Report on CH₄ in the Representative Concentration Pathways

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1 Executive Summary

- Scenarios are fundamental in climate research because they show how our climate may develop with respect to certain variables. The representative concentration pathways (RCPs) were developed to provide a new set of scenarios that explore the full range of climate policies. Methane (CH\textsubscript{4}) is a potent greenhouse gas which also affects the lower ozone (O\textsubscript{3}), another warming agent. Due to its short atmospheric lifetime, CH\textsubscript{4} reduction makes it possible to reduce near-term global warming; this is important because it will help prevent crossing a threshold that will exacerbate warming even further. (Section 2)

- RCP development led to the creation of four scenarios, whose names denote their radiative forcing target for the year 2100. These include RCP8.5, RCP6, RCP4.5 and RCP2.6 (Section 3.1)

- Socio-economic parameters like population and GDP are assumptions made by the original scenario developers, which provide insight into the internal logic and plausibility of each scenario. For example, the rate of technology improvement is influenced by GDP (and climate policy). (Section 3.2)

- Energy sector emissions can be explained by primary energy consumption (dependent upon technology improvement and population) and carbon factor (primarily determined by the mix of energy carriers). Carbon factor is important because it determines average emissions emitted per unit of energy. CH\textsubscript{4} emissions are highest in fossil fuel extraction and transport (Section 3.3)

- Land-use CH\textsubscript{4} emissions in the RCPs are mainly considered in terms of agricultural use. Animal husbandry and rice cultivation are considerable sources of CH\textsubscript{4} emissions. Although CH\textsubscript{4} emissions from these sources can be reduced, their abatement potential is limited. Increasing the potential beyond this would require extreme measures such as global-scale vegetarianism (Section 3.4)

- RCP8.5 assumes no climate policy, making it a “business as usual” scenario. As a result, technology improvement is low and energy consumption/carbon factor are high, leading to high CH\textsubscript{4} emissions. Agriculture CH\textsubscript{4} emissions increase considerably. By 2100, total CH\textsubscript{4} emissions increase by 195%. (Section 4.1)

- RCP6 and RCP4.5 assume climate policy in the form of emission permits. Though RCP6 has a higher carbon factor than RCP4.5, its energy consumption is lower, making its decrease in CH\textsubscript{4} emissions greater. Both scenarios experience slight increases in CH\textsubscript{4} agricultural emissions. By 2100, total CH\textsubscript{4} emissions will decrease 18% in RCP6 and 11% in RCP4.5; however, such high reductions in RCP6 do not occur until later in the century (Section 4.2 & 4.3)
RCP2.6 assumes stringent climate policy to limit global mean temperature rise to 2°C. Due to progressive climate policy, technology improvement is strong. Primary energy consumption/carbon factor are low, reducing CH$_4$ energy emissions to nearly zero. A decrease in agricultural emissions is also seen, though not as progressive as in the energy sector. Total CH$_4$ emissions will decrease 53% by 2100. (Section 4.4)

The vast discrepancy in CH$_4$ trends between RCP8.5 and the others is primarily the result of assumed climate policy. Though policy can strongly reduce CH$_4$, it cannot mitigate it entirely. Uncertainty is still considerable in CH$_4$ emissions on a regional basis and their conversion to mixing ratios and radiative forcing. Critical research is needed to better understand these points. (Sections 5 and 6)

Given the nearly 3-fold difference between the RCP8.5 and RCP2.6 CH$_4$ emissions already by 2040, and a 6-fold difference by 2100, there is great justification in understanding these trends better.

2 Introduction

In climate research, scenarios are used to show how decisions we make today may affect our future with respect to certain variables. Such variables include changes in the socio-economic realm, technological development, energy consumption, land use, as well as greenhouse gas and air pollutant emissions. Before development of the RCPs, the sets of scenarios available were insufficient because they did not specifically explore climate policy, among other things (e.g. more information from scenarios was also needed for the latest versions of climate models). Additionally, investigating the effect of climate policy in scenarios has become of increasing interest in the past years because it can show mitigation options, help assist policy makers in their decisions, and so on (Van Vuuren et al., 2011a). This is what led the IPCC in 2007 to call upon the scientific community for creation of a scenario set that includes climate policy (IPCC, 2007b). The resulting scenarios, the representative concentration pathways, were selected from the past literature, updated, and importantly were made to be representative of total scenario literature during the time of their development (i.e. including extreme and intermediate scenarios). These scenarios include important information on various agents, such as greenhouse gases (e.g., CO$_2$, CH$_4$, N$_2$O and O$_3$), including the sources of these agents (e.g., ozone precursors NO$_x$, VOC, CO and CH$_4$), as well as how and to what extent these agents can be mitigated (Van Vuuren et al., 2011a). Although reduction of CO$_2$ is of heightened importance in mitigation since it contributes ~60% of total global radiative forcing (Butler, 2011), the problem of climate change indeed cannot be solved by focusing on CO$_2$ alone. This is why mitigation of other forcing agents, such as CH$_4$, was also explored in the RCPs. CH$_4$ is a potent and direct contributor to global warming. Additionally, CH$_4$ influences many atmospheric pollutants; CH$_4$ is both a source and sink for hydroxyl (OH), which is the initiator for breakdown of most air pollutants. CH$_4$ is also a precursor for tropospheric ozone, which is another GHG and an air pollutant that is detrimental to human health. Atmospheric
CH₄ has a global warming potential (GWP), or ability to trap radiant energy, 72 times the same mass of CO₂ over a 20 year period, and a GWP of 25 compared to CO₂ over a 100 year period (IPCC 2007a). In total, CH₄ makes up about 18% of total global radiative forcing (as of 2010) (Butler 2011), where greater than 50% of its emissions come from anthropogenic sources (U.S. EPA). Despite the evident importance of CH₄ mitigation, this greenhouse gas is often overlooked by current policies which place a central focus on CO₂ reduction. However, CH₄ has a short atmospheric lifetime of about 10 years on average; it is mainly oxidized by OH, forming various intermediates such as formaldehyde (CH₂O), which are eventually oxidized further to form CO₂. This means that if extensive action were taken immediately to greatly reduce CH₄ emissions, initial benefits of reduced warming would be seen already in less than a decade. Reduction of near-term warming is considerably more important because it could prevent crossing the threshold of large-scale CH₄ release from melting permafrost, among other positive climate feedbacks, which would exacerbate warming even further. This makes analysis of CH₄ in the representative concentration pathways critical, as it can show how climate policy can abate CH₄ emissions, and when and to what extent these emissions can be reduced for global warming mitigation in the short term.

3 Background Information
3.1 RCP Summary

The RCP names are derived from their radiative forcing target for the year 2100 (pg. 11). Estimates of radiative forcing for each RCP were calculated by combining the individual forcing of greenhouse gases, aerosols and other agents (Van Vuuren et al., 2011a; pg. 11). RCP8.5, developed using the MESSAGE model, reaches its radiative forcing target of 8.5 W/m² in the year 2100, with radiative forcing continuing to rise. RCP8.5 is a baseline scenario, meaning that there is no target for emissions reductions due to a lack of climate mitigation policies (“business as usual”), making it representative of scenarios leading to very high emissions (Riahi et al., 2011). RCP6, developed using the Asia-Pacific Integrated Model (AIM), stabilizes its radiative forcing target at 6.0 W/m² in the year 2100, without ever exceeding that level. RCP6 is a stabilization scenario which represents a medium-high emission pathway as a result of certain limited climate policies (Masui et al., 2011). RCP4.5, developed using the Global Change Assessment Model (GCAM), stabilizes its radiative forcing target at 4.5 W/m² in the year 2100 without ever exceeding that level (pg. 77). RCP4.5 is a stabilization scenario which represents a medium-low emission pathway as a result of its assumed climate policy (Thomson et al., 2011). RCP2.6, developed using the IMAGE model, initially peaks at 3 W/m² and then declines to 2.6 W/m² by the year 2100 (pg. 11, 95) The RCP2.6 scenario is representative of a low emission pathway that is reached by stringent climate policies (Van Vuuren et al., 2011b).

1 Note that page numbers in the following refer to the Representative Concentration Pathways literature, whose pages are consecutively numbered.
3.2 Socio-Economic Assumptions

Certain socio-economic parameters in the RCPs, such as population and gross domestic product (GDP; Fig. 1), are simply assumptions made by the different modeling teams during each scenario’s original publication. Accordingly, these parameters are not based on any consistent design. In fact, after initial RCP scenario development, new socio-economic parameters will be developed by integrated assessment models (IAMs) to see how other arrangements could lead to the same concentration pathway (for more information, refer to Van Vuuren et al., 2011a). Nonetheless, this information is still important, since it is factored into scenario development, and as such provides insight into the internal logic and plausibility of each scenario (pg. 16). For all scenarios (with the exception of RCP8.5), intermediate assumptions about population and GDP were made to reflect their target radiative forcing level. It follows that global population in RCP8.5 is projected to be high, while it is assumed to be intermediate in RCP6, RCP4.5 and RCP2.6. GDP is deliberately assumed to be lower in RCP8.5 and RCP6 while it is assumed to be intermediate to high for RCP4.5 and RCP2.6 (pg. 16 and 17). One way in which these socio-economic parameters influence scenario development concerns energy technology development. GDP combined with climate policy influence the rate of energy technology development, where a high GDP projection and progressive climate policy will push towards energy efficient technologies, and vice-versa. Improvement in energy technology is important because it means greater efficiency and therefore less energy consumption overall (Van Vuuren et al., 2011a).
3.3 Energy Emissions: Primary Energy Consumption, EnergySupply Mix and Carbon Factor

Accordingly, primary energy consumption is dependent upon energy technology development and population. Scenarios for energy consumption underlying each RCP are consistent with the literature, where RCP2.6, RCP4.5 and RCP6 represent intermediate scenarios, while RCP8.5 represents scenarios with relatively high energy consumption (pg. 17). The energy supply mix (primary energy use) shows which forms of primary energy (e.g. coal, oil, nuclear) are used to make up total primary energy consumption; this reflects the scenario’s radiative forcing target for 2100 (pg. 17). The mix of energy carriers is an important consideration because it (along with carbon reducing technologies, e.g., CCS) determines how large the carbon factor will be, or the average emissions produced per unit of energy (Fig. 2). Generally, a scenario consisting of relatively high amounts of fossil fuels will have a large carbon factor and produce more CH<sub>4</sub> emissions. Though RCP6 and RCP8.5 both have high carbon factors compared to the average in the literature, the energy consumption of RCP6 is intermediate while that for RCP8.5 is high (therefore less CH<sub>4</sub> emissions in RCP6 compared to RCP8.5). The carbon factor for RCP2.6 and RCP4.5 are both at the low end of the literature, though it is much lower in RCP2.6 compared to RCP4.5 (pg. 17). Both energy consumption and the carbon factor are important because they influence the amount of GHG emissions coming from the energy sector, which is a large source of anthropogenic CH<sub>4</sub> emissions. With regards to CH<sub>4</sub>, energy
sector emissions specifically come from coal mining and the extraction and transport of fossil fuels. Unfortunately, however, the RCP papers did not discuss specific technologies (e.g. CCS) or methods responsible for CH₄ emission reductions in the energy sector. Therefore, abatement of CH₄ emissions from the energy sector will mostly be explained here simply in terms of primary energy consumption and the carbon factor (Van Vuuren et al., 2011b).

3.4 Land Use Emissions: Agriculture

Land-use is a crucial component of RCP analysis because it allows the effects of important anthropogenic activities on the carbon-climate system to be assessed (Van Vuuren et al., 2011a; pg. 19, 117). Though land use influences the climate system in many ways, the most important consideration with respect to CH₄ emissions is agricultural use. Specifically, animal husbandry and rice production are considerable sources of CH₄ agricultural emissions, which are driven by population and meat-intensive dietary patterns. Animal husbandry, the raising of livestock for food, produces considerable CH₄ emissions that come from two major areas- enteric fermentation (digestion in ruminants, e.g., cows), and manure livestock management systems. Rice production also produces considerable CH₄ emissions due to the cultivation process involved (U.S. EPA). The projected CH₄ agriculture emission trends in the RCP scenarios are reflective of the scenarios specific radiative forcing target for the year 2100. Although CH₄ emissions from these agricultural sources can be reduced, their abatement potential is limited (Van Vuuren et al., 2011b). Since the main source of CH₄ land use emissions discussed in the RCP papers come from the agricultural sector, land use emissions will be considered here only in terms of agriculture.

4 RCP Analysis

4.1 RCP8.5

The RCP8.5 scenario is “business as usual”, meaning it assumes no climate policy that explicitly mitigates emissions of greenhouse gases. This scenario projects a relatively high rate of population growth, leveling off to about 12 billion people by 2100 (Riahi et al., 2011). Economic development is slow, leading to an intermediate global GDP of $225 trillion (2000 USD constant) in the year 2100 (Van Vuuren et al., 2011a). The slow GDP growth compounded with no climate policy leads to a modest rate of technological change, especially with regards to low-carbon technologies. A slow improvement in energy efficiency technologies combined with a large population leads to a substantial increase in primary energy consumption throughout the 21st century (nearly by a factor of three by 2100; pg. 43 and 44). Due to the low rate of improvement in low-carbon technologies, the energy sector shifts towards high fossil fuel use and in particular, coal use (coal use increases about 10 fold by 2100) to meet the energy demand (pg. 42 and 43, fig. 9 pg. 49); this leads to a high carbon factor in this scenario. Although the projected fossil fuel consumption here surpasses currently extractable reserves, fossil use is extended by unconventional fossil forms (e.g., tar sands and oil shale; pg. 42, 43). A high energy demand and high carbon factor lead to very high CH₄ emissions from the energy sector, which in 2100 have increased 365% (Fig.
3) compared to year 2000 values (all increases and decreases will be compared to year 2000 values unless stated otherwise). Since CH$_4$ emissions from the agriculture sector are also unregulated, no considerable shifts in the world dietary pattern (e.g., shifts to less meat intensive diets) are expected in this scenario. Therefore, the large global population drives a great expansion in agricultural resource use (pg. 47). Increases in animal husbandry and rice cultivation cause a substantial increase in CH$_4$ emissions, which have increased 153% by the year 2100 (pg. 47 and 48). RCP8.5, like the other scenarios, does assume that air quality measures will be introduced with increasing wealth. Although these measures presumably cause a decrease in CH$_4$ emissions, it appears as though this decrease is not considerable in RCP8.5. This is partially the result of air pollution trends also being influenced by climate policy; the assumed climate policy of reduction trends in general (due to climate policy’s system-wide influence on the energy sector), compared to scenarios with stricter climate policy (e.g., RCP2.6) (Van Vuuren et al., 2011a; pg. 21). Additionally, mounting air quality concerns coupled with no climate policy in RCP8.5 leads to decoupling of CH$_4$ emissions from pollutant emissions. As an example, the energy supply can produce high levels of CH$_4$ emissions while pollutant emissions are sharply reduced through advanced technologies (Riahi et al., 2011; pg. 51). Spatial patterns of global CH$_4$ emissions show that by 2100, emissions are concentrated mainly in the Eastern United States, Western Europe, India and China; however, emissions are most concentrated in India and China (Van Vuuren et al., 2011a; pg. 22). By 2100, total global CH$_4$ emissions have increased by 195%, resulting in a 114% increase in CH$_4$ mixing ratio and a 126% increase in CH$_4$ radiative forcing. Another interesting consideration is how CH$_4$ indirectly affects radiative forcing, since it is a precursor of tropospheric O$_3$, which is also a GHG. In the second half of the century, tropospheric ozone is expected to increase in RCP8.5 due to significantly higher CH$_4$ emissions, increasing its radiative forcing by 0.2 W/m$^2$ (Lamarque et al., 2011; pg. 197, 198, 199 fig. 4 on page 198).

Figure 3 RCP8.5 methane emissions in the energy sector, agricultural sector and total emissions (left to right, respectively), in TgCH$_4$/yr (Riahi et al., 2007)
4.2 RCP6

In RCP6, the radiative forcing target is reached based on the assumption that emissions are reduced cost-effectively in a global market for emissions permits (pg. 59). The assumed population growth in this scenario is intermediate, as it reaches approximately 9.8 billion in 2100 (pg. 67). Economic development is slow, where global GDP attains approximately $220 trillion (2000 USD constant) by the end of the century (Van Vuuren et al., 2011a). Despite this relatively low GDP, climate policy drives a relatively high rate of technological development in the energy sector. However, the energy sector is somewhat complex due to the assumed level of climate policy in this scenario. In the first half of the century, carbon prices remain nearly zero, which results in only modest technological improvement and correspondingly intermediate-high growth of primary energy consumption. Due to intermediate technological improvement and relaxed climate policy during this time, the carbon factor is high as the energy demand is primarily met by fossil fuel technologies, most notably coal (pg. 67, 68 and 69). This causes increasing CH$_4$ emissions from the energy sector for the first half of the century (though emission reductions are enacted in 2010; pg. 67). However, from 2060-2080, the carbon price rises substantially, reaching a total of $180/tC (2001 constant USD) in 2080; this price remains relatively stable throughout the rest of the century (pg. 69; fig. 10 on pg. 71). Therefore primary energy consumption peaks in 2060, and by 2100 energy consumption is relatively low (838 EJ/year; pg. 67). Carbon emissions are reduced by a shift in the energy sector from coal to oil and gas around 2060 (pg. 69, fig. 5 pg 69), accompanied by a small increase in renewable energies and implementation of carbon capture and storage (CCS) (pg. 68). Though the carbon factor is still relatively high in this scenario, the low energy consumption leads to CH$_4$ emissions peaking around 2060 and declining thereafter (pg. 70). Overall, CH$_4$ emissions from the energy sector in 2100 decrease by 50% (Fig. 4). CH$_4$ emissions from land use are mixed- although climate policy reduces expansion of livestock as a way to mitigate CH$_4$, an increase in CH$_4$ emissions is caused by heightened agriculture overall (Masui et al., 2011). By 2100, CH$_4$ emissions from the agricultural sector have increased 15%. The spatial pattern for CH$_4$ emissions shows that by 2100, emissions are most concentrated in India and China, though high CH$_4$ emissions are also seen concentrated over the Eastern United States and Western Europe (Van Vuuren et al., 2011a; pg. 22). Total CH$_4$ emissions remain roughly stable throughout the course of the 21st century and have decreased 18% by 2100; this translates to a 6% decrease in CH$_4$ mixing ratio and 9% decrease in CH$_4$ radiative forcing. Also noteworthy is that the decreased CH$_4$ emissions in RCP6 cause a reduction in tropospheric ozone by the end of the 21st century, thereby indirectly decreasing radiative forcing through this agent (Lamarque et al., 2011; pg. 198, 199, fig. 4 on page 198).
4.3 RCP4.5

RCP4.5 reaches its radiative forcing target in the year 2100 mainly through implementation of greenhouse gas valuation policies, cost-effectively, to reduce emissions in all sectors (pg. 77, 82). The assumed population growth in this scenario is intermediate, reaching 8.7 billion people by the end of the 21st century (pg. 81). Economic growth here is quite good as global GDP surpasses $300 trillion (2000 USD constant) by 2100 (Van Vuuren et al., 2011a). Due to the climate policy and considerably high GDP, the rate of technological development is progressive in this scenario, especially in non-fossil technologies. As a result of this and an intermediate population, the rate of growth in total energy use is low, where primary energy consumption by 2100 is relatively intermediate. In order to mitigate emissions in this scenario, carbon prices are invoked, which reach $85/\text{tCO}_2$ by 2100 (2005 USD constant; note that information was not provided for $$/\text{tC}) (pg. 84). A shift in the energy sector involving a decrease in fossil use results, while renewable and nuclear energy use increases substantially (pg. 83). Implementation of large-scale CCS mitigates some of the fossil fuels that are still used, and it is also applied towards bio-energy (pg. 83). This results in a low carbon-factor in this scenario. In 2100, CH$_4$ emissions from the energy sector have decreased 18% (Fig. 5). An interesting component to the mitigation strategy in this scenario is that emissions from land use are charged the same price as those from fossil fuels (pg. 83). Therefore, a shift in the world dietary pattern towards a low carbon footprint regimen is seen. This is mainly carried out by moving towards a less meat intensive diet to meet global food demand (pg. 84). However, CH$_4$ emissions from this sector still slightly increase as a result of increased agriculture resources needed overall to feed a growing population. Consequently, by 2100, CH$_4$ emissions from the agricultural sector have increased 8%. Significant geographical shifts are seen in CH$_4$ emissions in part to differences in driving forces of varying regions and in part to overall mitigation (pg. 84). RCP4.5 shows that throughout the century CH$_4$ emissions decrease in China, India, the United States and Western Europe, while they increase in South America and Africa (Thomson et al., 2011; pg. 84). Over the course of the century, total CH$_4$ emissions remain roughly stable, decreasing 11% by 2100;
Figure 5 RCP4.5 methane emissions in the energy sector, agricultural sector and total emissions (left to right, respectively), in TgCH\(_4\)/yr (Clarke et al., 2007; Smith and Wigley, 2006; Wise et al., 2009).

This translates to a 10% decrease in CH\(_4\) mixing ratio and 14% decrease in CH\(_4\) radiative forcing also by 2100. Decreased CH\(_4\) emissions in this scenario also indirectly reduce the radiative forcing of tropospheric ozone (Lamarque et al., 2011; pg. 198, 199 fig. 4 on page 198).

4.4 RCP2.6

RCP2.6 adopts a stringent climate policy to reduce emissions, as it represents scenarios aiming to limit global mean temperature rise to 2°C. In order to meet its radiative forcing target, RCP2.6 requires significant changes in energy use and reductions of non-CO\(_2\) gas emissions, which are done cost-effectively. Population growth in this scenario is intermediate, reaching about 9 billion people by 2100 (slightly larger than RCP4.5). Economic growth is relatively strong as global GDP attains about $360 trillion (2000 USD constant) by 2100 (Van Vuuren et al., 2011a). The strong GDP combined with a climate policy pushing for significant improvement in energy efficiency results in great technological progress, especially with regards to low-carbon technologies. The high rate of technological improvement combined with an intermediate population leads to relatively low primary energy consumption by 2100. In order to mitigate emissions, carbon prices in this scenario need to rise rapidly. Beginning at $25/tC in 2010, they rise to about $200/tC in 2020 and continuously increase, finally stabilizing around $700-900/tC from 2050 onwards (2005 USD constant; pg 107; graph on pg. 108). The energy demand in this scenario is met by substantial shifts in the energy sector, including a significant decrease in fossil-fuels, a substantial increase in bioenergy, as well as increased nuclear and renewable energies (i.e. PV/wind). Additionally, CCS is applied to the majority of unabated fossil fuels, as well as bioenergy (BECS), to further reduce emissions. This shift in the energy sector is seen as soon as 2020, and leads to a low carbon-factor by 2100 (pg. 102). By the end of the 21st century, CH\(_4\) emissions in the energy sector are reduced to nearly zero (Fig. 6). In fact, all that remains from this area are CH\(_4\) emissions from open-pit coal mining and some emissions from natural gas transport, resulting in a total decrease of 84%. On the other hand, CH\(_4\) emission reductions in the agricultural sector are not as optimistic as those from the energy sector. This is because RCP2.6 assumes a limited abatement potential in the agricultural sector, as stated earlier.
Figure 6 RCP2.6 methane emissions across all sectors throughout the 21st century (Van Vuuren et al., 2011b).

For certain CH$_4$ sources within the agricultural domain (e.g., enteric fermentation), emission reduction is difficult and therefore there is a limited ability as to how much emissions can be reduced. Additionally, as the majority of CH$_4$ emissions in the agricultural sector come from staples of the world diet (meat, dairy and rice), there is an assumed limit as to how much the world diet can be shifted and to what extent these staples can be reduced with a growing population. Nonetheless, by 2100 CH$_4$ emissions from the agricultural sector are reduced by 26%, mainly the result of rapidly increasing carbon prices throughout the century (pg. 107).

Agricultural-related CH$_4$ emissions are presumably mitigated by reducing livestock expansion and changing farming practices, though the methods for reductions in this area are not explicitly stated in this scenario. RCP2.6 shows that while year 2000 CH$_4$ emissions are highest in areas coinciding with major agricultural areas (i.e., Western Europe, Eastern China, South Asia and parts of North and South America), 2100 emissions are vastly reduced in most areas, with higher emissions mostly remaining in Eastern and Southern Asia (i.e. India and China) (Van Vuuren et al., 2011b; pg.108; figure on pg. 109). In total, overall CH$_4$ emissions in RCP2.6 have decreased 53% by the end of the 21st century, resulting in a 28% decrease in CH$_4$ mixing ratio and a 43% decrease in CH$_4$ radiative forcing. Also important to note here is that low CH$_4$ emissions in this scenario cause a reduction in tropospheric ozone, thereby indirectly decreasing the radiative forcing in 2100 (Lamarque et al., 2011; pg. 198, 199 fig. 4 on page 198).

Figure 7 RCP2.6 methane emissions in the energy sector, agricultural sector and total emissions (left to right, respectively), in TgCH$_4$/yr (Van Vuuren et al., 2007).
5 Conclusions

A vast discrepancy exists between the CH$_4$ emissions in RCP8.5 on the one hand and RCP6, RCP4.5 and RCP2.6 on the other (Fig. 8). Already by 2040 there is a nearly 3-fold difference between the RCP8.5 and RCP2.6 CH$_4$ emissions, which is consistent with the approximately 3.5-fold between these two scenarios for CO$_2$ emissions within the same time frame. The differences in CH$_4$ emissions across the RCPs are largely the result of differences in assumed climate policy, while differences in model and socio-economic assumptions also play a role (pg. 20). CH$_4$ emissions in RCP8.5 reach very high levels because they rise rapidly throughout the century as a result of no climate policy and high population. However, CH$_4$ emissions in RCP6 and RCP4.5 are roughly stabilized throughout the century by emission reductions in the energy sector and a reduction in the rate of emission increase in the agricultural sector. In RCP2.6, CH$_4$ emissions are significantly reduced throughout the century, mainly by eliminating energy sector emissions almost entirely. Reduction of agricultural emissions in RCP2.6 also contributes considerably to this overall decrease (in contrast, note that agricultural emissions increase in all the other RCP scenarios), though not to the same extent as energy sector emissions; the reason for this is that there is a limited abatement potential of CH$_4$ agricultural emissions, unless there were to be an unexpected radical transformation in eating habits, especially with respect to red meat consumption, around the world.

From the RCP2.6 scenario, one can conclude that, although CH$_4$ emissions can be greatly reduced, climate policy is not likely to reduce anthropogenic emissions entirely. Methane emissions can be converted into mixing ratios (ppb), from which the level of radiative forcing (W/m$^2$) can be calculated (Fig. 8). Mixing ratio trends of CH$_4$ in the RCPs are quite pronounced, and they closely resemble the increases and decreases of CH$_4$ emission trends due to CH$_4$’s relatively short atmospheric lifetime of about 10 years, with the differences caused by feedbacks such as with atmospheric OH levels. This highlights the importance of reducing methane emissions soon, as reducing emissions today would bring about initial positive responses within a decade. The level of climate policy is therefore also apparent in the CH$_4$ radiative forcing trends. CH$_4$ radiative forcing reactly increases in RCP8.5, where its year 2100 level is over twice as high as that in 2000. On the other hand, CH$_4$ radiative forcing slightly decreases in RCP6 and RCP4.5. Despite the fact that CH$_4$ emissions in RCP4.5 exceed those in RCP6 after about 2090, RCP4.5 radiative forcing in 2100 is still comparatively lower due to the decade long atmospheric lifetime of CH$_4$. Finally, CH$_4$ radiative forcing of RCP2.6 greatly decreases throughout the century, where its value in 2100 is about half that in the year 2000. Spatial patterns of CH$_4$ emissions follow two primary trends across the RCPs; first, CH$_4$ emissions are generally strongest in certain regions, namely, the Eastern United States, Western Europe, India and China. Second, as the radiative forcing target gets higher, emissions become more pronounced in areas that are currently low-income, namely India and China (Van Vuuren et al., 2011a).
Figure 8 Methane emissions, concentration, and radiative forcing of the four RCPs (Riahi et al., 2007; Fujino et al., 2006; Hijioka et al., 2008; Clarke et al., 2007; Smith and Wigley, 2006; Wise et al., 2009; Van Vuuren et al., 2007).

Finally, CH₄ is known to have a further, indirect radiative forcing effect through its influence on tropospheric ozone, as well as the production of CO₂ when it is oxidized. High CH₄ emissions in RCP8.5 increase tropospheric ozone, while lower CH₄ emission levels in the other RCPs contribute to a decrease in tropospheric ozone. Therefore, allowing CH₄ emissions to rise to very high levels as in RCP8.5 will further exacerbate radiative forcing, while reducing CH₄ will have additional benefits in overall radiative forcing (Lamarque et al., 2011).

6 Recommendations for Further Research

Uncertainty still remains in the RCPs, especially with regards to CH₄ emissions on a regional basis and their conversion to concentration and radiative forcing values (Van Vuuren et al., 2011a; pg. 28). Critical future research is needed to better understand these points in order to substantiate and improve this data in the RCPs. Also important to note is that by 2100, the remaining greenhouse gas emissions in RCP2.6 are mostly non-CO₂. Consequently, the ability to reach a radiative forcing level lower than 2.6 W/m² (and thus a lower rise in global mean temperature), is dependent upon greater abatement potential in gases such as CH₄. Therefore, the feasibility of a greater abatement potential in CH₄ agricultural emissions for this scenario must be explored. Because reductions of nearly all emission sources in RCP2.6 are close to the maximum potential, new results showing that current CH₄ abatement estimates are not possible may indicate that the 2ºC limit in temperature rise is
not possible (Van Vuuren et al., 2011b). Finally, more research and general information are needed on CH\textsubscript{4} emissions and mitigation in the RCPs. For example, greater research is needed to explore specific mechanisms/technologies accounting for CH\textsubscript{4} reduction in the energy and agricultural sectors. More general information is also needed about other important anthropogenic CH\textsubscript{4} sources (e.g. landfills). Finally, in order to get a more complete picture on CH\textsubscript{4}, it is important that CH\textsubscript{4} from melting permafrost is explicitly discussed in future scenarios.

**Figure 9** Methane emissions spatial patterns in 2100 for the four RCPs (Van Vuuren et al., 2011a).
References


UNEP and WMO (2011) Integrated Assessment of Black Carbon and Tropospheric Ozone: Summary for Decision Makers


