that regulatory inconsistency with respect to subsidy programs—such as feed-in tariffs in Spain or tax credits in the United States—can lead to temporarily overheated markets, pushing up investment costs and consumer prices, and reducing the pressure for technological development (Del Rio and Gual, 2007; Sáenz de Miera et al., 2008; Barradale, 2010).

In contrast to the large literature looking at the overall effects of uncertainty, there have only been a few empirical papers documenting the particular risks that concern investors the most. Leary and Esteban (2009) found regulatory uncertainty—particularly with respect to issues of siting—to concern investors in wave- and tide-based energy projects. Komendantova et al. (2012) examined perceptions among European investors in solar projects in North Africa, and found concerns about regulatory change and corruption were much greater than concerns about terrorism and technology risks. The same researchers modelled the sensitivity of required state subsidies for project development in response to these risks, and found the subsidies required to stimulate a given level of solar investment rose by a factor of three, suggesting large benefits from stemming corruption and stabilizing regulations (Komendantova et al., 2011). Meijer et al. (2007) examined the perceived risks for biogas project developers in the Netherlands, and found technological, resource, and political uncertainty to be their most important concerns. These studies are useful by documenting policymakers' concerns so they can address these issues in the future.

Table 2.3 synthesizes the modelling and empirical results on renewable quota systems and feed-in tariffs, as well as with results for cap-and-trade systems from the previous sub-section. The table highlights the

Table 2.3 | Uncertainties affecting the effectiveness of alternative policy instruments.

Instrument	Uncertainty	Investor fears	Effect on low carbon technology
Allowance trading market	Technological systems	Other low carbon technologies will prove more cost-effective	Dampened investment
	Market behaviour	Growth in energy demand will decline	Dampened investment
	Market behaviour	Fossil fuel prices will fall	Dampened investment
	Regulatory actions	Governments will increase the number of allowances	Dampened investment
Renewable quotas	Technological systems	Other low carbon technologies will prove more cost-effective	Dampened investment
	Market behaviour	Supply for renewable energy will rise faster than the quota	Dampened investment
Subsidies and feed-in tariffs	Regulatory actions	Subsidy for this particulartechnology will decline	Overheated market

effects of three of the classes of uncertainties identified earlier in this chapter, namely with respect to technological systems, market behaviour, and the future regulatory actions of governments.

2.6.5.3 Energy efficiency and behavioural change

As pointed out in Section 2.6.5.2 and earlier sections, one way to mitigate climate risk is to encourage RD&D with respect to providing energy from renewable sources, such as wind and solar, as well as to promote low energy use products. For firms to undertake these investments, there needs to be some guarantee that a market for their products will exist. Currently consumers are reluctant to adopt energy efficient measures, such as compact fluorescent bulbs, energy efficient refrigerators, boilers and cooling systems, as well as new technologies such as solar installations and wind power. This can be attributed to the uncertainties associated with future energy prices and consumption of energy coupled with misperceptions of the products' benefits and an unwillingness to incur the upfront costs of these measures as discussed in Section 2.4.3.2.

Gardner and Stern (2008) identified a list of energy efficient measures that could reduce North American consumers' energy consumption by almost 30 % but found that individuals were not willing to invest in them because they have misconceptions about the measures' effectiveness. Other studies show that the general public has a poor understanding of energy consumption associated with familiar activities (Sterman and Sweeney, 2007). A national online survey of 505 participants by Attari et al. (2010) revealed that most respondents felt that measures such as turning off the lights or driving less were much more effective as energy efficient improvements than experts' viewed them to be.

There are both behavioural and economic factors described in Section 2.4.3.2 that can explain the reluctance of households to incur the upfront costs of these energy efficient measures. Due to a focus on short-term horizons, individuals may underestimate the savings in energy costs from investing in energy efficient measures. In addition they are likely to discount the future hyperbolically so that the upfront cost is perceived to be greater than expected discounted reduction in energy costs (Dietz et al., 2013; Kunreuther et al., 2013b). Coupled with these descriptive models or choices that are triggered by intuitive thinking, households may have severe budget constraints that discourage them from investing in these energy efficient measures. If they intend to move in several years and feel that the investment in the energy efficient measure will not be adequately reflected in an increase in their property value, then it is inappropriate for them *not* to invest in these measures if they undertake deliberative thinking.

To encourage households to invest in energy efficient measures, messages that communicate information on energy use and savings from undertaking these investments need to be conveyed (Abrahamse et al., 2005). Recent research has indicated the importance of highlighting indirect and direct benefits (e.g., being 'green', energy independence, saving money) in people's adoption of energy efficiency measures to address the broad range and heterogeneity in people's goals and values that contribute to the subjective utility of different courses of action (Jakob, 2006). One also needs to recognize the importance of political identity considerations when choosing the nature of these messages, as different constituencies have different associations to options that mitigate climate change and labels that convey potential benefits from adopting energy efficient measures (Hardisty et al., 2010; Gromet et al., 2013).

The advent of the 'smart' grid in Western countries, with its 'smart' metering of household energy consumption and the development of 'smart' appliances will make it feasible to provide appliance-specific feedback about energy use and energy savings to a significant number of consumers within a few years. A field study involving more than 1,500 households in Linz, Austria revealed that feedback on electricity consumption corresponded with electricity savings of 4.5 % for the average household in this pilot group (Schleich et al., 2013).

To deal with budget constraints, the upfront costs of these measures need to be spread over time so the measures are viewed as economically viable and attractive. The Property Assessed Clean Energy (PACE) programme in the United States is designed to address the budget constraint problem. Participants in this programme receive financing for improvements that is repaid through an assessment on their property taxes for up to 20 years. Financing spreads the cost of energy improvements over the expected life of measures such as weather sealing, energy efficient boilers and cooling systems, and solar installations and allows for the repayment obligation to transfer automatically to the next property owner if the property is sold. The program addresses two important barriers to increased adoption of energy efficiency and small-scale renewable energy: high upfront costs and fear that project costs will not be recovered prior to a future sale of the property (Kunreuther and Michel-Kerjan, 2011).

Social norms that encourage greater use of energy efficient technology at the household level can also encourage manufacturers to invest in the R&D for developing new energy efficient technologies and public sector actions such as well-enforced standards of energy efficiency as part of building sale requirements, (Dietz et al., 2013).

2.6.5.4 Adaptation and vulnerability reduction

Compared to mitigation measures, investments in adaptation appear to be more sensitive to uncertainties in the local impacts associated with the damage costs of climate change. This is not surprising for two reasons. First, while both mitigation and adaptation may result in lower local damage costs associated with climate impacts, the benefits of adaptation flow directly and locally from the actions taken (Prato, 2008). Mitigation measures in one region or country, by contrast, deliver benefits that are global; however, they are contingent on the actions of people in other places and in the future, rendering their local benefits more uncertain. One cannot simply equate marginal local damage costs with marginal mitigation costs, and hence the importance of uncertainty with respect to the local damage costs is diminished (Webster et al., 2003).

Second, politically negotiated mitigation targets, such as the 2 °C threshold appear to have been determined by what is feasible and affordable in terms of the pace of technological diffusion, rather than by an optimization of mitigation costs and benefits (Hasselmann et al., 2003; Baker et al., 2008; Hasselmann and Barker, 2008). Hence, mitigation actions taken to achieve a temperature target would not be changed if the damage costs (local or global) were found to be somewhat higher or lower. This implies that mitigation measures will be insensitive to uncertainty of these costs associated with climate change. Adaptation decisions, in contrast, face fewer political and technical constraints, and hence can more closely track what is needed in order to minimize local expected costs and hence will be more sensitive to the uncertainties surrounding future damage costs from climate change (Patt et al., 2007, 2009).

There are two situations where decisions on adaptation policies and actions may be largely insensitive to uncertainties about the potential impacts of climate change on future damage. The first is where adaptation is constrained by the availability of finance, such as international development assistance. Studies by the World Bank, OECD, and other international organizations have estimated the financing needs for adaptation in developing countries to be far larger than funds currently available (Agrawala and Fankhauser, 2008; World Bank, 2010; Patt et al., 2010). In this case, adaptation actions are determined by decisions with respect to the allocation of available funds in competing regions rather than the local impacts of climate change on future damage (Klein et al., 2007; Hulme et al., 2011). Funding decisions and political constraints at the national level can also constrain adaptation so that choices no longer are sensitive to uncertainties with respect to local impacts (Dessai and Hulme, 2004, 2007).

The other situation is where adaptation is severely constrained by cultural norms and/or a lack of local knowledge and analytic skill as to what actions can be taken (Brooks et al., 2005; Füssel and Klein, 2006; O'Brien, 2009; Jones and Boyd, 2011). In this case, adaptive capacity could be improved through investments in education, development of local financial institutions and property rights systems, women's rights, and other broad-based forms of poverty alleviation. There is a growing literature to suggest that such policies bring substantial benefits in the face of climate change that are relatively insensitive to the precise nature and extent of local climate impacts (Folke et al., 2002; World Bank, 2010; Polasky et al., 2011). These policies are designed to reduce these countries' vulnerability to a wide range of potential risks rather than focusing on the impacts of climate change (Thornton et al., 2008; Eakin and Patt, 2011).

2.6.6 Public support and opposition to climate policy

In this section, we review what is known about public support or opposition to climate policy, climate-related infrastructure, and climate science. In all three cases, a critical issue is the role that perceptions of risks and uncertainties play in shaping support or opposition. Hence, the material presented here complements the discussion of perceptions of climate change risks and uncertainties (see Section 2.4.6). Policy discussions on particular technologies often revolve around the health and safety risks associated with technology options, transition pathways, and systems such as nuclear energy (Pidgeon et al., 2008; Whitfield et al., 2009), coal combustion (Carmichael et al., 2009; Hill et al., 2009), and underground carbon storage (Itaoka et al., 2009; Shackley et al., 2009). There are also risks to national energy security that have given rise to political discussions advocating the substitution of domestically produced renewable energy for imported fossil fuels (Eaves and Eaves, 2007; Lilliestam and Ellenbeck, 2011).

2.6.6.1 Popular support for climate policy

There is substantial empirical evidence that people's support or opposition to proposed climate policy measures is determined primarily by emotional factors and their past experience rather than explicit calculations as to whether the personal benefits outweigh the personal costs. A national survey in the United States found that people's support for climate policy also depended on cultural factors, with regionally differentiated worldviews playing an important role (Leiserowitz, 2006), as did a cross-national comparison of Britain and the United States (Lorenzoni and Pidgeon, 2006), and studies comparing developing with developed countries (Vignola et al., 2012).

One of the major determinants of popular support for climate policy is whether people have an underlying belief that climate change is dangerous. This concern can be influenced by both cultural factors and the methods of communication (Smith, 2005; Pidgeon and Fischhoff, 2011). Leiserowitz (2005) found a great deal of heterogeneity linked to cultural effects with respect to the perception of climate change in the United States. The use of language used to describe climate change—such as the distinction between 'climate change' and 'global warming'— play a role in influencing perceptions of risk, as well as considerations of immediate and local impacts (Lorenzoni et al., 2006). The portrayal of uncertainties and disagreements with respect to climate impacts was found to have a weak effect on whether people perceived the impacts as serious, but a strong effect on whether they felt that the impacts deserved policy intervention (Patt, 2007). Studies in China (Wang et al., 2012) and Austria (Damm et al., 2013) found that people's acceptance of climate-related policies was related to their underlying perceptions of risk but also to their beliefs about government responsibility.

An important question related to climate change communication is whether the popular reporting of climate change through disaster scenarios has the effect of energizing people to support aggressive policy intervention, or to become dismissive of the problem. A study examining responses to fictionalized disaster scenarios found them to have differential effects on perceptions and support for policy. They reduced people's expectation of the local impacts, while increasing their support for global intervention (Lowe et al., 2006). Other studies found interactive effects: those with a low awareness of climate change became concerned about being exposed to disaster scenarios, while those with a high awareness of climate change were dismissive of the possible impacts (Schiermeier, 2004).

Finally, the extent to which people believe it is possible to actually influence the future appears to be a major determinant of their support for both individual and collective actions to respond to climate change. In the case of local climate adaptation, psychological variables associated with self-empowerment were found to have played a much larger role in influencing individual behaviour than variables associated with economic and financial ability (Grothmann and Patt, 2005; Grothmann and Reusswig, 2006). With respect to mitigation policy, perceptions concerning the barriers to effective mitigation and beliefs that it was possible to respond to climate change were found to be important determinants of popular support (Lorenzoni et al., 2007).

2.6.6.2 Local support and opposition to infrastructure projects

The issue of local support or opposition to infrastructure projects in implementing climate policy is related to the role that perceived technological risks play in the process. This has been especially important with respect to nuclear energy, but is of increasing concern for carbon storage and renewable energy projects, and has become a major issue when considering expansion of low carbon energy technologies (Ellis et al., 2007; Van Alphen et al., 2007; Zoellner et al., 2008).

In the case of renewable energy technologies, a number of factors appear to influence the level of public support or opposition, factors that align well with a behavioural model in which emotional responses are highly contextual. One such factor is the relationship between project developers and local residents. Musall and Kuik (2011) compared two wind projects, where residents feared negative visual impacts. They found that their fear diminished, and public support for the projects increased when there was co-ownership of the development by the local community. A second factor is the degree of transparency surrounding project development. Dowd et al. (2011) investigated perceived risks associated with geothermal projects in Australia. Using a survey instrument, they found that early, transparent communication of geothermal technology and risks tended to increase levels of public support.

A third such factor is the perception of economic costs and benefits that go hand-in-hand with the perceived environmental risks. Zoellner et al. (2008) examined public acceptance of three renewable technologies (grid-connected PV, biomass, and wind) and found that perceived economic risks associated with higher energy prices were the largest predictor of acceptance. Concerns over local environmental impacts, including visual impacts, were of concern where the perceived economic risks were high. Breukers and Wolsink (2007) also found that that the visual impact of wind turbines was the dominant factor in explaining opposition against wind farms. Their study suggests that public animosity towards a wind farm is partly reinforced by the planning procedure itself, such as when stakeholders perceive that norms of procedural justice are not being followed.

Many studies have assessed the risks and examined local support for carbon dioxide capture and storage (CCS). According to Ha-Duong et al. (1997), the health and safety risks associated with carbon dioxide capture and transportation technologies differ across causal pathways but are similar in magnitude to technologies currently supported by the fossil-fuel industry. Using natural analogues, Roberts et al. (2011) concluded that the health risks of natural CO_2 seepage in Italy was significantly lower than many socially accepted risks. For example, it were three orders of magnitude lower than the probability of being struck by lightning.

Despite these risk assessments, there is mixed evidence of public acceptance of CO_2 storage. For example, a storage research project was authorized in Lacq, France, but another was halted in Barendreich, The Netherlands due to public opposition. On the other hand, Van Alphen et al. (2007) evaluated the concerns with CCS among important stakeholders, including government, industry, and NGO representatives and found support if the facility could be shown to have a low probability of leakage and was viewed as a temporary measure.

Wallquist et al. (2012) used conjoint analysis to interpret a Swiss survey on the acceptability of CCS and found that concerns over local risks and impacts dominated the fears of the long-term climate impacts of leakage. The local concerns were less severe, and the public acceptance higher, for CCS projects combined with biomass combustion, suggesting that positive feelings about removing CO_2 from the atmosphere, rather than simply preventing its emission into the atmosphere, influences perceptions of local risks. Terwel et al. (2011) found that support for CCS varied as a function of the stakeholders promoting and opposing it, in a manner similar to the debate on renewable energy. Hence, there was greater support of CCS when its promoters were perceived to be acting in the public interest rather than purely for profit. Those opposing CCS were less likely to succeed when they were perceived to be acting to protect their own economic interests, such as property values, rather than focusing on environmental quality and the public good.

In the period between the publication of AR4 and the accident at the Fukushima power plant in Japan in March 2011, the riskiness of nuclear power as a climate mitigation option has received increasing attention. Socolow and Glaser (2009) highlight the urgency of taking steps to reduce these risks, primarily by ensuring that nuclear fuels and waste materials are not used for weapons production. A number of papers examine the public's perceived risks of nuclear power. In the United States, Whitfield et al. (2009) found risk perceptions to be fairly stable over time, with those people expressing confidence in 'traditional values' perceiving nuclear power to be less risky than others. In the United Kingdom, Pidgeon et al. (2008) found a willingness to accept the risks of nuclear power when it was framed as a means of reducing the risks of climate change, but that this willingness largely dissipated when nuclear power was suggested as an alternative to renewable energy for accomplishing this same objective.

2.7 Gaps in knowledge and data

The interface between science and policy is affected by epistemic uncertainty or uncertainty due to lack of information or knowledge for characterizing phenomena. Below we characterize suggested areas for future research that may enable us to reduce epistemic uncertainty.

Perceptions and responses to risk and uncertainty:

- Examine cross-cultural differences in human perception and reaction to climate change and response options.
- Understand the rebound effect induced by adopting mitigation measures for reducing the impact of climate change (e.g., increased driving when switching to a more fuel efficient car).
- Consider the design of long-term mitigation and adaptation strategies coupled with short-term economic incentives to overcome myopic behaviour (e.g., loans for investing in energy efficient technologies so yearly payments are lower than the reduction in the annual energy bill).
- Encourage deliberative thinking in the design of policies to overcome biases such as a preference for the current state of affairs or business-as-usual.
- Understand judgment and choice processes of key decision makers in firms and policymakers, especially in a climate change response context.
- Use descriptive models and empirical studies to design strategies for climate change negotiations and implementation of treaties.

Tools and decision aids for improving choices related to climate change:

- Characterize the likelihood of extreme events and examine their impact on the design of climate change policies.
- Study how robust decision making can be used in designing climate policy options when there is uncertainty with respect to the likelihood of climate change and its impacts.
- Examine how integrated assessment models can quantify the value of new climate observing systems.
- Empirically study how decision makers could employ intuitive and deliberative thinking to improve decisions and climate policy choices.
- Study the effectiveness of experiential methods like simulations, games, and movies in improving public understanding and perception of climate change processes.
- Consider the role of structured expert judgment in characterizing the nature of uncertainties associated with climate change and the design of mitigation and adaptation policies for addressing this risk.

Managing uncertainty risk and learning:

- Exploit the effectiveness of social norms in promoting mitigation and adaptation.
- Quantify the environmental and societal risks associated with new technologies.
- Consider the special challenges faced by developing countries in dealing with risk and uncertainty with respect to climate change policies.
- Measure investor rankings of different risks associated with new technologies.
- Examine impact of government policy on mitigation decisions by firms and households.
- Determine what risks and uncertainties matter the most in developing policy instruments for dealing with climate change.
- Examine the risks to energy systems, energy markets, and the security of energy supply stemming from mitigation policies.
- Integrate analysis of the effects of interrelated policy decisions, such as how much to mitigate, what policy instruments to use for promoting climate change mitigation, and adaptation investment under conditions of risk and uncertainty.

2.8 Frequently Asked Questions

FAQ 2.1 When is uncertainty a reason to wait and learn rather than acting now in relation to climate policy and risk management strategies? [Section 2.6.3]

Faced with uncertainty, policymakers may have a reason to wait and learn before taking a particular action rather than taking the action now. Waiting and learning is desirable when external events are likely to generate new information of sufficient importance as to suggest that the planned action would be unwise. Uncertainty may not be a reason to delay when the action itself generates new information and knowledge.

Uncertainty may also be a reason to avoid actions that are irreversible and/or have lock-in effects, such as making long-term investments in fossil-fuel based energy systems when climate outcomes are uncertain. This behaviour would reflect the precautionary principle for not undertaking some measures or activities.

While the above criteria are fairly easy to understand, their application can be complicated because a number of uncertainties relevant to a given decision may reinforce each other or may partially cancel each other out (e.g., optimistic estimates of technological change may offset pessimistic estimates of climate damages). Different interested parties may reach different conclusions as to whether external information is likely or not to be of sufficient importance as to render the original action/inaction regrettable.

A large number of studies examine the act-now-or-wait-and-see question in the context of climate change mitigation. So far, most of these analyses have used integrated assessment models (IAMs). At the national level, these studies examine policy strategies and instruments to achieve mitigation targets; at the firm or individual level the studies examine whether one should invest in a particular technology.

A truly integrated analysis of the effects of multiple types of uncertainty on interrelated policy decisions, such as how much to mitigate, with what policy instruments, promoting what investments, has yet to be conducted. The probabilistic information needed to support such an analysis is currently not available.

FAQ 2.2 How can behavioural responses and tools for improving decision making impact on climate change policy? [Section 2.4]

The choice of climate change policies can benefit from examining the perceptions and responses of relevant stakeholders. Empirical evidence indicates decision makers such as firms and households tend to place undue weight on short-run outcomes. Thus, high upfront costs make them reluctant to invest in mitigation or adaptation measures. Consistent with the theory of loss aversion, investment costs and their associated risks have been shown to be of greater importance in decisions to fund projects that mitigate climate change than focusing on the expected returns associated with the investment.

Policy instruments (e.g., long-term loans) that acknowledge these behavioural biases and spread upfront costs over time so that they yield net benefits in the short-run have been shown to perform quite well. In this context, policies that make investments relatively risk free, such as feed-in tariffs, are more likely to stimulate new technology than those that focus on increasing the expected price such as cap-and-trade systems.

Human responses to climate change risks and uncertainties can also indicate a failure to put adequate weight on worst-case scenarios. Consideration of the full range of behavioural responses to information will enable policymakers to more effectively communicate climate change risks to stakeholders and to design decision aids and climate change policies that are more likely to be accepted and implemented.

FAQ 2.3 How does the presence of uncertainty affect the choice of policy instruments? [Section 2.6.5]

Many climate policy instruments are designed to provide decision makers at different levels (e.g., households, firms, industry associations, guilds) with positive incentives (e.g., subsidies) or penalties (e.g., fines) to incentivize them to take mitigation actions. The impact of these incentives on the behaviour of the relevant decision makers depends on the form and timing of these policy instruments.

Instruments such as carbon taxes that are designed to increase the cost of burning fossil fuels rely on decision makers to develop expectations about future trajectories of fuel prices and other economic conditions. As uncertainty in these conditions increases, the responsiveness of economic agents decreases. On the other hand, investment subsidies and technology standards provide immediate incentives to change behaviour, and are less sensitive to long-term market uncertainty. Feed-in tariffs allow investors to lock in a given return on investment, and so may be effective even when market uncertainty is high.

FAQ 2.4 What are the uncertainties and risks that are of particular importance to climate policy in developing countries? [Box 2.1]

Developing countries are often more sensitive to climate risks, such as drought or coastal flooding, because of their greater economic reliance on climate-sensitive primary activities, and because of inadequate infrastructure, finance, and other enablers of successful adaptation and mitigation. Since AR4, research on relevant risks and uncertainties in developing countries has progressed substantially, offering results in two main areas.

Studies have demonstrated how uncertainties often place low carbon energy sources at an economic disadvantage, especially in developing countries. The performance and reliability of new technologies may be less certain in developing countries than in industrialized countries because they could be unsuited to the local context and needs. Other reasons for uncertain performance and reliability could be due to poor manufacturing, a lack of adequate testing in hot or dusty environments, or limited local capacity to maintain and repair equipment. Moreover, a number of factors associated with economic, political, and regulatory uncertainty result in much higher real interest rates in developing countries than in the developed world. This creates a disincentive to invest in technologies with high upfront but lower operating costs, such as renewable energy, compared to fossil-fuel based energy infrastructure.

Given the economic disadvantage of low carbon energy sources, important risk tradeoffs often need to be considered. On the one hand, low-carbon technologies can reduce risks to health, safety, and the environment, such as when people replace the burning of biomass for cooking with modern and efficient cooking stoves. But on the other hand, low-carbon modern energy is often more expensive than its higher-carbon alternatives. There are however, some opportunities for win-win outcomes on economic and risk grounds, such as in the case of off-grid solar power.

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Social, Economic, and Ethical Concepts and Methods

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Contents

Executive Summary

This framing chapter describes the strengths and limitations of the most widely used concepts and methods in economics, ethics, and other social sciences that are relevant to climate change. It also provides a reference resource for the other chapters in the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5), as well as for decision makers.

The significance of the social dimension and the role of ethics and economics is underscored by Article 2 of the United Nations Framework Convention on Climate Change, which indicates that an ultimate objective of the Convention is to avoid dangerous anthropogenic interference with the climate system. Two main issues confronting society (and the IPCC) are: what constitutes 'dangerous interference' with the climate system and how to deal with that interference. Determining what is dangerous is not a matter for natural science alone; it also involves value judgements—a subject matter of the theory of value, which is treated in several disciplines, including ethics, economics, and other social sciences.

Ethics involves questions of justice and value. Justice is concerned with equity and fairness, and, in general, with the rights to which people are entitled. Value is a matter of worth, benefit, or good. Value can sometimes be measured quantitatively, for instance, through a social welfare function or an index of human development.

Economic tools and methods can be used in assessing the positive and negative values that result from particular decisions, policies, and measures. They can also be essential in determining the mitigation and adaptation actions to be undertaken as public policy, as well as the consequences of different mitigation and adaptation strategies. Economic tools and methods have strengths and limitations, both of which are detailed in this chapter.

Economic tools can be useful in designing climate change mitigation policies (*very high confidence*). While the limitations of economics and social welfare analysis, including cost-benefit analysis, are widely documented, economics nevertheless provides useful tools for assessing the pros and cons of taking, or not taking, action on climate change mitigation, as well as of adaptation measures, in achieving competing societal goals. Understanding these pros and cons can help in making policy decisions on climate change mitigation and can influence the actions taken by countries, institutions and individuals. [Section 3.2]

Mitigation is a public good; climate change is a case of 'the tragedy of the commons' (*high confidence*). Effective climate change mitigation will not be achieved if each agent (individual, institution or country) acts independently in its own selfish interest, suggesting the need for collective action. Some adaptation actions, on the other hand, have characteristics of a private good as benefits of actions may accrue more directly to the individuals, regions, or countries that undertake them, at least in the short term. Nevertheless, financing such adaptive activities remains an issue, particularly for poor individuals and countries. [3.1, 3.2]

Analysis contained in the literature of moral and political philosophy can contribute to resolving ethical questions that are raised by climate change (*medium confidence*). These questions include how much overall climate mitigation is needed to avoid 'dangerous interference', how the effort or cost of mitigating climate change should be shared among countries and between the present and future, how to account for such factors as historical responsibility for emissions, and how to choose among alternative policies for mitigation and adaptation. Ethical issues of wellbeing, justice, fairness, and rights are all involved. [3.2, 3.3, 3.4]

Duties to pay for some climate damages can be grounded in compensatory justice and distributive justice (*medium confidence*). If compensatory duties to pay for climate damages and adaptation costs are not due from agents who have acted blamelessly, then principles of compensatory justice will apply to only some of the harmful emissions [3.3.5]. This finding is also reflected in the predominant global legal practice of attributing liability for harmful emissions [3.3.6]. Duties to pay for climate damages can, however, also be grounded in distributive justice [3.3.4, 3.3.5].

Distributional weights may be advisable in cost-benefit analysis (*medium confidence*). Ethical theories of value commonly imply that distributional weights should be applied to monetary measures of benefits and harms when they are aggregated to derive ethical conclusions [3.6.1]. Such weighting contrasts with much of the practice of cost-benefit analysis.

The use of a temporal discount rate has a crucial impact on the evaluation of mitigation policies and measures. The social discount rate is the minimum rate of expected social return that compensates for the increased intergenerational inequalities and the potential increased collective risk that an action generates. Even with disagreement on the level of the discount rate, a consensus favours using declining risk-free discount rates over longer time horizons (*high confidence*). [3.6.2]

An appropriate social risk-free discount rate for consumption is between one and three times the anticipated growth rate in real per capita consumption (*medium confidence*). This judgement is based on an application of the Ramsey rule using typical values in the literature of normative parameters in the rule. Ultimately, however, these are normative choices. [3.6.2]

Co-benefits may complement the direct benefits of mitigation (*medium confidence*). While some direct benefits of mitigation are reductions in adverse climate change impacts, co-benefits can include a broad range of environmental, economic, and social effects, such as reductions in local air pollution, less acid rain, and increased energy security. However, whether co-benefits are net positive or negative in terms of wellbeing (welfare) can be difficult to determine because of interaction between climate policies and pre-existing non-climate policies. The same results apply to adverse side-effects. [3.6.3]

Tax distortions change the cost of all abatement policies (*high confidence*). A carbon tax or a tradable emissions permit system can exacerbate tax distortions, or, in some cases, alleviate them; carbon tax or permit revenue can be used to moderate adverse effects by cutting other taxes. However, regulations that forgo revenue (e.g., by giving permits away) implicitly have higher social costs because of the tax interaction effect. [3.6.3]

Many different analytic methods are available for evaluating policies. Methods may be quantitative (for example, cost-benefit analysis, integrated assessment modelling, and multi-criteria analysis) or qualitative (for example, sociological and participatory approaches). However, no single-best method can provide a comprehensive analysis of policies. A mix of methods is often needed to understand the broad effects, attributes, trade-offs, and complexities of policy choices; moreover, policies often address multiple objectives. [3.7]

Four main criteria are frequently used in evaluating and choosing a mitigation policy (*medium confidence*). They are: cost-effectiveness and economic efficiency (excluding environmental benefits, but including transaction costs); environmental effectiveness (the extent to which the environmental targets are achieved); distributional effects (impact on different subgroups within society); and institutional feasibility, including political feasibility. [3.7.1]

A broad range of policy instruments for climate change mitigation is available to policymakers. These include: economic incentives, direct regulatory approaches, information programmes, government provision, and voluntary actions. Interactions between policy instruments can enhance or reduce the effectiveness and cost of mitigation action. Economic incentives will generally be more cost-effective than direct regulatory interventions. However, the performance and suitability of policies depends on numerous conditions, including institutional capacity, the influence of rent-seeking, and predictability or uncertainty about future policy settings. The enabling environment may differ between countries, including between low-income and high-income countries. These differences can have implications for the suitability and performance of policy instruments. [3.8]

Impacts of extreme events may be more important economically than impacts of average climate change (*high confidence*). Risks associated with the entire probability distribution of outcomes in terms of climate response [WGI] and climate impacts [WGII] are relevant to the assessment of mitigation. Impacts from more extreme climate change may be more important economically (in terms of the expected value of impacts) than impacts of average climate change, particularly if the damage from extreme climate change increases more rapidly than the probability of such change declines. This is important in economic analysis, where the *expected* benefit of mitigation may be traded off against mitigation costs. [3.9.2]

Impacts from climate change are both market and non-market. Market effects (where market prices and quantities are observed) include impacts of storm damage on infrastructure, tourism, and increased energy demand. Non-market effects include many ecological impacts, as well as changed cultural values, none of which are generally captured through market prices. The economic measure of the value of either kind of impact is 'willingness-to-pay' to avoid damage, which can be estimated using methods of revealed preference and stated preference. [3.9]

Substitutability reduces the size of damages from climate change (*high confidence*). The monetary damage from a change in the climate will be lower if individuals can easily substitute for what is damaged, compared to cases where such substitution is more difficult. [3.9]

Damage functions in existing Integrated Assessment Models (IAMs) are of low reliability (*high confidence*). The economic assessments of damages from climate change as embodied in the damage functions used by some existing IAMs (though not in the analysis embodied in WGIII) are highly stylized with a weak empirical foundation. The empirical literature on monetized impacts is growing but remains limited and often geographically narrow. This suggests that such damage functions should be used with caution and that there may be significant value in undertaking research to improve the precision of damage estimates. [3.9, 3.12]

Negative private costs of mitigation arise in some cases, although they are sometimes overstated in the literature (*medium confidence*). Sometimes mitigation can lower the private costs of production and thus raise profits; for individuals, mitigation can raise wellbeing. Ex-post evidence suggests that such 'negative cost opportunities' do indeed exist but are sometimes overstated in engineering analyses. [3.9]

Exchange rates between GHGs with different atmospheric lifetimes are very sensitive to the choice of emission metric. The choice of an emission metric depends on the potential application and involves explicit or implicit value judgements; no consensus surrounds the question of which metric is both conceptually best and practical to implement (*high confidence*). In terms of aggregate mitigation costs alone, the Global Warming Potential (GWP), with a 100-year time horizon, may perform similarly to selected other metrics (such as the time-dependent Global Temperature Change Potential or the Global Cost Potential) of reaching a prescribed climate target; however, various metrics may differ significantly in terms of the implied distribution of costs across sectors, regions, and over time (*limited evidence, medium agreement*). [3.9]

The behaviour of energy users and producers exhibits a variety of anomalies (*high confidence*). Understanding climate change as a physical phenomenon with links to societal causes and impacts is a very complex process. To be fully effective, the conceptual frameworks and methodological tools used in mitigation assessments need to take into account cognitive limitations and other-regarding preferences that frame the processes of economic decision making by people and firms. [3.10]

Perceived fairness can facilitate cooperation among individuals (*high confidence*). Experimental evidence suggests that reciprocal behaviour and perceptions of fair outcomes and procedures facilitate voluntary cooperation among individual people in providing public goods; this finding may have implications for the design of international agreements to coordinate climate change mitigation. [3.10]

Social institutions and culture can facilitate mitigation and adaptation (*medium confidence*). Social institutions and culture can shape individual actions on mitigation and adaptation and be complementary to more conventional methods for inducing mitigation and adaptation. They can promote trust and reciprocity and contribute to the evolution of common rules. They also provide structures for acting collectively to deal with common challenges. [3.10]

Technological change that reduces mitigation costs can be encouraged by institutions and economic incentives (*high confidence*). As pollution is not fully priced by the market, private individuals and firms lack incentives to invest sufficiently in the development and use of emissions-reducing technologies in the absence of appropriate policy interventions. Moreover, imperfect appropriability of the benefits of innovation further reduces incentives to develop new technologies. [3.11]

3.1 Introduction

This framing chapter has two primary purposes: to provide a framework for viewing and understanding the human (social) perspective on climate change, focusing on ethics and economics; and to define and discuss key concepts used in other chapters. It complements the two other framing chapters: Chapter 2 on risk and uncertainty and Chapter 4 on sustainability. The audience for this chapter (indeed for this entire volume) is decision makers at many different levels.

The significance of the social dimension and the role of ethics and economics is underscored by Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC), which indicates that the ultimate objective of the Convention is to avoid dangerous anthropogenic interference with the climate system. Two main issues confronting society are: what constitutes 'dangerous interference' with the climate system and how to deal with that interference (see box 3.1). Providing information to answer these inter-related questions is a primary purpose of the IPCC. Although natural science helps us understand how emissions can change the climate, and, in turn, generate physical impacts on ecosystems, people, and the physical environment, determining what is dangerous involves judging the level of adverse consequences, the steps necessary to mitigate these consequences, and the risk that humanity is willing to tolerate. These are questions requiring value judgement. Although economics is essential to evaluating the consequences and trade-offs associating with climate change, how society interprets and values them is an ethical question.

Our discussion of ethics centres on two main considerations: justice and value. Justice requires that people and nations should receive what they are due, or have a right to. For some, an outcome is just if the process that generated it is just. Others view justice in terms of the actual outcomes enjoyed by different people and groups and the values they place on those outcomes. Outcome-based justice can range from maximizing economic measures of aggregate welfare to rights-based views of justice, for example, believing that all countries have a right to clean air. Different views have been expressed about what is valuable. All values may be anthropocentric or there may be non-human values. Economic analysis can help to guide policy action, provided that appropriate, adequate, and transparent ethical assumptions are built into the economic methods.

The significance of economics in tackling climate change is widely recognized. For instance, central to the politics of taking action on climate change are disagreements over how much mitigation the world should undertake, and the economic costs of action (the costs of mitigation) and inaction (the costs of adaptation and residual damage from a changed climate). Uncertainty remains about (1) the costs of reducing emissions of greenhouse gases (GHGs), (2) the damage caused by a change in the climate, and (3) the cost, practicality, and effectiveness of adaptation measures (and, potentially, geoengineering). Prioritizing action on climate change over other significant social goals with more near-term payoffs is particularly difficult in developing countries. Because social concerns and objectives, such as the preservation of traditional values, cannot always be easily quantified or monetized, economic costs and benefits are not the only input into decision making about climate change. But even where costs and benefits can be quantified and monetized, using methods of economic analysis to steer social action implicitly involves significant ethical assumptions. This chapter explains the ethical assumptions that must be made for economic methods, including cost-benefit analysis (CBA), to be valid, as well as the ethical assumptions that are implicitly being made where economic analysis is used to inform a policy choice.

The perspective of economics can improve our understanding of the challenges of acting on mitigation. For an individual or firm, mitigation involves real costs, while the benefits to themselves of their own mitigation efforts are small and intangible. This reduces the incentives for individuals or countries to unilaterally reduce emissions; free-riding on the actions of others is a dominant strategy. Mitigating greenhouse

Box 3.1 | Dangerous interference with the climate system

Article 2 of the United Nations Framework Convention on Climate Change states that "the ultimate objective of the Convention […] is to achieve […] stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system." Judging whether our interference in the climate system is dangerous, i.e., risks causing a very bad outcome, involves two tasks: estimating the physical consequences of our interference and their likelihood; and assessing their significance for people. The first falls to science, but, as the Synthesis Report of the IPCC Fourth Assessment Report (AR4) states, "Determining what constitutes 'dangerous anthropogenic interference with the climate system' in relation to Article 2 of the UNFCCC involves value judgements" (IPCC, 2007, p. 42). Value judgements are governed by the theory of value. In particular, valuing risk is covered by decision theory and is dealt with in Chapter 2. Central questions of value that come within the scope of ethics, as well as economic methods for measuring certain values are examined in this chapter.

gas (GHG) emissions is a public good, which inhibits mitigation. This also partly explains the failure of nations to agree on how to solve the problem.

In contrast, adaptation tends not to suffer from free-riding. Gains to climate change from adaptation, such as planting more heat tolerant crops, are mainly realized by the parties who incur the costs. Associated externalities tend to be more localized and contemporaneous than for GHG mitigation. From a public goods perspective, global coordination may be less important for many forms of adaptation than for mitigation. For autonomous adaptation in particular, the gains from adaptation accrue to the party incurring the cost. However, public adaptation requires local or regional coordination. Financial and other constraints may restrict the pursuit of attractive adaptation opportunities, particularly in developing countries and for poorer individuals.

This chapter addresses two questions: what *should be done* about action to mitigate climate change (a normative issue) and how the world works in the multifaceted context of climate change (a descriptive or positive issue). Typically, ethics deals with normative questions and economics with descriptive or normative questions. Descriptive questions are primarily value-neutral, for example, how firms have reacted to cap-and-trade programmes to limit emissions, or how societies have dealt with responsibility for actions that were not known to be harmful when they were taken. Normative questions use economics and ethics to decide what *should* be done, for example, determining the appropriate level of burden sharing among countries for current and future mitigation. In making decisions about issues with normative dimensions, it is important to understand the implicit assumptions involved. Most normative analyses of solutions to the climate problem implicitly involve contestable ethical assumptions.

This chapter does not attempt to answer ethical questions, but rather provides policymakers with the tools (concepts, principles, arguments, and methods) to make decisions. Summarizing the role of economics and ethics in climate change in a single chapter necessitates several caveats. While recognizing the importance of certain non-economic social dimensions of the climate change problem and solutions to it, space limitations and our mandate necessitated focusing primarily on ethics and economics. Furthermore, many of the issues raised have already been addressed in previous IPCC assessments, particularly AR2 (published in 1995). In the past, ethics has received less attention than economics, although aspects of both subjects are covered in AR2. The literature reviewed here includes pre-AR4 literature in order to provide a more comprehensive understanding of the concepts and methods. We highlight 'new' developments in the field since the last IPCC assessment in 2007.

3.2 Ethical and socio-economic concepts and principles

When a country emits GHGs, its emissions cause harm around the globe. The country itself suffers only a part of the harm it causes. It is therefore rarely in the interests of a single country to reduce its own emissions, even though a reduction in global emissions could benefit every country. That is to say, the problem of climate change is a "tragedy of the commons" (Hardin, 1968). Effective mitigation of climate change will not be achieved if each person or country acts independently in its own interest.

Consequently, efforts are continuing to reach effective international agreement on mitigation. They raise an ethical question that is widely recognized and much debated, namely, 'burden-sharing' or 'effort-sharing'. How should the burden of mitigating climate change be divided among countries? It raises difficult issues of justice, fairness, and rights, all of which lie within the sphere of ethics.

Burden-sharing is only one of the ethical questions that climate change raises.[1] Another is the question of how much overall mitigation should

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[1] A survey of the ethics of climate change is Gardiner (2004), pp. 555–600.

take place. UNFCCC sets the aim of "avoiding dangerous anthropogenic interference with the climate system", and judging what is dangerous is partly a task for ethics (see Box 3.1). Besides justice, fairness, and rights, a central concern of ethics is *value*. Judgements of value underlie the question of what interference with the climate system would be dangerous.

Indeed, ethical judgements of value underlie almost every decision that is connected with climate change, including decisions made by individuals, public and private organizations, governments, and groupings of governments. Some of these decisions are deliberately aimed at mitigating climate change or adapting to it. Many others influence the progress of climate change or its impacts, so they need to take climate change into account.

Ethics may be broadly divided into two branches: justice and value. Justice is concerned with ensuring that people get what is *due* to them. If justice requires that a person should not be treated in a particular way—uprooted from her home by climate change, for example—then the person has a *right* not to be treated that way. Justice and rights are correlative concepts. On the other hand, criteria of value are concerned with improving the world: making it a better place. Synonyms for 'value' in this context are 'good', 'goodness' and 'benefit'. Antonyms are 'bad', 'harm' and 'cost'.

To see the difference between justice and value, think of a transfer of wealth made by a rich country to a poor one. This may be an act of restitution. For example, it may be intended to compensate the poor country for harm that has been done to it by the rich country's emissions of GHG. In this case, the transfer is made on grounds of justice. The payment is taken to be due to the poor country, and to satisfy a right that the poor country has to compensation. Alternatively, the rich country may make the transfer to support the poor country's mitigation effort, because this is beneficial to people in the poor country, the rich country, and elsewhere. The rich country may not believe the poor country has a right to the support, but makes the payment simply because it does 'good'. This transfer is made on grounds of value. What would be good to do is not necessarily required as a matter of justice. Justice is concerned with what people are entitled to as a matter of their rights.

The division between justice and value is contested within moral philosophy, and so is the nature of the interaction between the two. Some authors treat justice as inviolable (Nozick, 1974): justice sets limits on what we may do and we may promote value only within those limits. An opposite view—called 'teleological' by Rawls (1971)—is that the right decision to make is always determined by the value of the alternatives, so justice has no role. But despite the complexity of their relationship and the controversies it raises, the division between justice and value provides a useful basis for organizing the discussion of ethical concepts and principles. We have adopted it in this chapter: sections 3.3 and 3.4 cover justice and value, respectively. One topic appears in both sections because it bridges the divide: this topic is distributive justice viewed one way and the value of equality viewed the other. Section 3.3.7 on geoengineering is also in an intermediate position because it raises ethical issues of both sorts. Section 3.6 explains how some ethical values can be measured by economic methods of valuation. Section 3.5 describes the scope and limitations of these methods. Later sections develop the concepts and methods of economics in more detail. Practical ways to take account of different values in policy-making are discussed in Section 3.7.1.

3.3 Justice, equity and responsibility

Justice, fairness, equity, and responsibility are important in international climate negotiations, as well as in climate-related political decision making within countries and for individuals.

In this section we examine distributive justice, which, for the purpose of this review, is about outcomes, and procedural justice or the way in which outcomes are brought about. We also discuss compensation for damage and historic responsibility for harm. In the context of climate change, considerations of justice, equity, and responsibility concern the relations between individuals, as well as groups of individuals (e.g., countries), both at a single point in time and across time. Accordingly, we distinguish intra-generational from intergenerational justice. The literature has no agreement on a correct answer to the question, what is just? We indicate where opinions differ.

3.3.1 Causal and moral responsibility

From the perspective of countries rather than individuals or groups of individuals, historic emissions can help determine causal responsibility for climate change (den Elzen et al., 2005; Lamarque et al., 2010; Höhne et al., 2011). Many developed countries are expected to suffer relatively modest physical damage and some are even expected to realize benefits from future climate change (see Tol, 2002a; b). On the other hand, some developing countries bear less causal responsibility, but could suffer significant physical damage from climate change (IPCC, 2007, WG II AR4 SPM). This asymmetry gives rise to the following questions of justice and moral responsibility: do considerations of justice provide guidance in determining the appropriate level of present and future global emissions; the distribution of emissions among those presently living; and the role of historical emissions in distributing global obligations? The question also arises of who might be considered morally responsible for achieving justice, and, thus, a bearer of duties towards others. The question of moral responsibility is also key to determining whether anyone owes compensation for the damage caused by emissions.

3.3.2 Intergenerational justice and rights of future people

Intergenerational justice encompasses some of the moral duties owed by present to future people and the rights that future people hold against present people.[2] A legitimate acknowledgment that future or past generations have rights relative to present generations is indicative of a broad understanding of justice.[3] While justice considerations so understood are relevant, they cannot cover all our concerns regarding future and past people, including the continued existence of humankind and with a high level of wellbeing.[4]

What duties do present generations owe future generations given that current emissions will affect their quality of life? Some justice theorists have offered the following argument to justify a cap on emissions (Shue, 1993, 1999; Caney, 2006a; Meyer and Roser, 2009; Wolf, 2009). If future people's basic rights include the right to survival, health, and subsistence, these basic rights are likely to be violated when temperatures rise above a certain level. However, currently living people can slow the rise in temperature by limiting their emissions at a reasonable cost to themselves. Therefore, living people should reduce their emissions in order to fulfil their minimal duties of justice to future generations. Normative theorists dispute the standard of living that corresponds to people's basic rights (Page, 2007; Huseby, 2010). Also in dispute is what level of harm imposed on future people is morally objectionable. Some argue that currently living people wrongfully harm future people if they cause them to have a lower level of wellbeing than their own (e.g., Barry, 1999); others that currently living people owe future people a decent level of wellbeing, which might be lower than their own (Wolf, 2009). This argument raises objections on grounds of justice since it presupposes that present people can violate the rights of future people, and that the protection of future people's rights is practically relevant for how present people ought to act.

Some theorists claim that future people cannot hold rights against present people, owing to special features of intergenerational relations: some claim that future people cannot have rights because they cannot exercise them today (Steiner, 1983; Wellman, 1995, ch. 4). Others point out that interaction between non-contemporaries is impossible (Barry, 1977, pp. 243–244, 1989, p. 189). However, some justice theorists argue that neither the ability to, nor the possibility of, mutual interaction are necessary in attributing rights to people (Barry, 1989; Buchanan, 2004). They hold that rights are attributed to beings whose interests are important enough to justify imposing duties on others.

The main source of scepticism about the rights of future people and the duties we owe them is the so-called 'non-identity problem'. Actions we take to reduce our emissions will change people's way of life and so affect new people born. They alter the identities of future people. Consequently, our emissions do not make future people worse off than they would otherwise have been, since those future people would not exist if we took action to prevent our emissions. This makes it hard to claim that our emissions harm future people, or that we owe it to them as a matter of their rights to reduce our emissions.[5]

It is often argued that the non-identity problem can be overcome (McMahan, 1998; Shiffrin, 1999; Kumar, 2003; Meyer, 2003; Harman, 2004; Reiman, 2007; Shue, 2010). In any case, duties of justice do not include all the moral concerns we should have for future people. Other concerns are matters of value rather than justice, and they too can be understood in such a way that they are not affected by the non-identity problem. They are considered in Section 3.4.

If present people have a duty to protect future people's basic rights, this duty is complicated by uncertainty. Present people's actions or omissions do not necessarily violate future people's rights; they create a risk of their rights being violated (Bell, 2011). To determine what currently living people owe future people, one has to weigh such uncertain consequences against other consequences of their actions, including the certain or likely violation of the rights of currently living people (Oberdiek, 2012; Temkin, 2012). This is important in assessing many long-term policies, including on geoengineering (see Section 3.3.7), that risk violating the rights of many generations of people (Crutzen, 2006; Schneider, 2008; Victor et al., 2009; Baer, 2010; Ott, 2012).

3.3.3 Intergenerational justice: distributive justice

Suppose that a global emissions ceiling that is intergenerationally just has been determined (recognizing that a ceiling is not the only way to deal with climate change), the question then arises of how the ceiling ought to be divided among states (and, ultimately, their individual members) (Jamieson, 2001; Singer, 2002; Meyer and Roser, 2006; Caney, 2006a). Distributing emission permits is a way of arriving at a globally just division. Among the widely discussed views on distributive justice are strict egalitarianism (Temkin, 1993), indirect egalitarian views including prioritarianism (Parfit, 1997), and sufficientarianism (Frankfurt, 1999). Strict egalitarianism holds that equality has value in itself. Prioritarianism gives greater weight to a person's wellbeing the less well off she is, as described in Section 3.4. Sufficientarianism recommends that everyone should be able to enjoy a particular level of wellbeing.

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[2] In the philosophical literature, "justice between generations" typically refers to the relations between people whose lifetimes do not overlap (Barry, 1977). In contrast, "justice between age groups" refers to the relations of people whose lifetimes do overlap (Laslett and Fishkin, 1992). See also Gardiner (2011), pp. 145–48.

[3] See Rawls (1971, 1999), Barry (1977), Sikora and Barry (1978), Partridge (1981), Parfit (1986), Birnbacher (1988), and Heyd (1992).

[4] See Baier (1981), De-Shalit (1995), Meyer (2005), and for African philosophical perspectives see, Behrens (2012). See Section 3.4 on the wellbeing of future people.

[5] For an overview of the issue see Meyer (2010). See also Schwartz (1978), Parfit (1986), and Heyd (1992). For a different perspective see Perrett (2003).