Chapter 3
Paris INDCs

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Abstract This chapter begins with a description of the Paris Climate Agreement, which was formulated during the 21st meeting of the Conference of the Parties to the United Nations Framework Convention on Climate Change (UNFCCC) in late 2015. The goal of this agreement is to limit future emission of greenhouse gases (GHGs) such that global warming will not exceed 1.5 °C (target) or 2.0 °C (upper limit). Future emissions of GHGs are based on unilateral pledges submitted by UNFCCC member nations, called Intended Nationally Determined Contributions (INDCs). We compare the global emission of GHGs calculated from the INDCs to the emissions that had been used to formulate the various Representative Concentration Pathway (RCP) trajectories for future atmospheric abundance of GHGs. The RCP 4.5 scenario is particularly important, because our Empirical Model of Global Climate (EM-GC) indicates there is a reasonably good probability (~75 %) the Paris target will be achieved, and an excellent probability (>95 %) the upper limit for global warming will be attained, if the future atmospheric abundance of GHGs follows RCP 4.5. Our analysis of the Paris INDCs shows GHG emissions could remain below RCP 4.5 out to year 2060 if: (1) conditional as well as unconditional INDCs are followed; (2) reductions in GHG emissions needed to achieve the Paris INDC commitments, which generally stop at 2030, are propagated forward to 2060. Prior and future emissions of GHGs are graphically illustrated to provide context for the reductions needed to place global GHG emissions on the RCP 4.5 trajectory.

Keywords Paris Climate Agreement • Paris INDCs • Greenhouse gas emissions • CO_2-equivalent emissions • Unconditional INDC • Conditional INDC

3.1 Introduction

The Paris Climate Agreement has a structure distinctly different than its predecessor, the Kyoto Protocol. The Kyoto Protocol was approved at the third meeting of the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) held in Kyoto, Japan during December, 1997. The goal of Kyoto was to minimize the adverse effects of climate change due to rising

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Table 3.1 Annex I nations of the Kyoto Protocol

Australia	Greece	Norway
Austria	Hungary	Poland
Belarus	Iceland	Portugal
Belgium	Ireland	Romania
Bulgaria	Italy	Russia
Canada	Japan	Slovakia
Croatia	Latvia	Slovenia
Cyprus	Liechtenstein	Spain
Czech Republic	Lithuania	Sweden
Denmark	Luxembourg	Switzerland
Estonia	Malta	Turkey
Finland	Monaco	Ukraine
France	Netherlands	United Kingdom
Germany	New Zealand	United States

levels of greenhouse gases (GHGs).[1] The governing document focused on reducing emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) (Article 3), known as the Kyoto basket of GHGs. The world was split into two categories: Annex I nations (Table 3.1) and the rest of the world, which we refer to as the Non-Annex I nations. The Annex I nations consist of what most would have considered to be a reasonably good representation of the developed world in 1997.

According to the terms of the Protocol, Annex I nations had varying emission reduction targets for the Kyoto basket of GHGs, relative to emissions in year 1990 from that particular country. Total emissions of GHGs were combined into a single emission metric, termed CO_2-equivalent (CO_2-eq) emission, attained by multiplying the annual emissions of each compound by the global warming potential of that compound.[2] Each Annex I signatory nation negotiated an emission reduction target, except that the 15 European nations agreed to follow a single, combined target referred to as EU15. The target for the US was a 7 % reduction in CO_2-eq emissions and the EU15 target was an 8 % reduction, both to be achieved by 2005 relative to 1990. The largest reduction was 8 % (shared by several other nations in addition to EU15). Some signatories were allowed to increase emissions at a prescribed limit to growth, such as

[1] See http://unfccc.int/essential_background/kyoto_protocol/items/1678.php for the actual document; versions in many other languages at http://unfccc.int/kyoto_protocol/items/2830.php

[2] Typically, emissions are quantified as mass of each compound released over a year, and GWPs are based on the use of a 100-year time horizon for the governing equation. By definition, the GWP for CO_2, regardless of the source, is unity (i.e., equals 1). Numerous complications arise from the CO_2-equivalence convention, most notably the fact that best-estimates of GWPs change over time (Table 1.2), and often papers and reports do not document which GWP was actually used. Throughout this book, we use GWPs for CH_4 and N_2O of 28 and 265, respectively, unless otherwise stated. Another complication is that the effect of inadvertent release of CH_4 on global warming over the decadal time scale is not properly represented by the use of GWP on a 100-year time horizon, as discussed in Sects. 1.2.2 and 4.4.2, as well as by Pierrehumbert (2014).

Australia which agreed to have CO_2-eq emissions in 2005 be no more than 8 % larger than had occurred in 1990. The highest increase allowed was 10 %, for Iceland.

A few more pertinent details of the Kyoto Protocol follow. The Protocol allowed nations to use reductions in CO_2 attributed to land use change (LUC) to meet their commitment,[3] provided the decline in emission occurred due to direct human induced LUC since 1990. Kyoto included three mechanisms to assist nations in meeting their targets: Joint Implementation,[4] Clean Development,[5] and Emissions Trading.[6] If a country or the EU15 group failed to achieve their target during the first commitment period, which ended in 2012, two consequences ensued: a 30 % penalty of additional emission reductions for the second commitment period, and suspension of the ability to sell emissions trading credits. Details of the Kyoto Protocol were continually refined at subsequent meetings of the UNFCCC COP, held annually towards the end of the calendar year.[7]

There has been so much written about the Kyoto Protocol that references hardly seem necessary. At the time of writing, the Amazon website returns 5011 results for a search on "Kyoto protocol" in Books. We do, however, suggest *The Collapse of the Kyoto Protocol and the Struggle to Slow Global Warming* (Victor 2001) as a concise and accessible account of this agreement and its subsequent amendments, including thoughtful exposition about positive aspects of the Protocol as well as suggestions for what could have been done better.

The Kyoto Protocol did not place restrictions on GHG emissions from developing countries (i.e., all countries not listed in Table 3.1). A sub-group of Annex I nations, termed Annex II and consisting of Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States, were tasked with providing financial support for the development of technology to reduce GHG emissions in developing countries.

At some point in time, the Kyoto Protocol had been signed and ratified by all nations except Afghanistan, Southern Sudan, Taiwan, and the United States.[8] Canada withdrew from Kyoto in 2011, due to perceived pressure on the extraction of bitumen from Canadian tar sands. The US Congress failed to ratify the Protocol,

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[3] The official language for LUC in the Protocol calls this land use, land-use change and forestry and uses the abbreviation of LULUCF. Here and throughout, we use the more simple abbreviation LUC, with recognition of the importance of forestry.

[4] Joint implementation allowed Annex I countries to implement projects that reduce emissions or increase natural GHG sinks in other Annex I countries; such projects could be counted towards the emission reductions of the investing country.

[5] Clean Development allows Annex I countries to implement projects that reduce emissions or increase natural GHG sinks in non-Annex I countries; such projects can be counted towards the emission reductions of the investing country.

[6] Annex I countries could purchase emission units from other Annex I countries that found it easier to reduce their own emissions.

[7] A UNFCCC COP schedule is at http://unfccc.int/meetings/items/6240.php

[8] Observer nations Andorra and Vatican City are sometimes listed as non-participants, but their emissions are too small to matter, plus Vatican City answers to a higher authority.

which required Congressional Approval because it was viewed as a treaty by the US Government. In fact, on 25 July 1997 the Senate of the 105th Congress approved, by a vote of 95 to 0, a resolution[9] that declared:

> the United States should not be a signatory to any protocol to, or other agreement regarding, the United Nations Framework Convention on Climate Change of 1992, at negotiations in Kyoto in December 1997 or thereafter which would: (1) mandate new commitments to limit or reduce greenhouse gas emissions for the Annex 1 Parties, unless the protocol or other agreement also mandates new specific scheduled commitments to limit or reduce greenhouse gas emissions for Developing Country Parties within the same compliance period; or (2) result in serious harm to the US economy.

This resolution was passed *six months prior* to the Kyoto meeting. Since the Protocol did not include "specific scheduled commitments" to limit GHG reductions from developing countries, approval by the US Congress was always going to be an uphill battle (Victor 2001; Falkner et al. 2010).

On 12 November 2014, nearly 20 years after the Kyoto meeting, President Obama of the US and President Xi of China announced a set of crucially important, bilateral GHG reduction targets.[10] According to their announcement, by 2025 the US would reduce its total GHG emissions to be 26–28 % below the total emission that had occurred in 2005. China agreed to have their CO_2 emissions peak by 2030 and to make best effort to peak early. China also stated it would increase its share of the use of non-fossil fuels in its primary energy consumption to about 20 % by 2030. There were a variety of other actions, such as joint efforts to phase down the global use of HFCs, a class of GHGs introduced by the ban on chlorofluorocarbons to comply with the Montreal Protocol (Velders et al. 2007; see also Sect. 1.2.3.5), promote energy efficiency in buildings, and support research into carbon capture and sequestration (CCS) technologies (Sect. 4.2).

The structure of the Paris Climate Agreement is quite different than that of the Kyoto Protocol. First and foremost, the Paris Agreement has specific goals for limiting future global warming relative to the pre-industrial baseline. The Agreement[11] seeks to reduce cumulative emission of GHGs such that the increase in global mean surface temperature (GMST) is "well below 2 °C" and to "pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial". Throughout this book, we have interpreted these two numbers as being the "Paris target of 1.5 °C warming" and the "Paris upper limit of 2.0 °C warming".

The second aspect of the Paris Agreement that differs from the Kyoto Protocol is that individual nations were encouraged to submit, prior to the COP 21 meeting in Paris, their unilateral Intended Nationally Determined Contribution (INDC) for the reduction of GHG emissions. There are two types of INDCs: unconditional (firm commitments) and conditional (commitments contingent on financial assistance and/or technology transfer). The INDCs from most participating nations in the

[9] https://www.congress.gov/bill/105th-congress/senate-resolution/98

[10] https://www.whitehouse.gov/the-press-office/2014/11/11/us-china-joint-announcement-climate-change

[11] English language version at http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf

developing world are conditional. The Green Climate Fund (Sect. 4.3), established during COP 15, is recognized as one of several means to facilitate the flow of resources needed to implement the conditional INDCs. The Paris INDCs consider the original Kyoto basket of GHGs (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) plus NF_3, which was added at the COP 17 meeting held in Durban, South Africa during 2011.[12] Below, we refer to this group of seven as the UNFCCC basket of GHGs.

The Obama-Xi announcement was instrumental in the framing of the Paris Climate Agreement. The INDCs submitted by the US and China, both unconditional, build closely on the language of this bilateral plan. These nations emit more GHGs than any other: China bypassed the US to become the world's largest emitter of CO_2 during 2006. The importance of these two nations arriving at mutually agreeable language to combat global warming, prior to the Paris meeting, cannot be understated. To date, INDCs from 190 out of the 196 nations in the world have been submitted to UNFCCC. For the first time in history, there is consensus among the world's nations that a collective effort is needed to combat global warming.

Much will be written comparing and contrasting the Paris Climate Agreement and the Kyoto Protocol. The Paris Climate Agreement has a top-down, quantitative goal of limiting global warming from rising either 1.5 °C (target) or 2.0 °C (upper limit) above pre-industrial. The method of achieving the necessary reduction in GHG emissions is a bottom-up approach, conducted via unilateral INDCs. The Obama administration maintains the agreement is not a treaty and, as such, does not require Congressional approval. The Obama administration has proposed to fulfill the US commitment via the Clean Power Plan, an Environmental Protection Agency proposal to limit the emission of CO_2 from power plants within each of the 50 states (Sect. 4.4.2).

An overview of the historical emission of GHGs is provided in Sect. 3.2. Agreements such as Paris do not occur in a vacuum: i.e., an enormous amount of effort takes place prior to each COP meeting. Past emissions, economic resources, technology, and each nation's perspective on environmental responsibility play large roles in the framing of the guiding document as well as the content of individual INDCs. Past emissions of GHGs are illustrated in Sect. 3.2, both globally and nationally, because these data are readily available and provide an interesting backdrop to the Paris Climate Agreement.

Global emissions of GHGs implied by the Paris INDCs are quantified in Sect. 3.3. Projected emissions of GHGs inferred from the Paris INDCs are compared to the emissions that were used to drive the RCP 8.5 (Riahi et al. 2011), RCP 4.5 (Thomson et al. 2011), and RCP 2.6 (van Vuuren et al. 2011) scenarios, which are central to IPCC (2013). The RCP 4.5 scenario is a particularly important benchmark. Calculations shown in Chap. 2, conducted using our Empirical Model of Global Climate (EM-GC) (Canty et al. 2013), indicate there is a reasonably high probability (~75 %) that the Paris target of 1.5 °C warming will be achieved, and an excellent probability (>95 %) that global warming will remain below 2.0 °C, if the

[12] http://unfccc.int/press/news_room/newsletter/in_focus/items/6672.php. The decision to add NF_3 to the Kyoto basket was made at Durban, South Africa in 2011, this GHG was formally added via an amendment to the protocol approved in Doha, Qatar in 2012. More information about NF_3 is given in Sect. 1.2.3.5.

atmospheric abundance of GHGs follows RCP 4.5. Conversely, there is little to no chance these warming limits will be achieved if emissions follow RCP 8.5.

Our evaluation of GHG emissions comes with an important condition as well as a crucial caveat. The condition is that, to properly evaluate the Paris Agreement, emissions of GHGs must be examined at least out to year 2060. Most of the INDCs extend only to year 2030. As shown in Sects. 3.3 and 4.2, the 2030–2060 time period is crucial. Assuming populations continue to grow and standards of living continue to rise as projected, then the production of a large amount of total global energy by methods that release little or no atmospheric GHGs by 2060 will be vital for the achievement of the Paris Agreement. While it is tempting to extend the comparison of GHG emission projections out to 2100, it is not realistic to consider policy measures out to end of century. However, power plants commissioned during the next decade will almost certainly be designed to be operational in 2030. As shown in Sect. 4.2, for the world to achieve the reduction in GHG emissions needed to lie along the RCP 4.5 trajectory in 2060, we must meet about half of the projected global demand for energy without releasing GHGs to the atmosphere. For this to happen, it is incumbent that planning begin now.

The crucial caveat of our projections is that use of RCP 4.5 as the benchmark for evaluating the Paris Agreement depends on the veracity of the calculations conducted using our EM-GC framework. The coupled atmospheric, oceanic general circulation models (GCMs) used extensively by IPCC (2013) indicate that the RCP 2.6 scenario (van Vuuren et al. 2011), which imposes much tighter constraints on GHG emissions than RCP 4.5, is the appropriate benchmark for Paris (Rogelj et al. 2016). In Chap. 2, values of the Attributable Anthropogenic Warming Rate (AAWR) inferred from the climate record were compared to AAWR from GCMs. We concluded that GCMs tend to warm too quickly, by a rate that exceeds the observed warming rate by nearly a factor of two. Our conclusion that GCMs warm too quickly is consistent with the findings of Chap. 11 of IPCC (2013), particularly their expert judgement of projected warming over the next two decades that plays a prominent role in our Chap. 2.

The global warming target (1.5 °C) and upper limit (2.0 °C) of the Paris Climate Agreement will undoubtedly spur many other evaluations of GCMs, as well as other empirical forecasts of global warming. If the consensus of this research demonstrates that RCP 2.6 is indeed a more appropriate benchmark for achieving the goal of Paris than RCP 4.5, then GHG emissions will need to be reduced much faster than in the present INDC commitments to have any hope of achieving either the target or upper limit of the Paris Climate Agreement (Rogelj et al. 2016; see also Sect. 4.2).

3.2 Prior Emissions

Here, an overview of the historical emission of GHGs is provided. Numerous papers, reports, and blogs focus solely on emissions of CO_2 (Pacala and Socolow 2004; Canadell et al. 2007; Raupach et al. 2007; Friedlingstein et al. 2014), in most cases due only to the combustion of fossil fuels. However, the Paris Climate Agreement covers the UNFCCC basket of GHGs, and CO_2 emission from land use change, in addition to fossil fuels. As shown below, the average global, per-capita emission of

CO_2, CH_4, and N_2O summed among all human sources is about 7.5 metric tons of CO_2-eq per person per year. Conversely, the global, per-capita emission of CO_2 due to the combustion of fossil fuels is about 5 metric tons of CO_2 per person per year. Adding CH_4, N_2O, and CO_2 from LUC to the mix requires even steeper cuts in total GHG emissions to achieve the goals of the Paris Climate Agreement than would be needed if the focus were solely on release of CO_2 from combustion of fossil fuels.

Prior emission of GHGs by individual nations played an important role in the framing of the Paris Climate Agreement. Many of the INDCs use language that makes specific reference to prior emissions. We therefore show maps of national emissions of GHGs, presented in terms of CO_2 from the combustion of fossil fuels as well as human emission of CO_2, CH_4, and N_2O from all sources.

In the material that follows, our focus is solely on anthropogenic emission of CO_2, CH_4, and N_2O. This is not to diminish the importance of other GHGs, as well as other human drivers of climate change such as rising tropospheric O_3 and industrial release of CFCs and other ozone depleting substances (Fig. 1.4). We neglect tropospheric O_3 here because the precursors of tropospheric O_3 are regulated by Air Quality policy makers rather than the climate community. We neglect ozone depleting substances because these compounds are regulated, quite effectively, by the Montreal Protocol (Sect. 1.2.3.4). And, we do not discuss other fluorine-bearing GHGs such as HFCs, PFCs, SF_6, and NF_3 because, to date, their contribution to the RF of climate has been small (Fig. 1.4). Projections of the future radiative impacts of HFCs, PFCs, SF_6, and NF_3, due to market forces independent of the Paris Climate Agreement, are discussed in Sect. 1.2.3.5. The climate impact of HFCs could be considerable in the future, particularly if compounds with extremely high GWPs are left unregulated (Velders et al. 2009). As discussed in Chap. 1, future regulation of HFCs has recently been approved by the Parties of the Montreal Protocol. Given this effort, plus the very minor role attributed to SF_6, PFCs, and HFCs out to 2060 in the RCP projections, it seemed prudent to restrict our focus to the big three: CO_2, CH_4, and N_2O.

3.2.1 Global

Figure 3.1a illustrates global, annual emission of atmospheric CO_2 from the combustion of fossil fuels, over the prior two centuries. As noted in Sect. 1.2.3.2, about half of the CO_2 released to the atmosphere by human activity remains airborne, while the rest is removed by either the world's oceans or terrestrial biosphere (mainly trees). This figure shows the total global, annual emission of atmospheric CO_2 from the combustion of coal, natural gas, liquid fuels, cement manufacture, and gas flaring (CO_2^{FF}), obtained from the US Carbon Dioxide Information and Analysis Center (CDIAC)(Boden et al. 2013; Le Quéré et al. 2015). Data are shown in units of Gt CO_2 per year.[13] Global population is also shown.

[13] 1 Gt of CO_2 = 10^9 metric tons of CO_2. Emissions of CO_2 are expressed either as Gt C or Gt CO_2. Emissions given in Gt C can be converted to Gt CO_2 by multiplying the value by 3.664 (Table 1 of Le Quéré et al. (2015)).

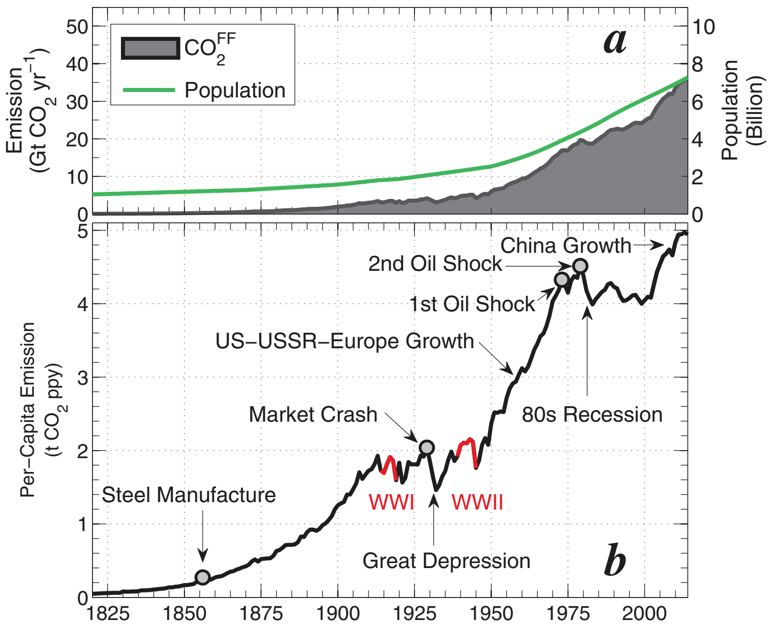

Fig. 3.1 Total global emission of atmospheric CO_2. (**a**) Emission of CO_2 from combustion of fossil fuels, flaring, and cement manufacture (CO_2^{FF}, *grey shaded*) as well as global population (*green*), from 1820 to 2014; (**b**) per-capita emission of global atmospheric CO_2 (pC^{GL}) expressed in metric tons of CO_2 per person, per year (t CO_2 ppy). World events associated with changes in pC^{GL} are noted. See Methods for further information

Figure 3.1b shows global, per-capita emission of CO_2 from the combustion of fossil fuel,[14] which we abbreviate as pC^{GL}. Values of pC^{GL} are presented in units of metric tons of CO_2 per person per year, abbreviated as t CO_2 ppy. There was a steady rise in pC^{GL} from 1856, which marks the beginning of the mass production of steel (Adams and Dirlam 1966), until the start of World War I. A hiatus in pC^{GL} then occurred until the end of World War II, followed by a rapid rise until 1973. Most of this growth drove the economic development of the US, Europe, and the former USSR. Many attribute the abrupt leveling off of pC^{GL} in 1973 to the rapid rise in the price of oil that followed the 6-day Yom Kippur war between Egypt and Israel (first Oil Shock) (Hamilton 2003). This second hiatus in pC^{GL} lasted until 2000. During this 27 year period, there was a series of world events, such as a second rapid rise in the price of oil driven by the Iranian revolution (second Oil Shock) and the 1980s economic recession, all of which contributed to significant increases in carbon efficiency within the developed world. Since 2002, the economic development of China has led to a third period marked by a rise in pC^{GL} (Le Quéré et al. 2015). It is remarkable how many world events are apparent in the record of per-capita con-

[14] Per-capita equals global emissions divided by global population; the work capita has Latin roots, meaning head.

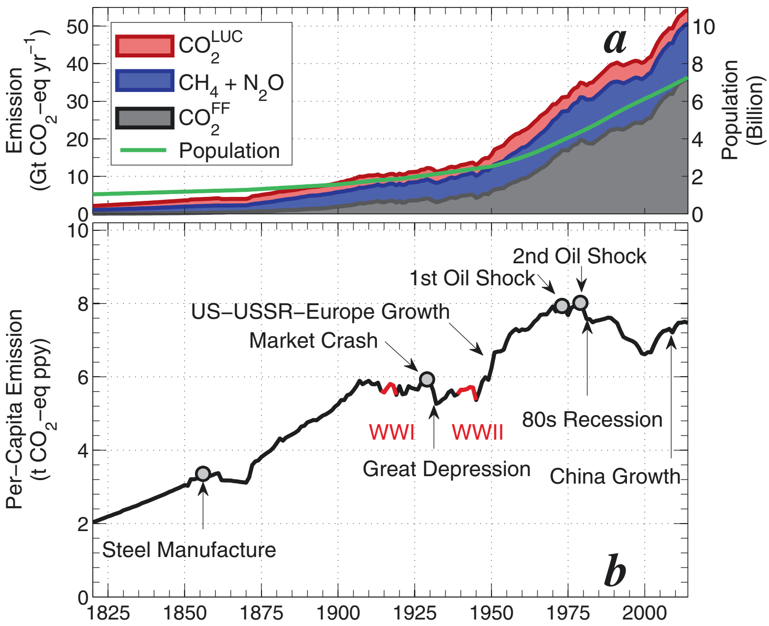

Fig. 3.2 Total global emission of atmospheric CO_2, CH_4, and N_2O. (**a**) Emission of CO_2 from combustion of fossil fuels (CO_2^{FF}; same as Fig. 3.1), anthropogenic emission of CH_4 plus N_2O expressed as CO_2-equivalent (CO_2-eq) (*blue*), and emission of CO_2 from land use change (CO_2^{LUC}, *red*); global population (*green*) is also shown; (**b**) per-capita emission of CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O, termed $pC^{EQ\text{-}GL}$, expressed in metric tons of CO_2-eq per person, per year (t CO_2-eq ppy). World events associated with changes in $pC^{EQ\text{-}GL}$ are noted. See Methods for further information

sumption of fossil fuel, which has had two distinct growth spurts (1860–1910; 1950–1973) and appears to be entering a third period of growth.

The Paris INDCs focus on reducing the emission of the UNFCCC basket of GHGs, expressed in terms of CO_2-eq (Sect. 3.1). Release of CO_2 by the combustion of fossil fuel is the most important contributor to this total GHG emission burden. Total anthropogenic emission of CH_4, which is released to the atmosphere by many aspects of our industrialized world (Sect. 1.2.3.3), is the second largest contributor. The release of CO_2 by land use change (CO_2^{LUC}) and the emission of N_2O (Sect. 1.2.3.4) make additional contributions, nearly equal in magnitude, that must be considered when examining the Paris INDCs.

Figure 3.2a shows a time series of CO_2-eq emission of GHGs. The four most important terms are included: CO_2^{FF}, CO_2^{LUC}, CH_4, and N_2O. Global population is also shown in Fig. 3.2a. The per-capita emission of GHGs in the Paris INDC relevant metric, CO_2-eq, is shown in Fig. 3.2b. The quotient of CO_2-eq emissions divided by global population, which reflects the globally averaged contribution to global warming by the world's population, is termed $pC^{EQ\text{-}GL}$.

Figure 3.3 shows the breakdown of anthropogenic release of CH_4 and N_2O, in CO_2-eq units. Figure 3.3a shows emission estimates for CH_4 and N_2O from the same source, RCP (Meinshausen et al. 2011), which has been the resource used for global

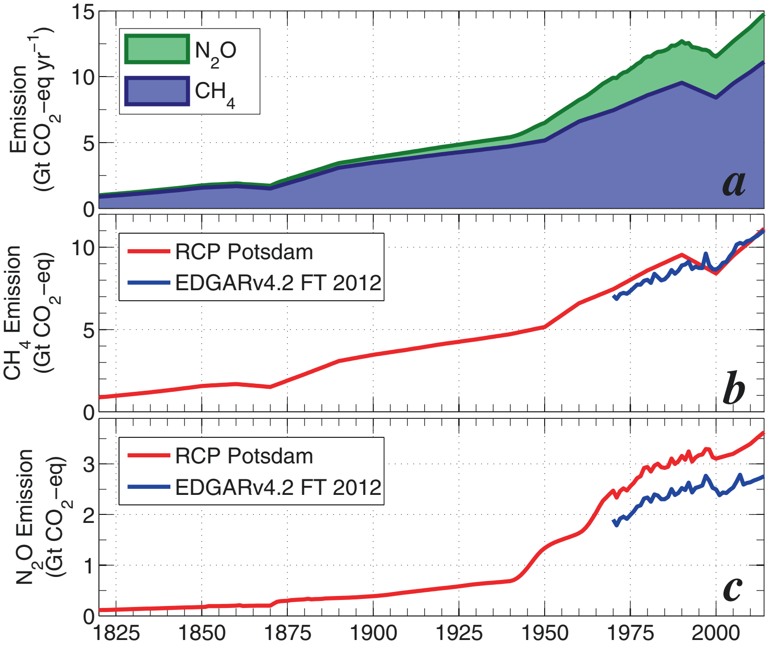

Fig. 3.3 Total global emissions of atmospheric CH_4 and N_2O. (**a**) Emission of CH_4 (*blue*) and N_2O (*green*) expressed as CO_2-equivalent (CO_2-eq) from the RCP Potsdam database (Meinshausen et al. 2011); (**b**) comparison of global emissions of CH_4 from the RCP Potsdam database and from the Emissions Database for Global Atmospheric Research (EDGAR) version 4.2 FT2012 database (Rogelj et al. 2014); (**c**) same as panel (**b**), but for N_2O. See Methods for further information

emission of GHGs throughout this book. In this case, the two estimates represent an attempt to harmonize the emissions used to drive the RCP scenarios with atmospheric observations of CH_4 and N_2O.[15] Emissions of CH_4, expressed as CO_2-eq using a 100-year time horizon, constitute about 80 % of the sum.

Figures 3.3b, c compare the RCP emissions of CH_4 and N_2O, respectively, to values from the Emissions Database for Global Atmospheric Research (EDGAR)[16] database (Rogelj et al. 2014). The two estimates for CH_4 are in very good agreement. However, they both use similar (or perhaps the same) measurements of the atmospheric abundance of CH_4 versus time (Fig. 2.1) to guide the respective time series. Both emission time series show that human release of CH_4 appears to have stalled in the 1990s, before pickup up in the most recent decade. The precise reason for this behavior is the subject of considerable uncertainty, perhaps best summarized by Kirschke et al. (2013), who in their abstract state:

> Although uncertainties in emission trends do not allow definitive conclusions to be drawn, we show that the observed stabilization of methane levels between 1999 and 2006 can potentially be explained by decreasing-to-stable fossil fuel emissions, combined with stable-to-

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[15] See http://www.pik-potsdam.de/~mmalte/rcps for further information.

[16] Here and throughout, we use version 4.2 FT 2012 emissions from EDGAR.

increasing microbial emissions. We show that a rise in natural wetland emissions and fossil fuel emissions probably accounts for the renewed increase in global methane levels after 2006, although the relative contribution of these two sources remains uncertain.

Figure 3.3c compares the RCP (Meinshausen et al. 2011) and EDGAR (Rogelj et al. 2014) estimates of the global emission of N_2O. Clearly there are common roots to these two estimates, based on the synchronization of the fluctuations. However, the RCP estimate exceeds the EDGAR by about 1 Gt CO_2-eq, for reasons that are unclear.

The emissions of CH_4 and N_2O from EDGAR and RCP have been compared in Fig. 3.3 because of their complementary importance to this book. The emissions from RCP, which are provided globally, extend back to 1765 (Meinshausen et al. 2011). This allows the historical evolution of the most important subset of the UNFCCC basket of GHGs (i.e., CO_2, CH_4, and N_2O) to be examined over the past two centuries (Fig. 3.2). Conversely, the emissions from EDGAR extend back to 1970. However, EDGAR documents national emissions of CH_4 and N_2O for each year, from 1970 to present. This is vitally important information for assessing national burdens towards global warming, as well as the evaluating the Paris INDCs.

We now turn our attention to comparing and contrasting the time series of per-capita emission of CO_2 from the combustion of fossil fuels (pC^{GL}) (Fig. 3.2a) with per-capita emission of all human sources of CO_2, CH_4, and N_2O ($pC^{EQ\text{-}GL}$) (Fig. 3.2b). Most of the world events are still evident in $pC^{EQ\text{-}GL}$ (Fig. 3.2), but all of the signatures are less dramatic than for per-capita release of CO_2 from the combustion of fossil fuels (Fig. 3.1). The exponential rise of pC^{GL} prior to 1910 (Fig. 3.1b) is replaced by a slow, steady, nearly linear rise in $pC^{EQ\text{-}GL}$ (Fig. 3.2b) over this same period of time. The time series for $pC^{EQ\text{-}GL}$ has a much stronger representation of agriculture than the time series of pC^{GL}. Much of the atmospheric release of CH_4 and N_2O, historically, has been associated with the production of food (Sects. 1.2.3.3 and 1.2.3.4), as has CO_2 released due to land use change. The recent rise in the release of atmospheric CO_2 due to the development of China imposes a different signature when viewed in the context of only fossil fuel CO_2 (start of 3^d growth spurt, Fig. 3.1b) than when examined using the UNFCCC basket of GHGs (moderate uptick, Fig. 3.2b). The major reason for the different appearance, when viewed using these two metrics, is a slower rate of rise of the human release of CH_4 (Fig. 3.3b) during the time when emission of CO_2 from the combustion of fossil fuel from China had accelerated.

The contrast in how per-capita emissions appear, when viewed in terms of release of CO_2 by the combustion of fossil fuels versus release of the UNFCCC basket of GHGs, epitomizes the challenge faced for achievement of the Paris Climate Agreement. The world's peoples must eat. Production of food imposes a considerable burden on atmospheric CH_4 and N_2O, as well as atmospheric CO_2 from the parts of the world that rely on slash and burn agriculture. Whereas future levels of N_2O are projected to rise in both RCP 2.6 (van Vuuren et al. 2011) and RCP 4.5 (Thomson et al. 2011), future levels of CH_4 decline by end of century for both of these RCP scenarios (Fig. 2.1). Reducing the emission of the UNFCCC basket of GHGs will require developing methods to feed a growing global population while, at the same time, reducing emissions of CH_4, N_2O, and CO_2 from land use change. We would be remiss if we did not mention that emission of GHGs could be reduced, particularly the release of CH_4, if more of the world adopted a plant-based diet (Stehfest et al. 2009; Pierrehumbert and Eshel 2015).

3.2.2 National

Figure 3.4 shows maps of the emission of CO_2 due to combustion of fossil fuels, flaring, and cement manufacture from individual nations ($CO_2^{FF\text{-}IN}$) for four selected years. Data are based on national inventories maintained and regularly updated by the US CDIAC (Boden et al. 2013), and are shown in units of Gt CO_2 per year. The maps reflect modern political boundaries. The CDIAC estimates are widely used in the climate community and are generally considered to be very reliable (Le Quéré et al. 2015), although there is some debate about the accuracy of the estimates for China in recent years (Guan et al. 2012; Liu et al. 2015). Our maps rely on the most recent CDIAC emission estimates for China, as well as other nations, to ensure a consistent approach for all countries.

Figure 3.5 shows national maps of per-capita release of CO_2 due to the combustion of fossil fuel (pC^{IN}). The population of individual nations is based on data provided by the Population Division of the United Nations (UN) Department of Economic and Social Affairs (see Methods, Fig. 3.1). Values of pC^{IN} are presented in units of metric tons of CO_2 per person per year, abbreviated as t CO_2 ppy.

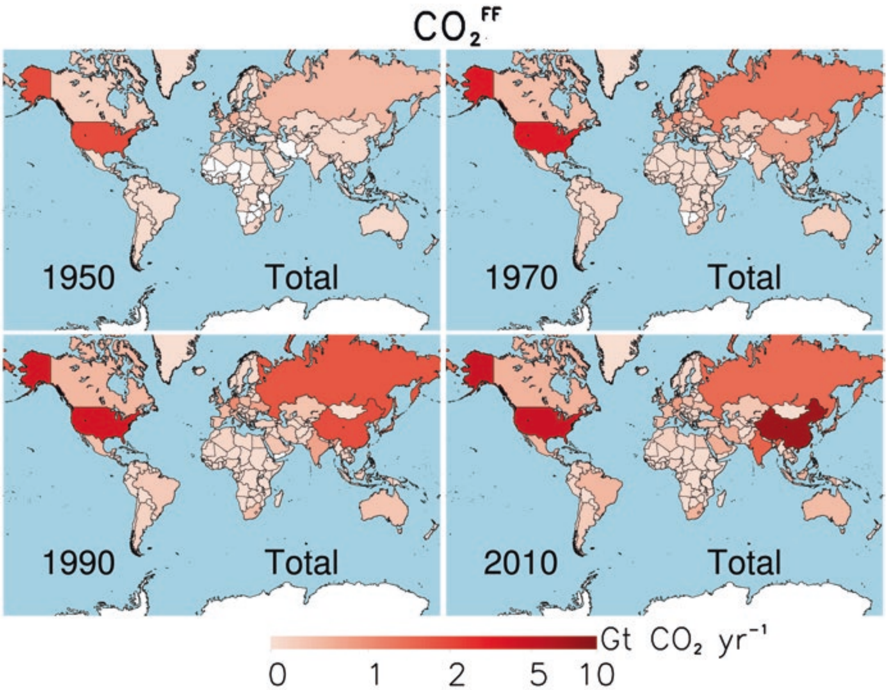

Fig. 3.4 Atmospheric fossil fuel CO_2 emission maps, 1950–2010. Emissions of $CO_2^{FF\text{-}IN}$ in units of 10^9 metric tons of CO_2 per year (Gt CO_2 year^{-1}). Maps reflect modern political boundaries. The progression of $CO_2^{FF\text{-}IN}$ from 1950 onwards is more informative when viewed as an animation, which can be found at: http://parisbeaconofhope.org/index_animations.htm. See Methods for further information

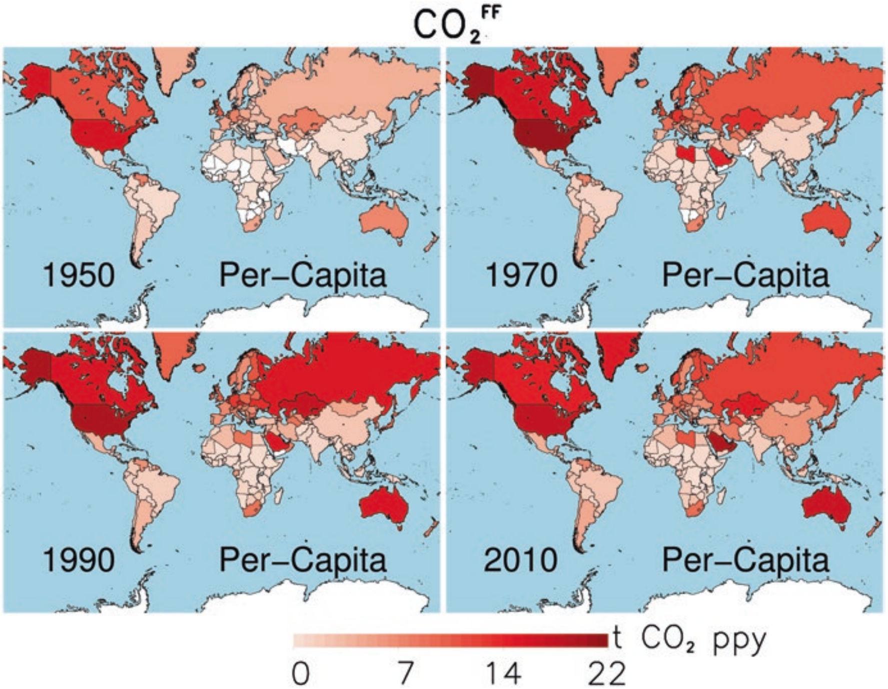

Fig. 3.5 Per-capita fossil fuel CO_2 emission maps, 1950–2010. Per-capita national emissions of CO_2^{FF}, termed pC^{IN}, in units of metric tons of CO_2 per person per year (t CO_2 ppy). The color bar was chosen to highlight emissions from large nations that dominate the global burden of total emissions, and therefore does not cover the full range of pC^{IN}. In 2010, the largest values of pC^{IN} were from Qatar and the nation of Trinidad and Tobago, at 44.7 and 39.5 t CO_2 ppy, respectively. See Methods for further information

The US emitted 2.6 Gt CO_2 in 1950, which was the largest individual national source, followed by the former Soviet Union and the UK, at 0.67 and 0.52 Gt CO_2, respectively (Fig. 3.4). At that time, there was a wide disparity in pC^{IN}. The island nation of Bahrain led the way at 29.5 t CO_2 ppy, followed by Luxembourg and Kuwait at 25.1 and 20.0 t CO_2 ppy, respectively. We have chosen both the color bar for Fig. 3.5 (does not cover the full range of pC^{IN}) and the method of presentation (world map) to highlight major emitters in terms of $CO_2^{FF\text{-}IN}$, rather than small nations that have very large values of pC^{IN}. Of the major emitters in 1950 (i.e., top six emitters in terms of $CO_2^{FF\text{-}IN}$), the US had a pC^{IN} of 16.3 t CO_2 ppy, followed by Canada and the UK, at 11.6 and 10.3 t CO_2 ppy, respectively. In 1950, China emitted 0.081 Gt CO_2, with a per-capita emission of 0.15 t CO_2 ppy.

The release of CO_2 by the combustion of fossil fuels was in the midst of a rapid rise in 1970 (Fig. 3.1). The US was the largest emitter, at 4.38 Gt CO_2, followed by the former Soviet Union and Germany, at 2.32 and 1.04 Gt CO_2, respectively (Fig. 3.4). In 1970, the largest per-capita emissions were from the nations of Qatar, UAE, and Brunei Darussalam, at 69.2, 64.9, and 63.3 t CO_2 ppy, respectively. Of the top six emitters in terms of $CO_2^{FF\text{-}IN}$, the US had the highest per-capita emission at 20.9 t CO_2 ppy, followed by Germany and the UK at 13.3 and 12.2 t CO_2 ppy, respectively (Fig. 3.5). In 1970, China emitted 0.97 Gt CO_2, with a per-capita emission of 0.78 t CO_2 ppy.

The global value of CO_2^{FF} was lower in 1990 compared to 1970, due to improvements in efficiency spurred by the two oil shocks, as well as the economic recession of the 1980s (Fig. 3.1). The US was still the largest emitter, at 4.95 Gt CO_2, followed by the former Soviet Union and China, at 3.72 and 2.50 Gt CO_2, respectively (Fig. 3.4). Largest per-capita emissions in 1990 were from UAE, Singapore, and Luxembourg, at 29.2, 28.8, and 27.2 t CO_2 ppy, respectively. Of the major emitters, the US had the highest per-capita emission at 19.6 t CO_2 ppy, followed by Germany and the former Soviet Union, at 13.1 and 12.9 t CO_2 ppy, respectively (Fig. 3.5). In 1990, the per-capita emission of $CO_2^{FF\text{-}IN}$ from China was 2.15 t CO_2 ppy.

In 2010, global emissions of CO_2 due to the combustion of fossil fuels had reached an all-time high of 33.5 Gt CO_2 (Fig. 3.1).[17] China was the largest emitter, at 8.38 Gt CO_2, followed by the United States and India, at 5.56 and 1.97 Gt CO_2, respectively (Fig. 3.4). Had the former Soviet Union remained together, the combined emissions of member nations would have been 2.65 Gt CO_2 in 2010. Russia emitted 1.77 Gt CO_2 in 2010, which was the fourth highest national total. Largest per-capita emissions in 2010 were from Qatar, Trinidad and Tobago, and Kuwait, at 44.7, 39.3, and 31.0 t CO_2 ppy, respectively. Of the top six emitters in 2010, the US still had the highest per-capita emission at 17.9 t CO_2 ppy, followed by Russia and Germany, at 12.3 and 9.7 t CO_2 ppy, respectively (Fig. 3.5). In 2010, the per-capita emission of $CO_2^{FF\text{-}IN}$ from India was 1.60 t CO_2 ppy, whereas per-capita emissions from China had risen to 6.22 t CO_2 ppy.

Figure 3.6 shows maps of the emission of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$, expressed as CO_2-eq, from individual nations ($CO_2^{EQ\text{-}IN}$) for 1990 and 2010. Emission of CH_4 and N_2O from individual nations is based on EDGAR (Rogelj et al. 2014) and emission of CO_2 from land use change is based on data provided by the United Nations Food and Agriculture Organization (FAO) (Houghton et al. 2012). Figure 3.7 shows per-capita emission of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from the world's nations ($pC^{EQ\text{-}IN}$), again for 1990 and 2010. As for Fig. 3.5, the color bar in Fig. 3.7 has been chosen to highlight the major emitters, rather than all nations. And, as noted above, values of CO_2^{LUC} from individual nations are available only from 1990 onwards, so global maps for $CO_2^{EQ\text{-}IN}$ cannot be extended as far back in time as for $CO_2^{FF\text{-}IN}$.

Table 3.2 lists the top 12 emitters, in terms of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$, for 1990 and 2010. The ascension of China, which was third in global emissions in 1990 and top in 2010, is apparent in Fig. 3.6 (national totals), Fig. 3.7 (per-capita), and Table 3.2. Over this two decade period, $CO_2^{EQ\text{-}IN}$ from China nearly tripled, and the per-capita emission more than doubled. India, which now ranks third in the world in terms of national value of CO_2-eq emission, saw its emissions double from 1990 to 2010, while the per-capita emissions from this nation only rose by 35 %. As will be apparent in Sect. 3.3, GHG emissions from India are projected to play an increasingly larger role in the global total over the next four decades.

[17] In 2014, another all-time high of 35.9 Gt CO_2 was reached. It is likely this annual emission value will be surpassed in both 2015 as well as 2016, once data for these years are released.

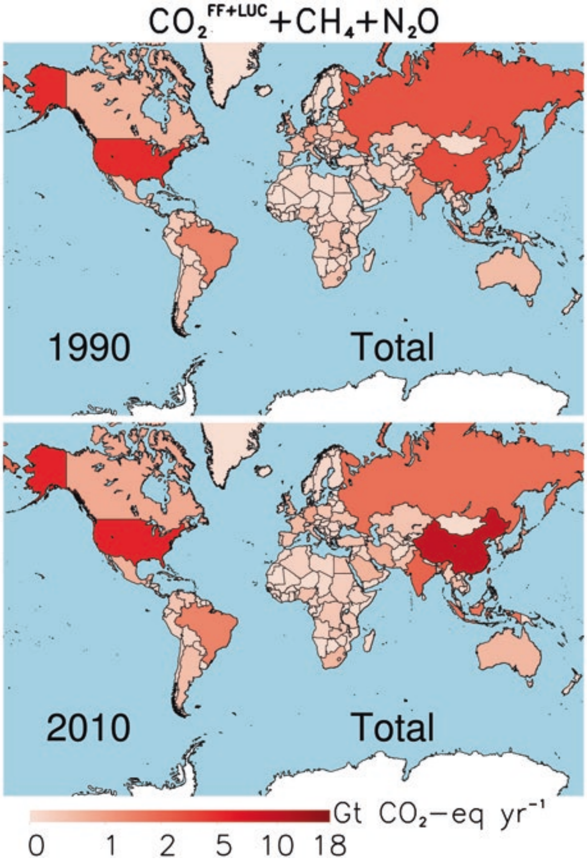

Fig. 3.6 Atmospheric GHG emission maps, 1990 and 2010. National emissions of CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O in units of 10^9 metric tons of CO_2-eq per year (Gt CO_2-eq year^{-1}). See Methods for further information

Table 3.2 has some additional numbers worth noting. The top 12 emitters contributed 65.3 % of the global total in 1990, and 62.6 % of the global total in 2010. Over this two decade period, global total emission of CO_2-eq rose by 32 %, with nearly no change in global per-capita emissions. Most interestingly, the per-capita emission of the top 12, in aggregate, nearly equaled the global per-capita emission for both 1990 and 2010. In other words, reducing the emission of GHGs to achieve the goal of the Paris Climate Agreement is a global problem: the actions of any one nation, or handful of nations, will have little effect unless the majority of nations participate.

In conclusion of this section, we shall make mention of the numerical entries for Germany in Table 3.2. The pC-eq^{IN} of Germany fell from 15.2 t CO_2 ppy in 1990 to 10.9 t CO_2 ppy in 2010. The drop in per-capita emission of Germany is also apparent in Fig. 3.7. As highlighted towards the end of Chap. 4, Germany has set the standard for generation of energy by renewables that release little or no GHGs, which the rest of the world will have to emulate to achieve the goal of the Paris Climate Agreement.

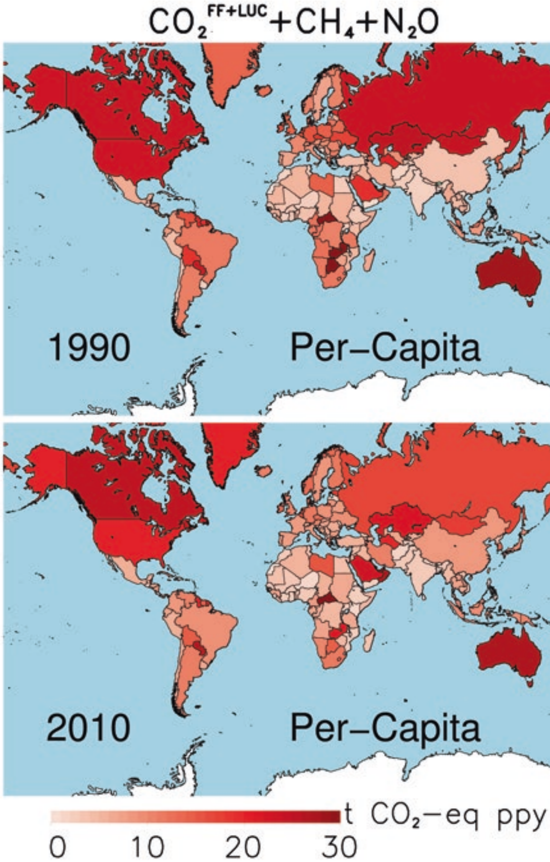

Fig. 3.7 Per-capita atmospheric GHG emission maps, 1990 and 2010. Per-capita national emissions of CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O, termed $pC^{EQ\text{-}IN}$, in units of metric tons of CO_2-eq per person per year (t CO_2-eq ppy). As for Fig. 3.4, the color bar was chosen to highlight emissions from large nations that dominate the global burden of total emissions. In 2010, the largest values of $pC^{EQ\text{-}IN}$ were from Qatar and Trinidad and Tobago, at 75.4 and 54.3 t CO_2-eq ppy, respectively. See Methods for further information

3.3 Future Emissions

Future emissions of GHGs are now examined. As noted in the Introduction, our focus is on emissions of CO_2 due to combustion of fossil fuel[18] and land use change, as well as anthropogenic emissions of CH_4 and N_2O: i.e., the primary drivers of

[18] The fossil fuel category also includes emissions from the manufacture of cement and from flaring, which are traditionally lumped into the FF category. Also, all estimates for individual nations or groups of nations include estimates from the combustion of bunker fuels, which is the term used to refer to the mixture of hydrocarbons burned by ships.

Table 3.2 Top Emitters, $CO_2^{FF} + CO_2^{LUC} + CH_{4l} + N_2O$

2010			1990		
Nation	$CO_2^{EQ\text{-}IN}$	$pC^{EQ\text{-}IN}$	Nation	$CO_2^{EQ\text{-}IN}$	$pC^{EQ\text{-}IN}$
China	10.65	7.9	US	5.75	22.8
US	6.15	19.8	USSR	5.38	18.7
India	2.87	2.3	China	3.83	3.30
Russia	2.39	16.7	Brazil	1.65	11.0
Indonesia	2.11	8.7	India	1.48	1.7
Brazil	1.72	8.7	Indonesia	1.42	7.8
Japan	1.13	8.9	Germany	1.20	15.2
Germany	0.88	10.9	Japan	1.17	9.6
Canada	0.85	24.8	UK	0.78	13.6
Iran	0.75	10.2	Canada	0.65	22.3
Mexico	0.66	5.6	France	0.53	9.37
Saudi Arabia	0.64	22.6	Poland	0.53	13.7
Sum, Top 12	30.79	7.82	Sum, Top 12	24.36	7.41
Global	49.19	7.37	Global	37.32	7.53

$CO_2^{EQ\text{-}IN}$ in units of Gt CO_2 per year; $pC^{EQ\text{-}IN}$ in units of t CO_2 ppy

climate change that are addressed by the Paris Climate Agreement. All emissions are expressed in CO_2-eq, found using GWPs of 28 and 265, respectively, for CH_4 and N_2O (Table 1.1). For the four figures described in this section, total global emissions are shown in all of the top panels. The global emissions from our projections are always represented using grey shading. The thick grey line represents a projection for the UN mid-fertility growth population projection, whereas the top and bottom bounds of the grey shaded region represent emission estimates for high-fertility and low-fertility population projections, respectively. Hence, the grey shaded region represents our estimate of the impact of population on the global emissions of CO_2-eq.

The US, China and India are the top three emitters, nationally, of CO_2-eq (Table 3.2). Therefore, we have chosen to highlight the emission projections from these three nations in the middle and lower panels of the four figures shown in this section. Projections are also shown for Annex I* nations (i.e., all nations *listed* in Table 3.1 other than US), and non-Annex I* nations (i.e., all nations *not listed* in Table 3.1 other than the China and India). We are aware that the Paris Climate Agreement does not make explicit reference to Annex I and non-Annex I nations. Nonetheless, this still seems like a reasonable way to represent the Developed and Developing World, which are referenced in the Paris document.

Figure 3.8 shows projections for the Business as Usual (BAU) scenario. As detailed in Methods, our BAU estimate of global CO_2-eq emissions (grey) considers projections of population from the UN, and forecasts of gross domestic product (GDP) from the Organization for Economic Co-operation and Development (OECD 2016). Data for CO_2-eq emissions from the five groups (US, China, India, Annex I*, and non-Annex I*) from 2000 to 2014 are used to define time series of carbon intensity, I_C, where I_C = (CO_2-eq emission)/(GDP). Past data are used to infer trends in I_C, which are projected forward in time. The world has become more carbon efficient in the past several decades. Not only has $pC^{EQ\text{-}GL}$ fallen from 1990 to 2010 (Table 3.2 and Fig. 3.2b), but world economic output has risen. The BAU projections of CO_2-eq are based on combining forecasts of I_C with forecasts of GDP, an approach known in the climate community as the simplified Kaya Identity (Friedlingstein et al. 2014). A more sophisticated approach, termed the full Kaya Identity, would include additional terms that represent energy demand and energy generation technologies (Raupach et al. 2007). In a sense, we have used the full Kaya Identity approach for Chap. 4, albeit in a global sense.

Figure 3.8a compares our projected global CO_2-eq emissions (grey) to those from RCP 8.5, RCP 4.5, and RCP 2.6. On all of the figures described in this section, our projections and those from RCP represent only CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O, found using the same numerical values of GWP. Figure 3.8a also shows projections of global emissions for the Kyoto basket of GHGs from the Joint Research Center (JRC) of the European Commission (Kitous and Keramidas 2015): their BAU projection, their analysis of the INDCs, and their estimate of the pathway needed to achieve the Paris upper limit of 2 °C warming. The JRC projections for INDCs are for unconditional only (upper orange curve) and unconditional plus conditional (lower orange curve). Finally, the global GHG emission projection for 2030 from the Planbureau voor de Leefomgeving (PBL) Environmental Assessment Agency of the Netherlands, hereafter PBL, is shown for BAU (Admiraal et al. 2015).[19] Figure 3.8b shows the breakdown of global CO_2-eq between the US, China, India, and the rest of the world groups as Annex I* (surrogate for the Developed world) and non-Annex I*.

The BAU projections shown in Fig. 3.8 contain a few important messages. Without any specific attempt to control emission of GHGs, it appears total global emission will fall short of RCP 8.5 by 2030, albeit slightly. In 2060, the BAU projection indicates China and India will be the two top emitters. Not surprisingly, emissions from the Developing World (non-Annex I*) are projected to grow more strongly than for other regions (Fig. 3.8b), even as per-capita emission from the Developing World lags that of other regions (Fig. 3.8c). Our baseline BAU projection for mid-fertility population growth exceeds, by a very small amount, the PBL BAU projection for 2030 (black dot) as well as the JRC BAU projection. However, the grey shaded region of our projection (uncertainty due to population) encompasses the BAU projections from PBL and JRC. Finally, it is evident from the impact of the uncertainty of projected population in 2060 that, while a lower population trajectory is desirable for achievement of the Paris Climate Agreement, more than population control must be implemented. The projected emissions in the decade 2050–2060 for BAU lie about midway between RCP 4.5 and RCP 8.5, which would not enable the goals of Paris to be achieved.

Figure 3.9 shows our projected global emissions of CO_2-eq (grey) for a scenario we call Attain and Hold, Unconditional (AH^{UNC}). For AH^{UNC}, we have assumed emis-

[19] PBL has a most informative INDC webpage, at http://infographics.pbl.nl/indc

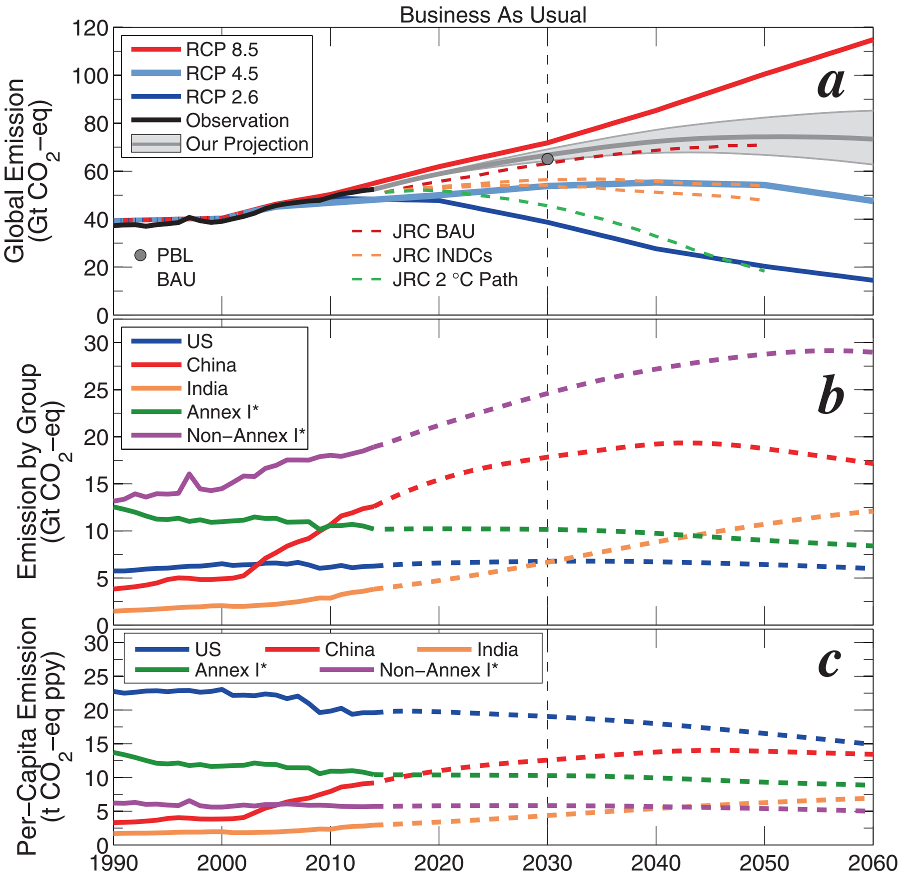

Fig. 3.8 Future GHG projections, Business as Usual (BAU). (**a**) Our projection of global emission of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$, expressed as CO_2-eq, for a BAU approach; shaded region represents uncertainty based on various population pathways (*grey*). Global emissions of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from RCP 2.6, 4.5, and 8.5, as indicated. Four projections of global emissions for the Kyoto basket of GHGs from JRC (Kitous and Keramidas 2015) are shown: BAU, their analysis of the INDCs, and their estimate of the pathway needed to achieve the Paris upper limit of 2 °C warming. The INDC projections of JRC are for unconditional only (*upper orange curve*) and unconditional plus conditional (*lower orange curve*). Finally, the global GHG emission BAU projection for 2030 from PBL (Admiraal et al. 2015) is shown. (**b**) Our projection of contributions to $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from the US, China, India, Annex I*, and non-Annex I*, all for BAU. (**c**) Per-capita emission of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from the five groups, based on our projections in panel (**b**). See Methods for further information

sions follow the submitted INDC, for the 117 nations that have submitted unconditional INDCs to UNFCCC at the time of writing, that include specific quantifiable reductions in GHG emissions. For a few nations, which shall remain unnamed, our best interpretation of their INDC leads to emissions that are larger than we have forecast under BAU. In these instances, the INDC-based forecast is used. Most of the

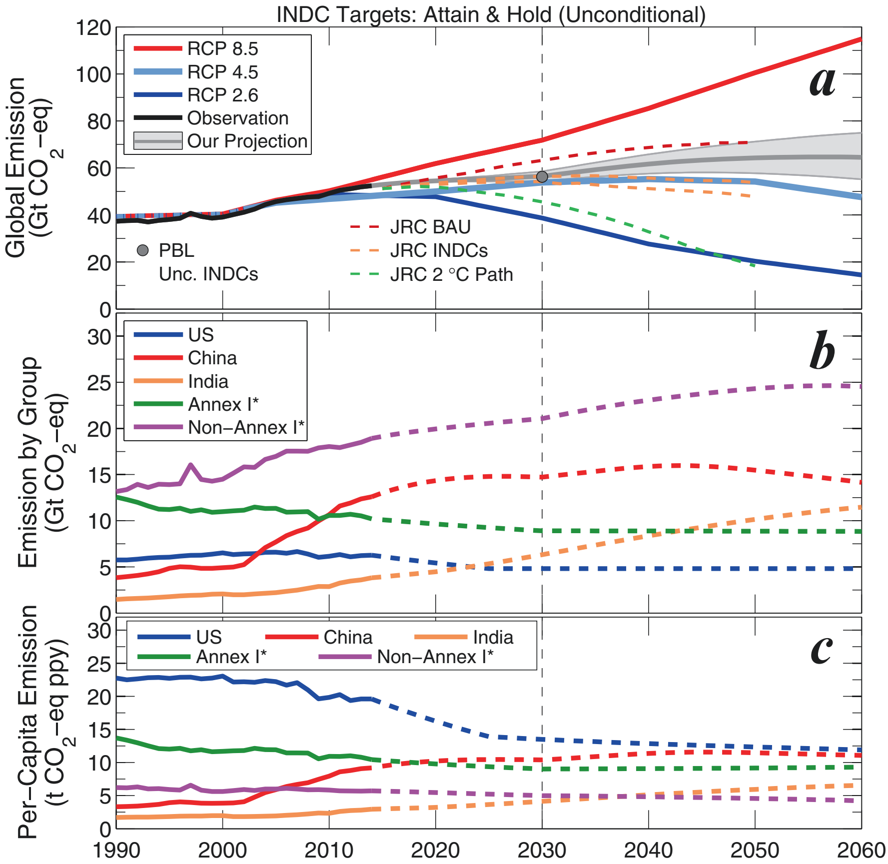

Fig. 3.9 Future GHG projections, Paris Unconditional INDCs, Attain and Hold. Same as Fig. 3.8, except our projections and that of PBL Netherlands (data point at 2030) are for our respective analyses of the Paris INDCs, considering departure from business as usual only for nations that have submitted unconditional INDCs to UNFCCC. For our projections, we assume all unconditional INDCs are followed out to the time of the commitment, and from that point onward carbon emissions hold steady. BAU projections are used for nations that submitted conditional INDCs, and for nations that did not submit an INDC. See Methods for further information

INDCs extend to 2030. The INDC-specific projections of CO_2-eq emissions extend to the target year of each submission.[20] From that year onward, CO_2-eq emissions are assumed to remain constant: hence, the use of “Hold” for this scenario.

Our AH^{UNC} projections of CO_2-eq are in extremely close agreement with the unconditional INDC projections of PBL and JRC for year 2030. Our projection tends to run higher than that of JRC for the latter years, most likely because they have assumed continued improvement in carbon intensity for years after 2030. Global emissions remain above RCP 4.5, regardless of population.

[20] The majority of the 190 INDCs, about 150, have an end year of 2030. We write “about” because some INDCs have multiple target years, whereas others lack specific target years.

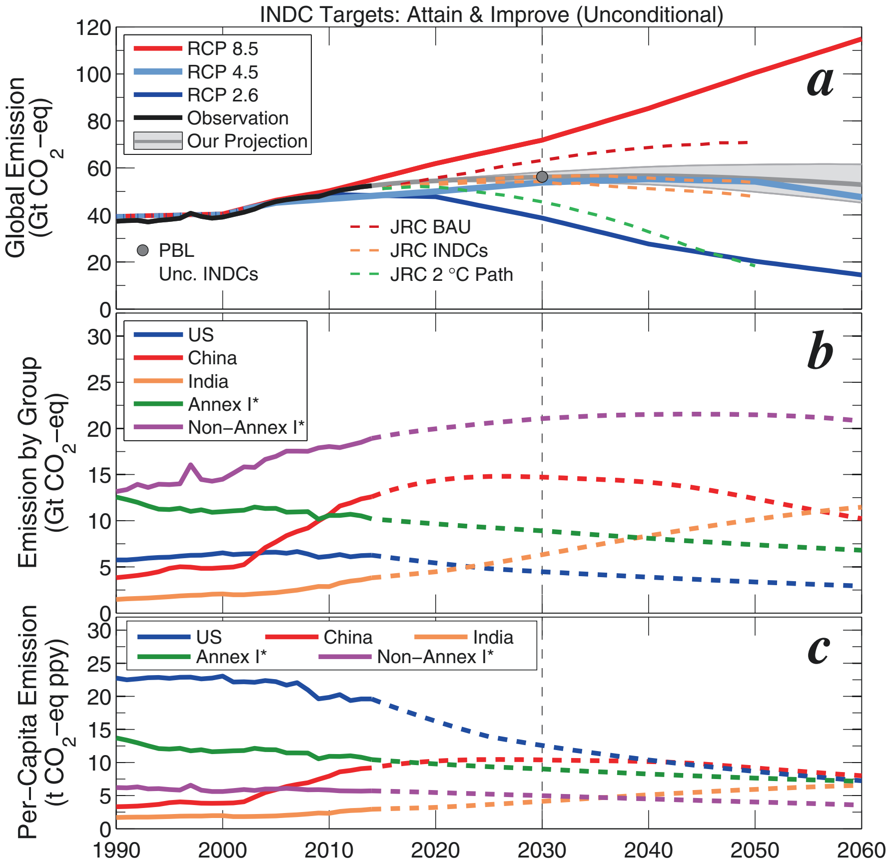

Fig. 3.10 Future GHG projections, Paris Unconditional INDCs, Attain and Improve. Same as Fig. 3.9, except we assume all of the unconditional INDCs are followed out to the time of the commitment and, from that point onward, CO_2-eq emissions *continue to decline* at the rate that had been needed for each nation to have achieved its commitment. The data point for PBL Netherlands is the same as that used for Fig. 3.8. See Methods for further information

Figure 3.10 shows our projected global emissions of CO_2-eq (grey) for a scenario we call Attain and Improve, Unconditional (AI^{UNC}). For AI^{UNC}, we again consider emissions will follow the specifications of all of the unconditional INDCs that have been submitted to UNFCCC. For this scenario, we assume carbon intensity will continue to improve, after 2030 (or whatever end year was used in the INDC), out to either 2060 or until CO_2-eq from a specific nation falls to 50 % of that nation's value in 2030. The projected value of CO_2-eq is in extremely close agreement with that of PBL in 2030, and the JRC projection that extends to 2050. The AI^{UNC} global emissions approach those of RCP 4.5 in 2060, but lie above RCP 4.5 for most population projections. Note the strong convergence of per-capita emissions from the US, China, India, and Annex I* in 2060 for AI^{UNC}, towards the value of 7.5 t CO_2-eq ppy (Fig. 3.10c). This convergence is in contrast to per-capita emissions from BAU, which exceed this value for the US, China, and Annex I* (Fig. 3.8c).

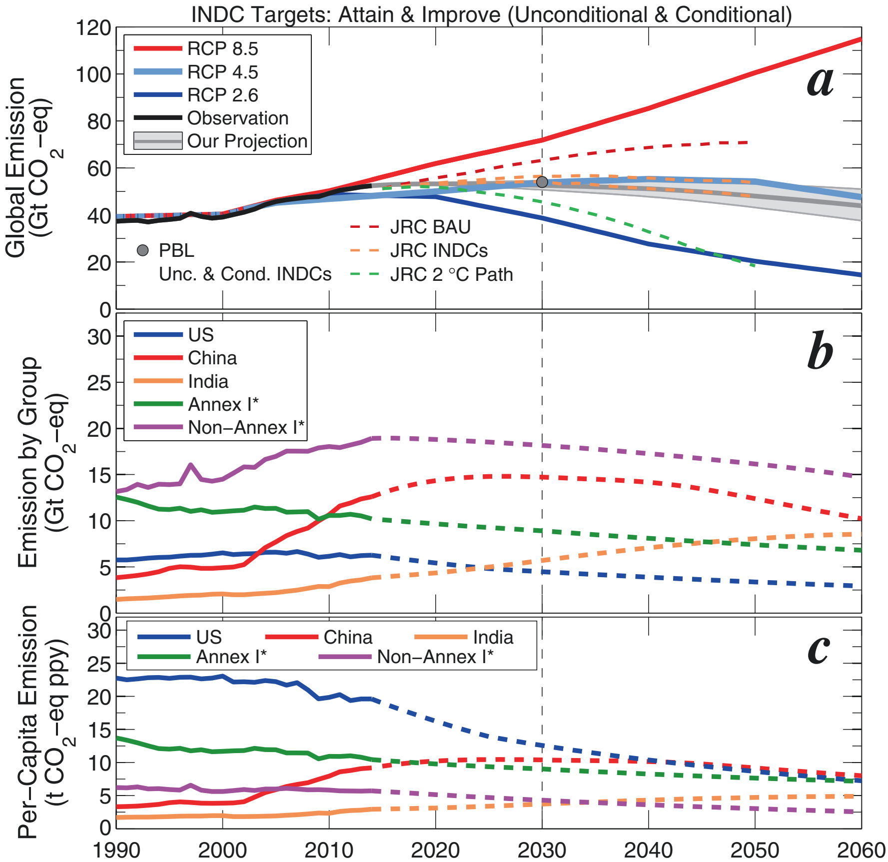

Fig. 3.11 Future GHG projections, Paris Unconditional and Conditional INDCs, Attain and Improve. Same as Fig. 3.10, except our projections consider both unconditional and conditional INDCs. We assume all of the unconditional and conditional INDCs are followed out to the time of the commitment and, from that point onward, CO_2-eq emissions *continue to decline* at the rate that had been needed for each nation to have achieved its commitment. The data point for PBL Netherlands is their projection for 2030, based on the unconditional and conditional INDCs. BAU projections are used for nations that that did not submit an INDC. See Methods for further information

Figure 3.11 shows projections for the final scenario, Attain and Improve, Unconditional and Conditional ($AI^{UNC+COND}$). Here, the treatment has been expanded to consider all 190 nations that have submitted an INDC, i.e., all plans whether conditional or unconditional.[21] Note the extraordinary good agreement with the

[21] Some of the INDCs are difficult to interpret quantitatively, with regards to reduction in the emission of GHGs. When in doubt, we used BAU for all projections. For 166 nations, the GHG emmision forecast is based on our best interprepation of the INDC. For the other 24 nations, the forecast is based on BAU, becaue for these nations, the submitted INDC was qualititive rather than quantitative.

PBL projection for 2030, and the JRC time series, both of which consider unconditional and conditional INDCs. Our analysis of the INDCs was conducted in-house, independent of PBL and JRC. A fair amount of judgement was needed to assess some of the plans. We have some trepidation about the veracity of the terms for a few nations (again, unnamed) in the INDC maps shown in Methods. Nonetheless, Fig. 3.11a shows remarkably good agreement between our independent analysis of the INDCs and the estimates of PBL and JRC.

One takeaway from Fig. 3.11 that the Paris Climate Agreement community should embrace is that if the world were to: (a) follow the unconditional and conditional INDCs; (b) commit to continued improvement in carbon intensity out to 2060, then global CO_2-eq emission would likely fall below that of RCP 4.5 regardless of future population. According to our Empirical Model of Global Climate projections, *RCP 4.5 is the 2 °C pathway* (Chap. 2). Of course, as is well known either from this book by now or from the literature (Rogelj et al. 2016), the CMIP5 GCMs indicate a steeper path of CO_2-eq emission reductions is needed to achieve 2 °C. The JRC pathway to achieve 2 °C warming, which is based on these GCMs, is illustrated on the top panel of Figs. 3.8, 3.9, 3.10, and 3.11.

We encourage critical evaluation of our EM-GC approach as well as the GCM forecasts, by other researchers, so that the COP of UNFCCC community has a means to evaluate these starkly contrasting assessments of how steep GHG emission must be reduced, to achieve the goals of the Paris Climate Agreement. In Chap. 4, Implementation, we consider both the RCP 4.5 and RCP 2.6 scenarios.

3.4 Methods

Many of the figures use data from publically available sources. Here, webpage addresses of these archives, citations, and details regarding how data and model output have been processed are provided. Only those figures with "see methods for further information" in the caption are addressed below. Electronic copies and animations of the figures are available on-line at http://parisbeaconofhope.org.

Figure 3.1 shows total global emissions of atmospheric CO_2 from fossil fuels and global population. The CO_2 emissions data were obtained from two files hosted by the Carbon Dioxide Information Analysis Center (CDIAC) at the US Department of Energy's (DOE) Oak Ridge National Laboratory (ORNL):

http://cdiac.ornl.gov/ftp/ndp030/global.1751_2013.ems
http://cdiac.ornl.gov/ftp/Global_Carbon_Project/Global_Carbon_Budget_2015_v1.1.xlsx

The first file was used for CO_2 emissions from 1820 to 2013; the second file was used to obtain data for 2014. The population data shown in Fig. 3.1a and that was used to find pC^{GL} shown in Fig. 3.2 originate from two sources. For years up to 1949, data from the Maddison Project (Bolt and van Zanden 2014) in file:

http://www.ggdc.net/maddison/maddison-project/data/mpd_2013-01.xlsx were used. For 1950 onward, global population is based on 2015 revision of data assembled by the Population Division of the United Nations Department of Economic and Social Affairs,[22] available on line at:

https://esa.un.org/unpd/wpp/DVD/Files/1_Indicators%20(Standard)/EXCEL_FILES/1_Population/WPP2015_POP_F01_1_TOTAL_POPULATION_BOTH_SEXES.XLS

Figure 3.2 shows total global emissions of atmospheric CO_2 due to the combustion of fossil fuels (CO_2^{FF}) and land use change (CO_2^{LUC}), emissions of CH_4 and N_2O expressed as CO_2-equivalent, and global population. The data used for CO_2^{FF} and population are the same as described above for Fig. 3.1. Emissions for CO_2^{LUC}, CH_4, and N_2O are based on Representative Concentration Pathway (RCP) values from files hosted by PICR (Meinshausen et al. 2011) at:

http://www.pik-potsdam.de/~mmalte/rcps/data

Data from file 20THCENTURY_EMISSIONS.DAT were used for years up to 2005, the last year covered in this file. Data from file RCP85_EMISSIONS.DAT were used for 2005–2014, because observed CH_4 over the past decade is closer to CH_4 from the RCP 8.5 scenario than any of the other three RCP scenarios. The RCP emissions for CH_4 are in units of 10^6 metric tons of CH_4 (Mt CH_4) and are converted to the CO_2-eq units used in Fig. 3.2 by multiplying the RCP data by 10^{-3} Gt/Mt × 28, where 28 is the GWP of CH_4 for a 100-year time horizon (IPCC (2013); see also Table 1.1). The conversion for N_2O requires an extra step. The RCP emissions for N_2O are in units of 10^6 metric tons of N (Mt N). However, the N represents *both* nitrogen atoms in a molecule of N_2O. As such, the conversion is accomplished by multiplying the RCP data by 10^{-3} Gt/Mt × 265 × (44/28), where 265 is the GWP of N_2O for a 100-year time horizon (IPCC (2013); see also Table 1.1) and 44/28 is the ratio of the molecular weight of N_2O to the molecular weight of N_2.

Figure 3.3 compares global emissions of CH_4 and N_2O from two databases. The top panel shows results from RCP, based on the same files as described for Fig. 3.2. Figure 3.3b compares emissions of CH_4 from RCP to emissions from version 4.2 FT2012 of the Emissions Database for Global Atmospheric Research (EDGAR) database (Rogelj et al. 2014) from the World Total row of file EDGARv42FT2012_CH4.xls, found at:

http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2012

Figure 3.3c compares emissions of N_2O from RCP to emissions from EDGAR. The EDGAR time series is based on file EDGARv42FT2012_N2O.xls from the same site, again using the EDGAR World Total entry.

Figure 3.4 shows maps of emissions of CO_2^{FF} from individual nations, termed $CO_2^{FF\text{-}IN}$. Data are from the US CDIAC (Boden et al. 2013) placed on-line at:

http://cdiac.ornl.gov/trends/emis/tre_coun.html

Current political boundaries are used for all four panels, and for all map plots in this chapter. Carbon emission from the former USSR is all that is available prior to 1992. Therefore, for years prior to 1992, former members of the USSR are assigned a value for CO_2^{FF} equal to the product of their fractional contribution to the former

[22] https://esa.un.org/unpd/wpp/Publications

USSR sum in 1992, times the total for USSR value for earlier years. The change in political boundaries for the rest of the world (i.e., Czech Republic and Slovakia of the former Czechoslovakia; Bosnia and Herzegovina, Croatia, Macedonia, Montenegro, Serbia, Slovenia of the former Yugoslavia; etc.) was handled in the same manner.

Figure 3.5 shows maps of per-capita emissions of CO_2^{FF} from individual nations. Data for $CO_2^{FF\text{-}IN}$ are the same as described in Methods for Fig. 3.4. Population data are from the United Nations Department of Economic and Social Affairs, as described in Methods for Fig. 3.1.

Figure 3.6 shows maps of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from individual nations. Data for $CO_2^{FF\text{-}IN}$ are as described for Fig. 3.4. Data for emissions of CH_4 and N_2O for individual nations are from version 4.2 FT2012 of the Emissions Database for Global Atmospheric Research (EDGAR) database (Rogelj et al. 2014), available on-line at:

http://edgar.jrc.ec.europa.eu/overview.php?v=42FT2012

Data for CO_2^{LUC} from individual nations are from the Food and Agriculture Organization (FAO) of the United Nations, available on line at:

http://faostat3.fao.org/download/G2/GL/E

A description of the FAO CO_2^{LUC} data set, and estimates of CO_2 released by LUC from other groups, is given by Houghton et al. (2012). These estimates are available starting in 1990.

Figure 3.7 shows maps of per-capita emissions of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$ from individual nations. Emission data are the same as for Fig. 3.6, and the population of individual nations is from the United Nations Department of Economic and Social Affairs, as described in Methods for Fig. 3.1.

Figures 3.8, **3.9**, **3.10**, and **3.11** show projections of emissions of $CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O$, in CO_2-eq, for business as usual (BAU) (Fig. 3.8) and the three scenarios for the Paris INDCs (Figs. 3.9, 3.10, and 3.11). Each is described below.

Figure 3.8 shows projections of future CO_2-eq emissions for BAU. These projections were found by analyzing the world based on division into five groups: US, China, India, Annex I* nations (all nations *listed* in Table 3.1 other than US), and non-Annex I* (all nations *not listed* in Table 3.1 other than China and India). For each of these groups, carbon intensity (I_C) was calculated over years 2000–2014,[23] where I_C is defined as the quotient of $\Sigma(CO_2^{EQ\text{-}IN})$ divided by $\Sigma(GDP)$. This approach is the same as used by Friedlingstein et al. (2014), except our projections use CO_2-eq emissions rather than CO_2^{FF} emissions. Values of GDP were obtained from the OECD (2016) database, on line at:

https://data.oecd.org/gdp/gdp-long-term-forecast.htm

[23] The use of 2000–2014 to define trends in I_C is somewhat arbitrary. The use of a much shorter time span introduces noise into the analysis, due to temporary economic fluctuations that are not reflective of decadal time-scale shifts. The use of a much longer time span introduces outdated technology into the analysis. We have chosen 2000 as the start time because this represents an inflection in both the global value of CO_2-eq (Fig. 3.2a) and the global per-capita value of this quantity (Fig. 3.2b). The projections shown in Fig. 3.8 are insensitive to small changes in the start date, particularly if the start year for defining trends in I_C is pushed forward in time by a few years.

In all cases, GDP is based on purchasing power parity in units of 10^{12} 2010 US dollars (USD). In other words, we use carbon emissions and GDP for the US, China, and India, since future carbon emissions from these three nations are highlighted in the figures, whereas we use aggregate sums for carbon emission and GDP for the two other groups. The quantity I_C has units of Gt CO_2-eq /10^{12} USD. For the five groups above, in the order listed, I_C declined at an annual rate of 2.06, 2.48, 2.18, 2.20, and 2.05 % from 2000 to 2014. The world is becoming more carbon efficient.

Figures 3.12 and **3.13** show global maps of BAU projections of the emissions of CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O, in CO_2-eq units, for 2030 and 2060. For the US, China, and India, future carbon emissions for BAU were found by multiplying the OECD projection of GDP by the projection of I_C, where I_C was assumed to decline at a rate of 2.06 % per year for the US. For projections of future CO_2-eq emissions from China and India, I_C was assumed to decline at 2.48 % and 2.18 % per year, respectively. For the rest of the world, BAU projections of CO_2-eq emissions were made using the OECD GDP projection for that group, combined with the rate of decline of I_C from that nations group (2.20 % per year for Annex I*, and 2.05 % per year for non-Annex I*). The specific contribution to future GHG emissions from any nation in the Annex I* or non-Annex I* group, which constitute the data shown in Figs. 3.12 and 3.13, was found from the product of the ratio of that nation's relative contribution to the emission total from the group in year 2014, times the projected future emission from the entire group.

The rest of world (nations other than the US, China, and India) have been combined in this aggregate fashion for numerous reasons. Since the US, China, and India were the top emitters in 2010, and are projected to remain the top emitters out to 2060, it seems appropriate to highlight these three nations in Figs. 3.8, 3.9, 3.10, and 3.11. Also, trends in I_C for some nations are skewed by jumps in CO_2^{LUC} that appear to be unrealistic. The 28 members of the European Union at the time of the Paris meeting submitted a single INDC, further supporting the validity of an aggregate approach. Finally, GDP forecasts are not available for many nations, particularly those in the non-Annex I* list. Hence, the use of a Kaya Identity approach for projecting future emissions involves some aggregation of data.

We recognize the future forecast for BAU from a nation that has already greatly reduced its value of I_C, such as Germany, does not fare well under our aggregate method. In other words, the CO_2-eq values for Germany shown in Figs. 3.12 and 3.13 are likely over-estimates, because Germany has reduced GHG emissions more quickly than the nations with which it has been combined. However, the success of Germany for large scale transition to renewables has been prominently mentioned in Sect. 3.2, and is emphasized in Chap. 4. We present maps in the form of Figs. 3.12 and 3.13, rather than tabular information for individual countries, to let the reader know we have indeed treated all 196 nations and 18 territories (Falkland Islands, Gibraltar, Greenland, Saint Pierre and Miquelon, etc.) of the world in our forecasts, while at the same time emphasizing that our approach is designed to provide realistic forecasts for the world in aggregate rather than for all nations.

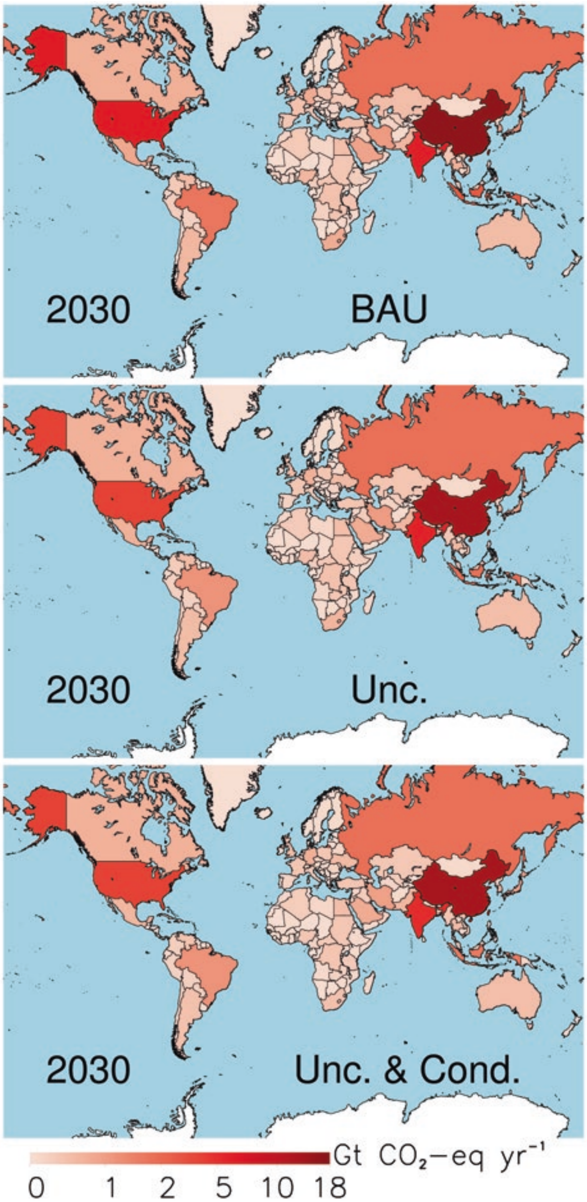

Fig. 3.12 Atmospheric GHG emission maps, Paris INDCs, 2030. National emissions of CO_2^{FF} + CO_2^{LUC} + CH_4 + N_2O in units of 10^9 metric tons of CO_2-eq per year (Gt CO_2-eq year^{-1}), projected to 2030, for the BAU, AH^{UNC}, and $AI^{UNC+COND}$ scenarios

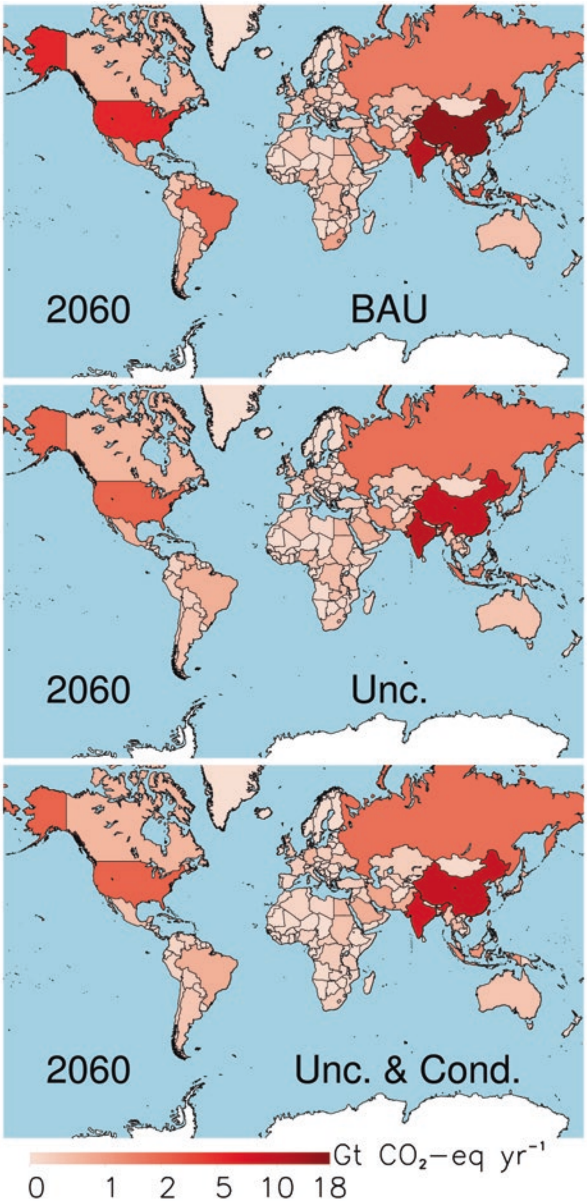

Fig. 3.13 Atmospheric GHG emission maps, Paris INDCs, 2060. Same as Fig. 3.12, but for 2060

Figure 3.8c shows per-capita emissions. Per-capita carbon emissions were found using mid-fertility future population estimates provided by the United Nations Department of Economic and Social Affairs (Methods, Fig. 3.1). The grey shaded region in Fig. 3.8a represents the uncertainty in future values of CO_2-eq, due to population. This was computed by fixing per-capita emission for each nation of the world, at the value calculated using the mid-fertility forecast, then re-computing CO_2-eq emission for either the high-fertility estimate of future population (upper extent of shaded region) or low-fertility estimate (bottom bound).

Figure 3.9 shows projections of CO_2-eq for the Attain and Hold (Unconditional) scenario. Here, future carbon emissions are held at BAU if a country did not submit an INDC, or if the INDC was purely conditional. For the US, the INDC is straightforward to implement. The last year for which CO_2-eq is available for the US, as for all nations, is 2014. We have assumed CO_2-eq from the US declines by 2.38 %/year, from 2015 to 2025, which leads to a value for CO_2-eq from the US in 2025 that is 27 % below the 2005 value.

The INDC submitted by China focuses solely on emissions of CO_2. Therefore, in all of our projections, we have assumed BAU for emissions of CH_4 and N_2O from China. The INDC from China sets a goal of 60 to 65 % reduction of I_C, relative to the 2005 value, in year 2030. We use 62.5 % in all of our projections. Our implementation of this goal for China, using GDP from OECD, leads to their emissions peaking in year 2026.

The INDC submitted by India has been interpreted to be part unconditional and part conditional. The unconditional component for India reduces I_C by 22.5 % by 2020, relative to 2005, assuming an 8 % per year growth in GDP. The conditional INDC for India imposes additional improvement on I_C, such that by 2030 it is reduced by 35 % of the 2005 value. The proposed additional carbon sink by India is applied to this CO_2 land use term.

It would take more pages than allocated to describe how each and every INDC was handled. Generally, the INDCs fall into three categories. Many give specific emission targets for CO_2-eq, in terms of percentage reduction relative to a base year. For countries that give specific targets, most use a base year of either 1990 or 2005. All European Union nations have based their emission targets off of 1990 values. The preference for 1990 is perhaps a holdover from the Kyoto Protocol. Projections of CO_2-eq emissions for INDCs that have specific targets are straightforward to implement.

Another group of nations have submitted plans to reduce their emission a certain percentage amount, relative to BAU. The implementation of these INDCs is a bit more subjective, as the BAU trajectory must first be calculated. Nonetheless, BAU projections have been found for all nations as outlined above, and the INDC commitment then leverages off our BAU projections for this group of INDCs.

A third type of INDC is based on reductions in carbon intensity, or I_C. Evaluation requires calculation of I_C for BAU, which is done as outlined above. There is again some subjectivity, as one must choose which prior years to use for the BAU projection of I_C. And, as noted above, for some nations I_C is particularly difficult to assess, due to large jumps in CO_2^{LUC}. We expect all of these complications will soon be addressed at upcoming meetings of the Conference of the Parties to UNFCCC.

The last detail that must be described is Attain and Hold (AH) versus Attain and Improve (AI). For countries that have submitted specific emission targets for their INDC, such as the US, the emissions under AH are *held fixed* at the targeted value (which for the US is 4.81 Gt CO_2-eq per year, 27 % below the 2005 value) for all years after the specified end year of the INDC (which for the US, is 2025). For countries that submitted carbon emission intensity targets, such as China and India, for all years after the specified end year (which is 2030 for both China and India), the annual decline of carbon intensity is assumed to revert to BAU. For countries that have submitted INDCs that reflect a percentage reduction relative to BAU, under AH the percentage difference between the BAU and INDC values of CO_2-eq is held fixed, for all years after the INDC end year (i.e., we assume emissions from these countries continue to "hold" steady at the same reduction, relative to BAU, for the latter years).

Under the AI projections, national CO_2-eq emissions are extrapolated forward in time, from the end year of the INDC out to 2060. Under AI, for these countries, values of CO_2-eq are linearly extrapolated forward in time, for the out years. For the US we have extrapolation $pC^{EQ\text{-}IN}$ from 13.9 t CO_2-eq ppy in 2025, the value achieved under the INDC submitted by the US, to 7.2 t CO_2-eq ppy in year 2060. This target value in 2060 matches the projection of the Annex I* nations, and is slightly less than the value of $pC^{EQ\text{-}IN}$ for China in 2060, 8.0 t CO_2-eq ppy. For countries that have submitted INDCs based on carbon intensity, then for years after the end of the INDC under AH, values of I_C found under BAU for the country's group are assumed to replace the state improvement in I_C. In other words, under AH for these countries, we assume the market will control I_C in the latter years. Under AI for the carbon intensity based INDCs, then I_C is allowed to continue to decline, at the annual rate needed to achieve the goal of the INDC, for the years between the end date of the INDC and 2060. Finally, there were a few INDCs that are not easily classified as having either specific targets, being tied to BAU, or leveraging off of carbon intensity. We used our best judgement for how to handle each of these special cases.

The final detail is that in all cases for AI we have set a floor for CO_2-eq from individual nations, such that it can never fall more than 50 % below the value assumed for 2030.[24] The INDCs of some nations commit to much more aggressive reductions in CO_2-eq than those of other nations. Ultimately, it seemed unrealistic to have CO_2-eq from these nations drop more than 50 % below the 2030 value, when other nations had not yet moved their respective needles. Like many of our assumptions, this too is clearly subject to considerable debate.

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[24] This was decided only after considerable internal discussion among the author team. The discussion focused on whether a floor to CO_2-eq should actually be imposed and, if so, what level to use for the floor.

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