The Beginner's Guide to

# Representative Concentration Pathways

G. P. WAYNE

Skeptical Science

# The Beginner's Guide to Representative Concentration Pathways

**By Graham Wayne** **Version 1.0, August 2013**

## Introduction

Many factors have to be taken into account when trying to predict how future global warming will contribute to climate change. The amount of future greenhouse gas emissions is a key variable. Developments in technology, changes in energy generation and land use, global and regional economic circumstances and population growth must also be considered.

So that research between different groups is complementary and comparable, a standard set of ***scenarios*** are used to ensure that starting conditions, historical data and projections are employed consistently across the various branches of climate science.

The Intergovernmental Panel on Climate Change (IPCC ) Fifth Assessment Report (AR5) is due for publication in 2013-14. Its findings will be based on a new set of scenarios that replace the Special Report on Emissions Scenarios (SRES) standards employed in two previous reports. The new scenarios are called **Representative Concentration Pathways (RCPs)**. There are four pathways: RCP8.5, RCP6, RCP4.5 and RCP2.6 - the last is also referred to as RCP3-PD. (The numbers refer to forcings for each RCP; PD stands for *Peak* and *Decline*).

> "The name "representative concentration pathways" was chosen to emphasize the rationale behind their use. RCPs are referred to as pathways in order to emphasize that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasize that it is not only a specific long-term concentration or radiative forcing outcome, such as a stabilization level, that is of interest, but also the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics". ***(IPCC Expert Meeting Report, Towards New Scenarios For Analysis Of Emissions, Climate Change, Impacts, And Response Strategies, IPCC 2007)***

**This guide to Representative Concentration Pathways assumes no prior knowledge.**

In **Part 1** we explore their historical background, explain why scenarios are necessary, and who uses them. Readers already familiar with the background may wish to skip this section.

**Part 2** starts with an examination of the demand for new scenarios, and why they were deemed necessary. The aims and requirements of stakeholders are described, how the development teams were selected, and the process by which the RCPs were created, checked and validated.

In **Part 3** we take a look at the scenarios in detail, consider the technical aspects, the differences between the four RCPs, and how they compare to earlier SRES scenarios.

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# Part 1: An introduction to scenarios

## Why are scenarios necessary?

> **"Scenarios of different rates and magnitudes of climate change provide a basis for assessing the risk of crossing identifiable thresholds in both physical change and impacts on biological and human systems".**
>
> *Source: "Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies", IPCC Technical Summary, 2007*

There are many climate modelling teams around the world. If they all used different metrics, made different assumptions about baselines and starting points, then it would be very difficult to compare one study to another. In the same way, models could not be validated against other different, independent models, and communication between climate modelling groups would be made more complex and time-consuming.

Another problem is the cost of running models. The powerful computers required are in short supply and great demand. Simulation programming that had to start from scratch for each experiment would be wholly impractical. Scenarios provide a framework by which the process of building experiments can be streamlined.

In order to address these issues, in 1992 the Intergovernmental Panel on Climate Change (IPCC) published the first set of climate change scenarios, called **IS92**. In year 2000 the IPCC released a second generation of projections, collectively referred to as the Special Report on Emissions Scenarios **(SRES)**. These were used in two subsequent reports; the Third Assessment Report **(TAR)** and Assessment Report Four **(AR4)** and have provided common reference points for a great deal of climate science research in the last decade.

In 2007, the IPCC responded to calls for improvements to SRES by catalysing the process that produced the Representative Concentration Pathways (RCPs). The RCPs are the latest iteration of the scenario process, and are used in the next IPCC report - Assessment Report Five **(AR5)** in preference to SRES. Here's how the IPCC describes the scenarios (emphasis added):

> "In climate change research, scenarios describe plausible trajectories of different aspects of the future that are constructed to investigate the potential consequences of anthropogenic climate change. Scenarios represent many of the major driving forces - including processes, impacts (physical, ecological, and socioeconomic), and potential responses that are important for informing climate change policy. They are used to hand off information from one area of research to another (e.g., from research on energy systems and greenhouse gas emissions to climate modeling). They are also used to explore the implications of climate change for decision making (e.g., exploring whether plans to develop water management infrastructure are robust to a range of uncertain future climate conditions). **The goal of working with scenarios is not to predict the future but to better understand uncertainties and alternative futures, in order to consider how robust different decisions or options may be under a wide range of possible futures".**
>
> *Source: IPCC Scenario Process for AR5*

## Who uses climate scenarios?

There are several primary groups who study the effects of climate change. Climate Model (CM) groups study the effects of global warming on the climate itself and how our emissions affect the environment. Integrated Assessment Model (IAM) groups combine information from diverse fields of study, primarily to assess the relationship between emissions and socio-economic scenarios. A third group studies Impacts, Adaptation and Vulnerabilities (IAV), often at regional scales, drawing on disciplines and research traditions including social sciences, economics, engineering, and the natural sciences.

This graphic from the IPCC shows the relationships between the various groups, and their main areas of exploration:

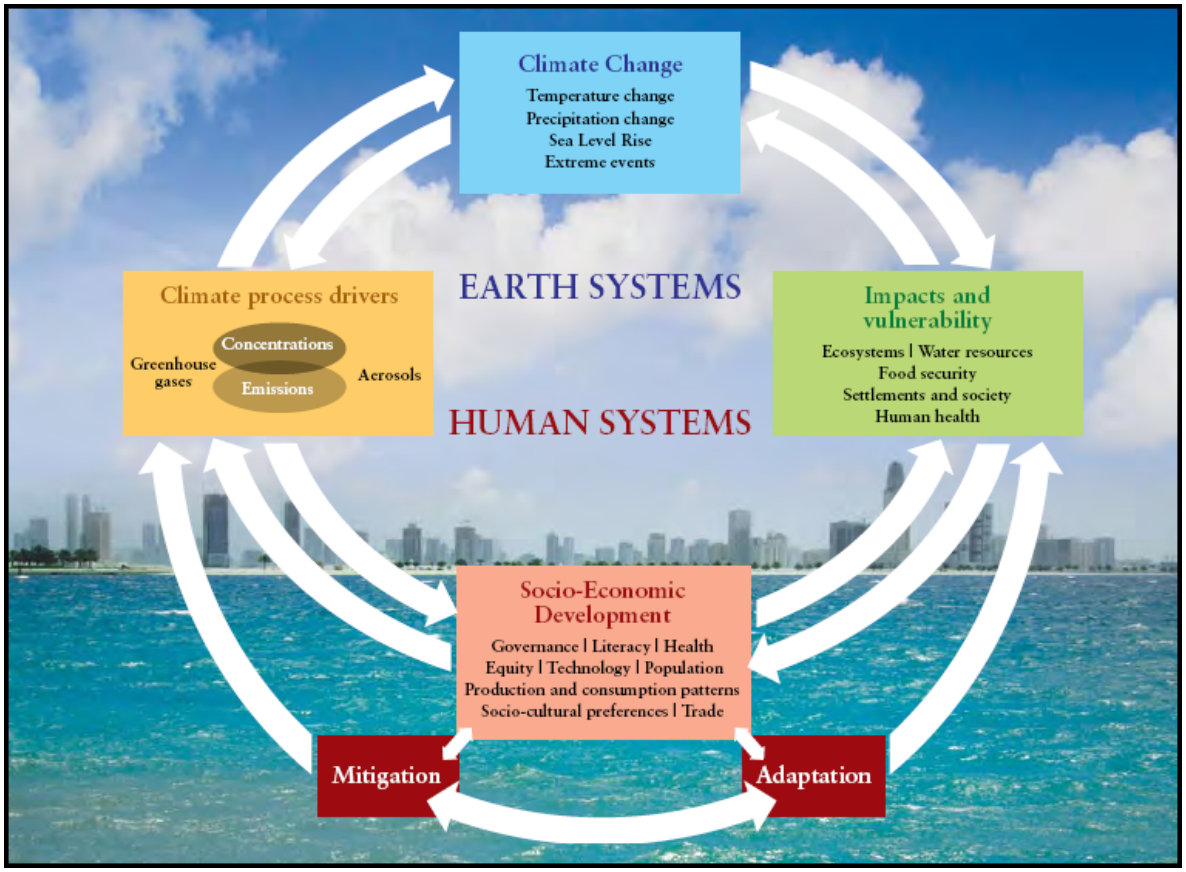


***Figure 1.*** *From the IPCC Expert Meeting Report: Towards New Scenarios - Technical Summary*

As well as the groups mentioned above, scenarios are used extensively by scientists, policy makers, NGOs and commentators as a common framework through which they can discuss climate change, exchange ideas and communicate with each other effectively.

## What do RCPs Consist Of ?

A RCP scenario basically consists of numbers - a prodigious amount of them. RCP data is in tables - if you're familiar with a spreadsheet, the format is somewhat similar.

For each category of emissions, an RCP contains a set of starting values and the estimated emissions up to 2100, based on assumptions about economic activity, energy sources, population growth and other socio-economic factors. (The data also contain historic, real-world information). While socio-economic projections were drawn from the literature in order to develop the emission pathways, the database does not include socio-economic data.

Modellers download the database sets to *initialise* their models, which jump-starts what would otherwise be a very lengthy process - one that each modelling team would have to attempt, thus duplicating effort. RCPs and previous scenarios were created exactly to avoid such duplication, and the inevitable initialisation inconsistencies that would ensue.

A quick look at the RCP database screenshot below shows how many emissions categories are addressed by the RCPs. Each RCP contains the same categories of data, but the values vary a great deal, reflecting different emission trajectories over time as determined by the underlying socio-economic assumptions (which are unique to each RCP).

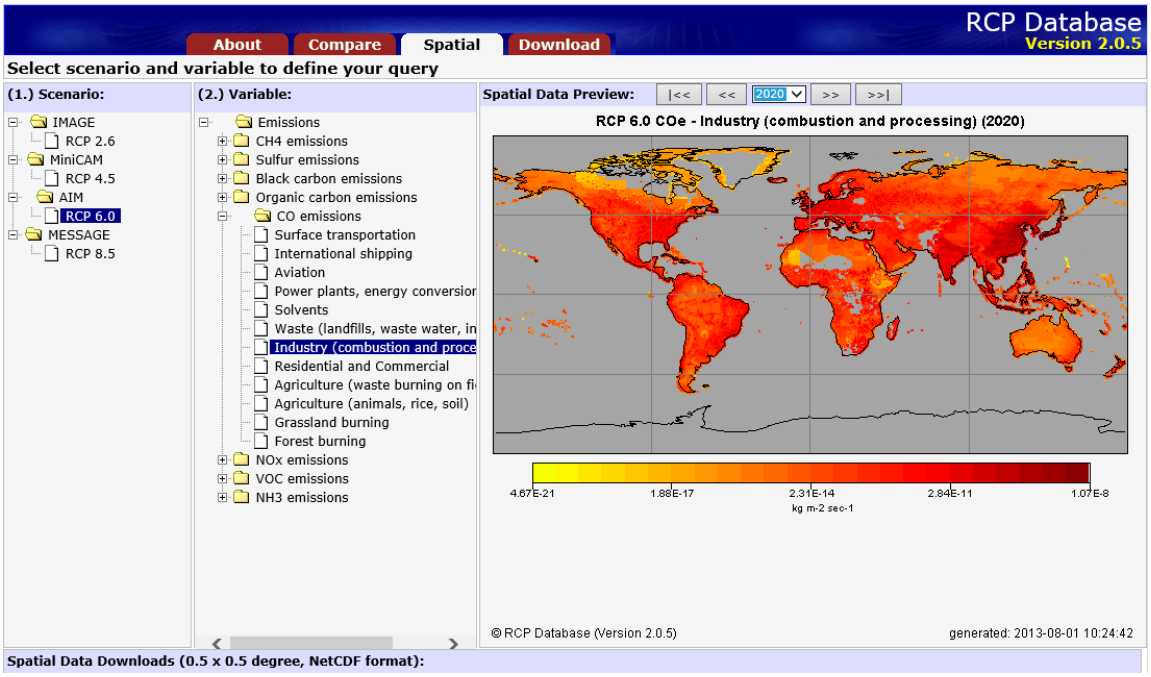


***Figure 2**: RCP on-line database showing RPC6 spatial data for industry COe emissions for the year 2020.*

High-resolution data is generated for a world divided into 'cells' measuring half a degree of latitude and longitude - 518,400 cells in total. The RCP database web interface provides only a preview of the data, which can comprise far more detail than a graphic can show. It is, however, a starting point for researchers, who can evaluate the data graphically before downloading it. (As an alternative, the Compare option allows researchers to plot a graph of trajectories for all four RCPs - some the graphs shown later in this guide were produced using the RCP on-line facility).

For example, here are two graphic representations of RCP6 spatial COe emissions for the years 2010 and 2100:

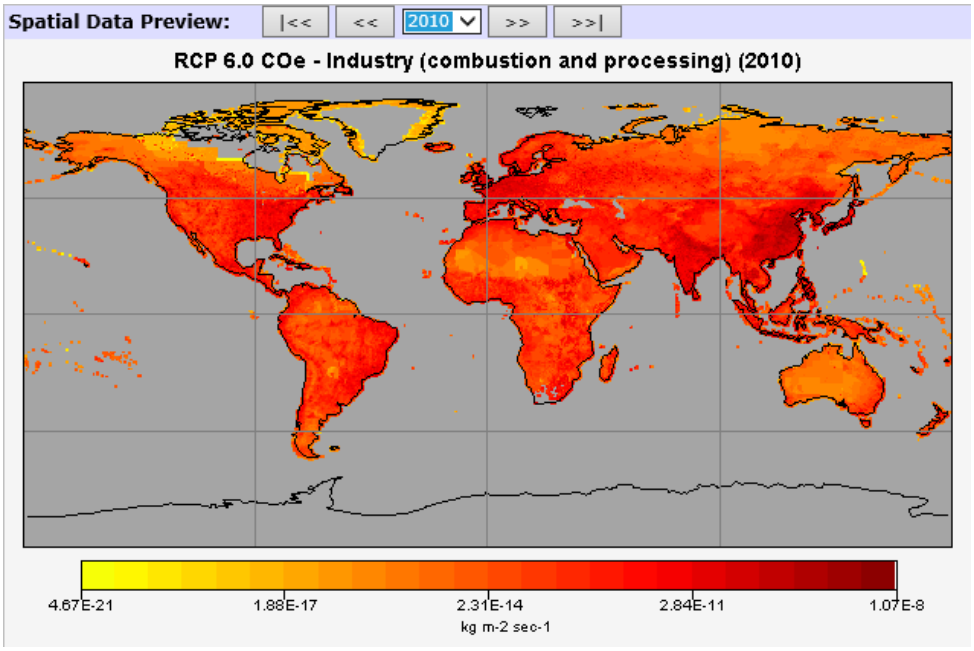


***Figure 3**: RCP on-line database graphic showing RPC6 spatial data for industry COe emissions for the year 2010…*

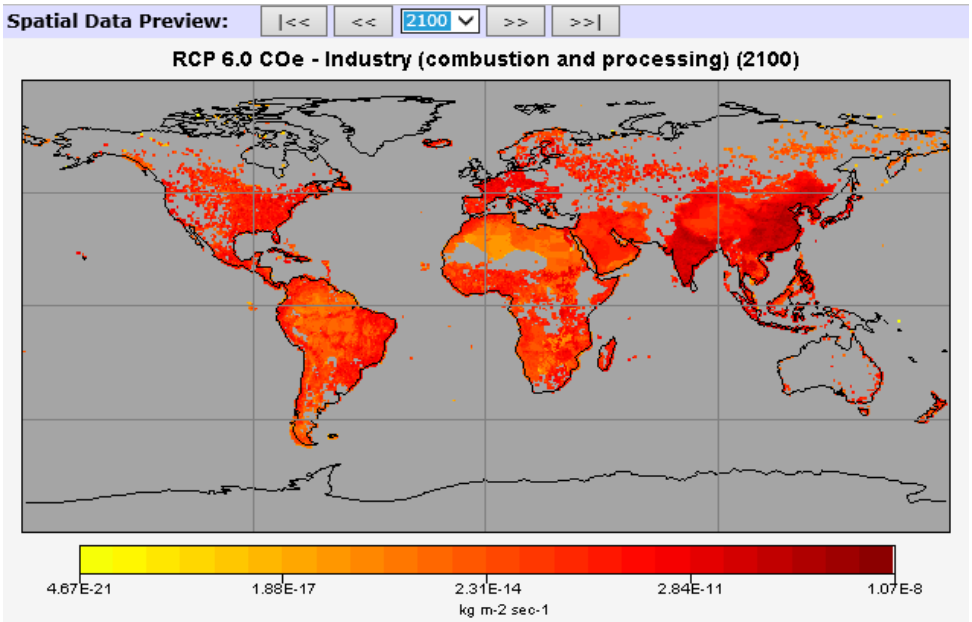


***Figure 4**: …and here's the comparison graphic showing the projected RCP6 emissions in the year 2100.*

By using the all the data available for the intervening years, a trajectory can be given for any specific emissions. Each RCP plots a different emissions trajectory (pathway) and cumulative emission concentration in 2100.

The deliverable is a download from a central repository. Scientists can preview and download data on emissions, concentrations, radiative forcing and land use, in regional and gridded form, following different trajectories over similar timescales. These data sets can then be incorporated into any modelling exercise, providing consistent parameters for each emissions trajectory, and a consistent foundation for all climate modelling teams anywhere in the world. The database is also open to the public and can be accessed without charge using any browser: http://tntcat.iiasa.ac.at:8787/RcpDb/dsd?Action=htmlpage&page=welcome

# Part 2: Creating new scenarios

> **"New sets of scenarios for climate change research are needed periodically to take into account scientific advances in understanding of the climate system as well as to incorporate updated data on recent historical emissions, climate change mitigation, and impacts, adaptation, and vulnerability".**
>
> *Source: IPCC Scenario Process For AR5*

Science always seeks to improve its knowledge, its skills, its tools and methods. As scientists make new discoveries, these have to be incorporated in the scenarios they use. Computers improve at tremendous rates, so models that would have been impossible to run 20 years ago are now not only feasible, but desirable. Scientists and decision makers investigating climate change want faster results, more resolution, more detail, better validation and easier data exchange between related and disparate lines of research. These demands inform an on-going requirement to improve the scenarios.

Scenarios don't just contain reference data; they also specify a *process*. The previous IPCC scenarios like SRES were run in sequence (see graphic below). This resulted in protracted development and delivery times. According to the IPCC: *"Lags in the development process meant that it was often many years until climate and socioeconomic scenarios were available for use in studies of impacts, adaptation, and vulnerability"*.

Not only that, but changes to prior processes in a sequential model meant going back and re-running the simulation in order to incorporate the new or changed data.

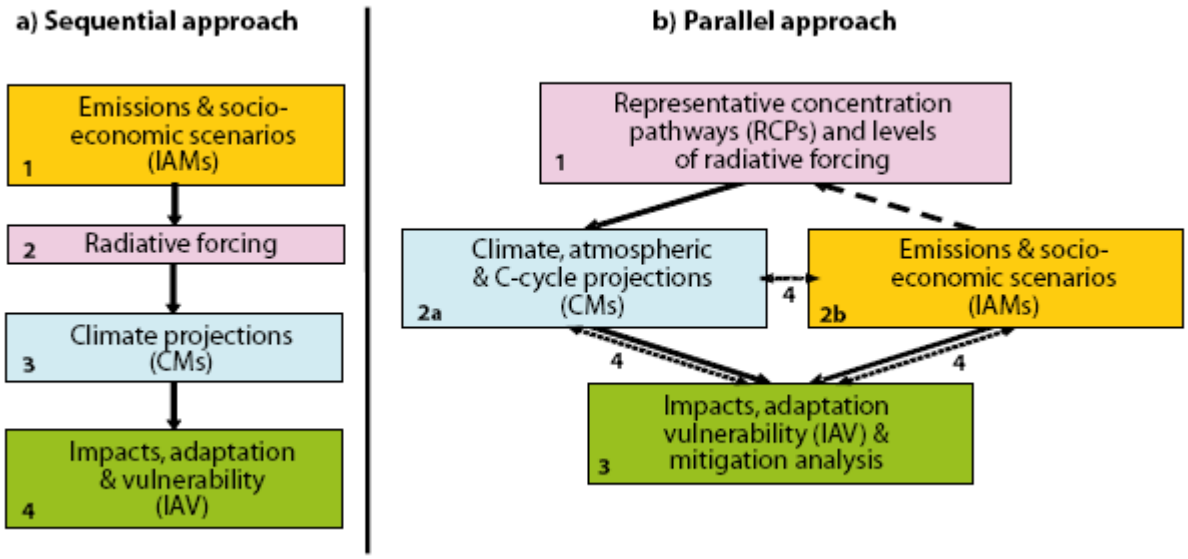


***Figure 5. Approaches to the development of global scenarios**: (a) previous sequential approach; (b) proposed parallel approach. Numbers indicate analytical steps (2a and 2b proceed concurrently). Arrows indicate transfers of information (solid), selection of RCPs (dashed), and integration of information and feedbacks (dotted). Source: Moss et al. (2008).*

The new Representative Concentration Pathways employ a process intended to make the modelling less time-consuming, more flexible, with a reduced economic cost of computation:

> "In the new process… emissions and socioeconomic scenarios are developed in parallel, building on different trajectories of radiative forcing over time…Rather than starting with detailed socio-economic storylines to generate emissions and then climate scenarios, the new process begins with a limited number of alternative pathways (trajectories over time) of radiative forcing levels (or CO2-equivalent concentrations) that are both representative of the emissions scenario literature and span a wide space of resulting greenhouse gas concentrations that lead to clearly distinguishable climate futures.
>
> "These radiative forcing trajectories were thus termed "Representative Concentration Pathways" (RCPs). The RCPs are not associated with unique socioeconomic assumptions or emissions scenarios but can result from different combinations of economic, technological, demographic, policy, and institutional futures".
>
> *(Source: IPCC Scenario Process for AR5)*

## Design Criteria

Four design criteria were agreed for the RCPs, as described in Moss et.al. 2008 and quoted here from van Vuuren 2011:

1. The RCPs should be based on scenarios published in the existing literature, developed independently by different modeling groups and, as a set, be 'representative' of the total literature, in terms of emissions and concentrations (see further in this section); At the same time, each of the RCPs should provide a plausible and internally consistent description of the future;
2. The RCPs should provide information on all components of radiative forcing that are needed as input for climate modeling and atmospheric chemistry modeling (emissions of greenhouse gases, air pollutants and land use). Moreover, they should make such information available in a geographically explicit way;
3. The RCPs should have harmonized base year assumptions for emissions and land use and allow for a smooth transition between analyses of historical and future periods;
4. The RCPs should cover the time period up to 2100, but information also needs to be made available for the centuries thereafter.
5. 

## Working with the Stakeholders

Early in the process of developing new scenarios, the IPCC decided to act only as a catalyst for the process, inviting the research community to develop the scenarios. The subsequent RCP development process was led by the research community (the Integrated Assessment Model Consortium) at the request of the IPCC, but independent of them. A meeting was convened in September 2007 to discuss and agree the way forward:

> "The meeting brought together over 130 participants, including users of scenarios and representatives of the principal research communities involved in scenario development and application. The representatives of the scenario user community included officials from

national governments, including many participating in the United Nations Framework Convention on Climate Change (UNFCCC), international organizations, multilateral lending institutions, and nongovernmental organizations (NGOs). The principal research communities represented at the expert meeting were the integrated assessment modeling (IAM) community; the impacts, adaptation, and vulnerability (IAV) community; and the climate modeling (CM) community. Because of this broad participation, the meeting provided an opportunity for the segments of the research community involved in scenario development and application to discuss their respective requirements and coordinate the planning process".

*Source: IPCC Expert Meeting Report*

The four IAM groups responsible for the four published scenarios that were selected as "predecessors" of the RCPs, generated the basic data sets from which the final RCPs were developed.

Over the following two years, a unique collaborative effort between integrated assessment modellers, climate modellers, terrestrial ecosystem modellers and emission inventory experts led to the agreement and specification of the four Representative Concentration Pathways (RCPs).

## Improvements over SRES

Perhaps the most innovative aspect of the RCPs is that instead of starting with socio-economic 'storylines' from which emission trajectories and climate impacts are projected (the SRES methodology), RCPs each describe an emission trajectory and concentration by the year 2100, and consequent forcing. Each trajectory represents a specific synthesis drawn from the published literature. From this 'baseline', researchers can then test various permutations of social, technical and economic circumstances. These permutations are called **'narratives'**, equivalent to the **'storylines'** employed in SRES.

"As stand alone products, the RCPs have limited usefulness to other research communities. First and foremost, they were selected with the sole purpose of providing data to climate models, taking into consideration the limitations in climate models differentiating levels of radiative forcing. They lack associated socioeconomic and ecological data. They were developed using idealized assumptions about policy instruments and the timing of participation by the international community.

"Therefore, there is a need to develop socioeconomic and climate impact scenarios that draw on the RCPs and associated climate change projections in the scenario process. Referencing the RCP and climate change projections has two potential benefits; they would facilitate comparison across research results in the CM, IAM, and IAV communities, and facilitate use of new climate modeling results in conjunction with IAV research.

"The *parallel phase* has several components. Within CMIP5, CM teams are using the RCPs as an input for model ensemble projections of future climate change. These projections will form the backbone of the IPCC's Working Group I assessment of future climate change in the 5th Assessment Report (AR5). The IAM community has begun exploring new socioeconomic scenarios and producing so-called RCP replications that study the range of socioeconomic scenarios leading to the various RCP radiative forcing levels. In the

meantime, IAV analyses based on existing emission scenarios (SRES) and climate projections (CMIP3) continue.

"In the *integration phase*, consistent climate and socioeconomic scenarios will inform IAM and IAV studies. For example, IAV researchers can use the new scenarios to project impacts, to explore the extent to which adaptation and mitigation could reduce projected impacts, and to estimate the costs of action and inaction. Also, mitigation researchers can use the global scenarios as "boundary conditions" to assess the cost and effectiveness of local mitigation measures, such as land-use planning in cities or changes in regional energy systems.

"These scenarios need to supply quantitative and qualitative narrative descriptions of potential socioeconomic and ecosystem reference conditions that underlie challenges to mitigation and adaptation. And they have to be flexible enough to provide a framework for comparison within which regional or local studies of adaptation and vulnerability could build their own narratives. The defining socioeconomic conditions of these scenarios have been designated **Shared Socioeconomic reference Pathways (SSPs)**."

*Source: A framework for a new generation of socioeconomic scenarios for climate change impact, adaptation, vulnerability, and mitigation research; Arnell, Kram, Carter et.al.*

For the first time, policy decisions can be tested; previous scenarios were describes as 'no-policy', meaning the scenarios did not respond to changes driven by political or legislative inputs, so mitigation or adaptation strategies could not be incorporated.

The principle difference in approach is that previously, SRES specified the socio-economic circumstances for each scenario, which essentially 'locked in' the options for socio-economic change (and led to a proliferation of SRES scenarios - 40 in total, each a slightly different variation on common socio-economic variables). Models were programmed to generate emissions and subsequent climate scenarios. The socio-economic variables of the SRES scenarios were socially and policy-proscriptive, inflexible in a way emissions and climate change outcomes were not.

By fixing the emissions trajectory and the warming, RCPs come at the problem the other way round. Socio-economic options become flexible and can be altered at will, allowing considerably more realism by incorporating political and economic flexibility at regional scales. Policy decisions on mitigation and adaptation can be tested for economic efficacy, both short and long term. Researchers can test various socio-economic measures against the fixed rates of warming built into the RCPs, to see which combinations of mitigation or adaptation produce the most timely return on investment and the most cost-effective response.

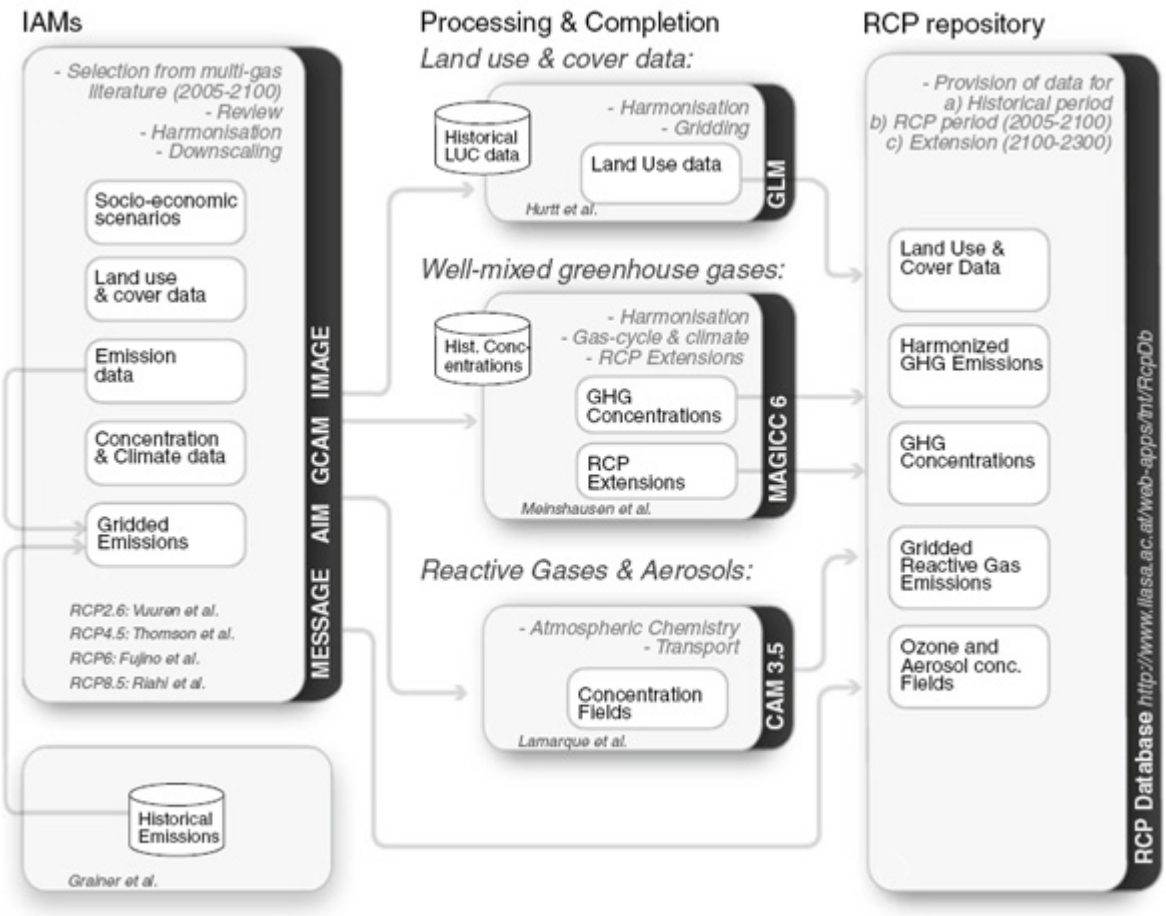


***Figure 6: Overview of the RCP development process**, adapted from van Vuuren et.al. 2011*

## Development Aims and Products

There were five end-products expected from development process:

**1. Four Representative concentration pathways (RCPs)**. Four RCPs…produced from IAM scenarios available in the published literature: one high pathway for which radiative forcing reaches >8.5 W/m2 by 2100 and continues to rise for some amount of time; two intermediate "stabilization pathways" in which radiative forcing is stabilized at approximately 6 W/m2 and 4.5 W/m2 after 2100; and one pathway where radiative forcing peaks at approximately 3 W/m2 before 2100 and then declines. These scenarios include time paths for emissions and concentrations of the full suite of GHGs and aerosols and chemically active gases, as well as land use/land cover…

**2. RCP-based climate model ensembles and pattern scaling**. Ensembles of gridded, time-dependent projections of climate change produced by multiple climate models including atmosphere–ocean general circulation models (AOGCMs), Earth system models (ESMs), Earth system models of intermediate complexity, and regional climate models will be prepared for the four long-term RCPs, and high-resolution, near-term projections to 2035 for the 4.5 W/m2 stabilization RCP only.

**3. New IAM scenarios**. New scenarios will be developed by the IAM research community in consultation with the IAV community exploring a wide range of dimensions associated with anthropogenic climate forcing…Anticipated outputs include alternative socioeconomic driving

forces, alternative technology development regimes, alternative realizations of Earth system science research, alternative stabilization scenarios including traditional "not exceeding" scenarios, "overshoot" scenarios, and representations of regionally heterogeneous mitigation policies and measures, as well as local and regional socioeconomic trends and policies…

**4. Global narrative storylines**. These are detailed descriptions associated with the four RCPs produced in the preparatory phase and such pathways developed as part of Product 3 by the IAM and IAV communities. These global and large-region storylines should be able to inform IAV and other researchers.

**5. Integrated scenarios**. RCP-based climate model ensembles and pattern scaling (Product 2) will be associated with combinations of new IAM scenario pathways (Product 3) to create combinations of ensembles. These scenarios will be available for use in new IAV assessments. In addition, IAM research will begin to incorporate IAV results, models, and feedbacks to produce comprehensively synthesized reference.

*(End-product definitions excerpted from the IPCC report "Towards New Scenarios...")*

## Beyond 2100 - Extended Concentration Pathways (ECP)

During the consultation phase, modelling communities made clear their interest in exploring longer-term processes. To facilitate these investigations, a single extension was developed for each RCP, extending the scenarios up to the year 2300. These data form the Extended Concentration Pathways (ECPs).

Since socio-economic factors cannot be predicted reliably over long timescales, the ECPs were developed using simple rules to extend GHG concentrations, emissions and land-use data series. The ECPs are intended only as the basis for long-term climate simulations.

A supplemental RCP called SCP6to4.5 was also developed with a peak at 2100, followed by a decline, to facilitate specific investigations into physical asymmetries and reversibility of climate, carbon cycle, and biophysical impacts systems (e.g. ecosystems, sea level rise).

| Parameter | ECP | Generic rule |
|---|---|---|
| **$CO_2$ and other well-mixed GHGs** | ECP8.5 | Follow stylized emission trajectory that leads to stabilization at 12 $W/m^2$ |
| | ECP6<br>ECP4.5 | Stabilize concentrations in 2150 (around 6.0 $W/m^2$)<br>Stabilize concentrations in 2150 (around 4.5 $W/m^2$) |
| | ECP3PD | Keep emissions constant at 2100 level |
| | SCP6to4.5 | Return radiative forcing of all gases from RCP6.0 to RCP4.5 levels by 2250 |
| **Reactive gases** | All ECPs | Keep constant at 2100 level |
| | SCP6to4.5 | Scale forcing of reactive gases with GHG forcing |
| **Land use** | All ECPs | Keep constant at 2100 level |

***Table 1: Basic rules for deriving extended concentration pathways*** *(van Vuuren et.al. 2011)*

# Part 3: RCP technical summary

This section contains a summary of the key metrics and assumptions that define the RCP architecture: emissions trajectories and concentrations, energy use, population, air pollutants and land use, and the consequent radiative forcing and temperature anomalies specified by each of the four RCP pathways.

The data employed in the development of the RCPs is drawn from the published literature. Each RCP was developed by an Integrated Assessment Modeling (IAM) group, whose published scenario papers were consistent with the base criteria for a particular RCP. Each team then surveyed and created synthesis data sets from available representative studies, which were reviewed repeatedly by different stakeholders. The final agreed set of RCPs was published:

| Pathway | Paper | Model |
|---|---|---|
| RCP 2.6 | Van Vuuren et al. 2007a; van Vuuren et al. 2006 | IMAGE |
| RCP 4.5 | Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009 | GCAM |
| RCP6 | Fujino et al. 2006; Hijioka et al. 2008 | AIM |
| RCP8.5 | Riahi et al. 2007 | MESSAGE |

***Table 2: RCP-specific publications and model group responsible.***

For comprehensive discussions of development methodologies and complete technical information on any RCP, please see the further reading section at the end of this guide.

## An important note about socio-economic data

The underlying assumptions about socio-economic trajectories and priorities are not consistent between the RCPs. This quote from van Vuuren 2011 makes clear this point (emphasis added):

> "The RCPs were selected from the existing literature on the basis of their emissions and associated concentration levels. This implies that the socio-economic assumptions of the different modeling teams were based on individual model assumptions made within the context of the original publication, and that **there is no consistent design behind the position of the different RCPs relative to each other for these parameters.**
>
> Scenario development after the RCP phase will focus on developing a new set of socio-economic scenarios. Therefore, socio-economic parameters have not been included in the RCP information available for download. Still, this information does form part of the underlying individual scenario development, and thus provides useful information on internal logic and the plausibility of each of the individual RCPs".
>
> ***van Vuuren et. al, 2011***

**Socio-economic data does not form any part of the RCP database.** Please note that in this guide, as in van Vuuren 2011, the primary socio-economic characteristics are discussed here only in the context of the RCP development.

## RCP Primary Characteristics

**RCP 8.5** was developed using the MESSAGE model and the IIASA Integrated Assessment Framework by the International Institute for Applied Systems Analysis (IIASA), Austria. This RCP is characterized by increasing greenhouse gas emissions over time, representative of scenarios in the literature that lead to high greenhouse gas concentration levels (Riahi et al. 2007).

**RCP6** was developed by the AIM modeling team at the National Institute for Environmental Studies (NIES) in Japan. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshoot, by the application of a range of technologies and strategies for reducing greenhouse gas emissions (Fujino et al. 2006; Hijioka et al. 2008).

**RCP 4.5** was developed by the GCAM modeling team at the Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI) in the United States. It is a stabilization scenario in which total radiative forcing is stabilized shortly after 2100, without overshooting the long-run radiative forcing target level (Clarke et al. 2007; Smith and Wigley 2006; Wise et al. 2009).

**RCP2.6** was developed by the IMAGE modeling team of the PBL Netherlands Environmental Assessment Agency. The emission pathway is representative of scenarios in the literature that lead to very low greenhouse gas concentration levels. It is a "peak-and-decline" scenario; its radiative forcing level first reaches a value of around 3.1 W/m2 by mid-century, and returns to 2.6 W/m2 by 2100. In order to reach such radiative forcing levels, greenhouse gas emissions (and indirectly emissions of air pollutants) are reduced substantially, over time (Van Vuuren et al. 2007a). ***(Characteristics quoted from van Vuuren et.al. 2011)***

## RCP Information, Data Types and Resolutions

The following table shows the data types available for the RCPs, the sectors by which emissions are broken down, and the geographical resolution of the information:

| **Available information from RCPs and resolution** | | |
|---|---|---|
| | **Resolution (sectors)** | **Resolution (geographical)** |
| **Emissions of greenhouse gases** | | |
| $CO_2$ | Energy/industry, land | Global and for 5 regions |
| $CH_4$ | 12 sectors | 0.5°×0.5° grid |
| $N_2O$, HFCs, PFCs, CFCs, $SF_6$ | Sum | Global and for 5 regions |
| **Emissions aerosols and chemically active gases** | | |
| $SO_2$, Black Carbon, Organic Carbon, CO, $NO_x$, VOCs, $NH_3$ | 12 sectors | 0.5°×0.5° grid |
| Speciation of VOC emissions | | 0.5°×0.5° grid |
| **Concentration of greenhouse gases** | | |
| ($CO_2$, $CH_4$, $N_2O$, HFCs, PFCs, CFCs, $SF_6$) | | Global |
| **Concentrations of aerosols & chemically active gases** | | |
| ($O_3$, Aerosols, N deposition, S deposition) | | 0.5°×0.5° grid |
| Land-use/land-cover data | Cropland, pasture, primary vegetation, secondary vegetation, forests | 0.5°×0.5° grid with subgrid fractions, (annual maps and transition matrices including wood harvesting) |

***Table 3: from van Vuuren et.al. 2011***

## Emissions and concentrations, forcings and temperature anomalies

Each Representative Concentration Pathway (RCP) defines a specific emissions trajectory and subsequent radiative forcing (a radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, measured in watts per square metre):

| Name | Radiative forcing | $CO_2$ equiv (p.p.m.) | Temp anomaly (°C) | Pathway | SRES temp anomaly equiv |
|---|---|---|---|---|---|
| RCP8.5 | 8.5 $Wm^2$ in 2100 | 1370 | 4.9 | Rising | SRES A1F1 |
| RCP6.0 | 6 $Wm^2$ post 2100 | 850 | 3.0 | Stabilization without overshoot | SRES B2 |
| RCP4.5 | 4.5 $Wm^2$ post 2100 | 650 | 2.4 | Stabilization without overshoot | SRES B1 |
| RCP2.6 (RCP3PD) | 3$Wm^2$ before 2100, declining to 2.6 $Wm^2$ by 2100 | 490 | 1.5 | Peak and decline | None |

***Table 4: from Moss et.al. 2010.*** *Median temperature anomaly over pre-industrial levels and SRES comparisons based on nearest temperature anomaly, from Rogelj et.al. 2012*

## Radiative Forcings

The graph below shows radiative forcing trajectories for the four RCPs, the other candidate scenarios that informed the final versions, and the modelling group associated with each.

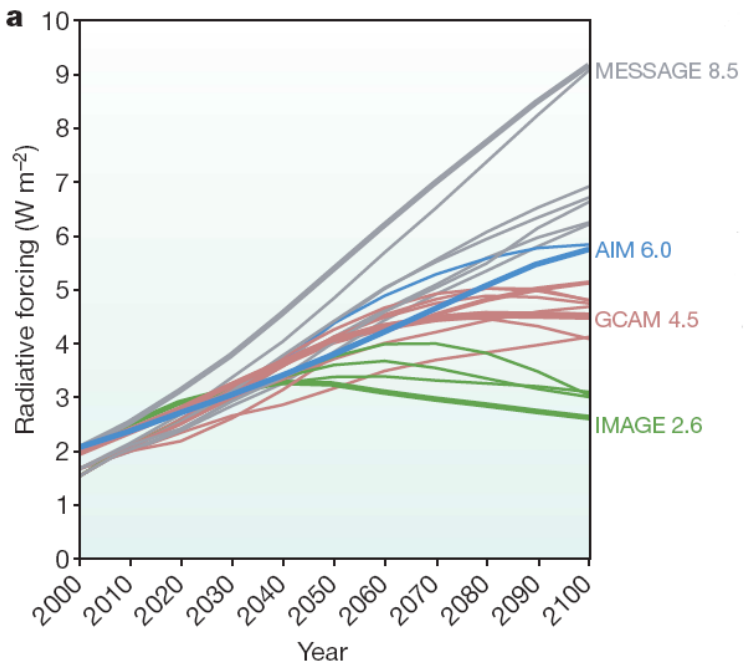


***Figure 7: Changes in radiative forcing relative to pre-industrial conditions.*** *Bold coloured lines show the four RCPs; thin lines show individual scenarios from approximately 30 candidate RCP scenarios that provide information on all key factors affecting radiative forcing… (Moss et.al., 2010)*

The forcing trajectories are consistent with socio-economic projections unique to each RCP. For example, RCP2.6 (RCP3PD) assumes that through drastic policy intervention, greenhouse gas emissions are reduced almost immediately, leading to a slight reduction on today's levels by 2100. The worst case scenario - RCP8.5 - assumes more or less unabated emissions.

## RCP Emission Trajectories

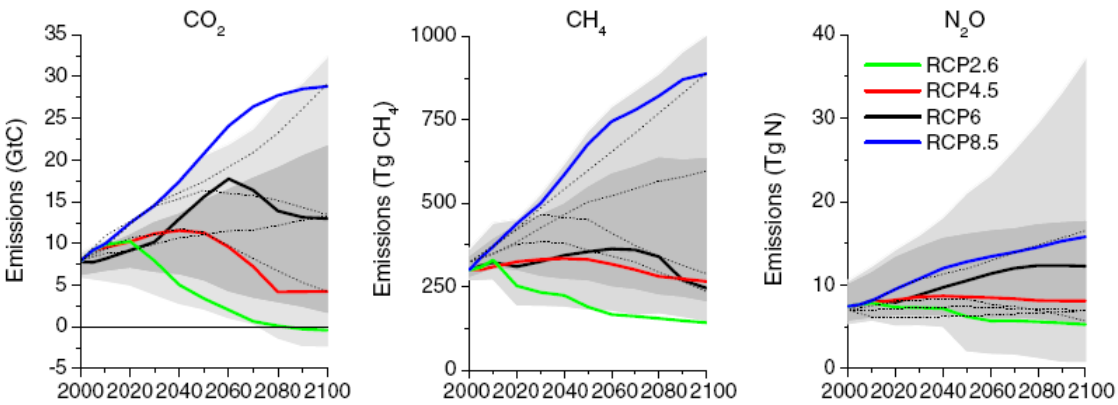


***Figure 8: Emissions of main greenhouse gases across the RCPs.*** *Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature…The dotted lines indicate four of the SRES marker scenarios. Note that the literature values are not harmonized (from van Vuuren et.al. 2011)*

"The CO2 emissions of the four RCPs correspond well with the literature range, which was part of their selection criterion (Fig. 8). The RCP8.5 is representative of the high range of non-climate policy scenarios. Most non-climate policy scenarios, in fact, predict emissions of the order of 15 to 20 GtC by the end of the century, which is close to the emission level of the RCP6. The forcing pathway of the RCP4.5 scenario is comparable to a number of climate policy scenarios and several low-emissions reference scenarios in the literature, such as the SRES B1 scenario. The RCP2.6 represents the range of lowest scenarios, which requires stringent climate policies to limit emissions.

"The trends in CH4 and N2O emissions are largely due to differences in the assumed climate policy along with differences in model assumptions (Fig. 8). Emissions of both CH4 and N2O show a rapidly increasing trend for the RCP8.5 (no climate policy and high population). For RCP6 and RCP4.5, CH4 emissions are more-or-less stable throughout the century, while for RCP2.6, these emissions are reduced by around 40%. The low emission trajectories for CH4 are a net result of low cost emission options for some sources (e.g. from energy production and transport), and a limited reduction for others (e.g. from livestock)" ***(van Vuuren et.al. 2011)***

## Greenhouse Gas Concentrations

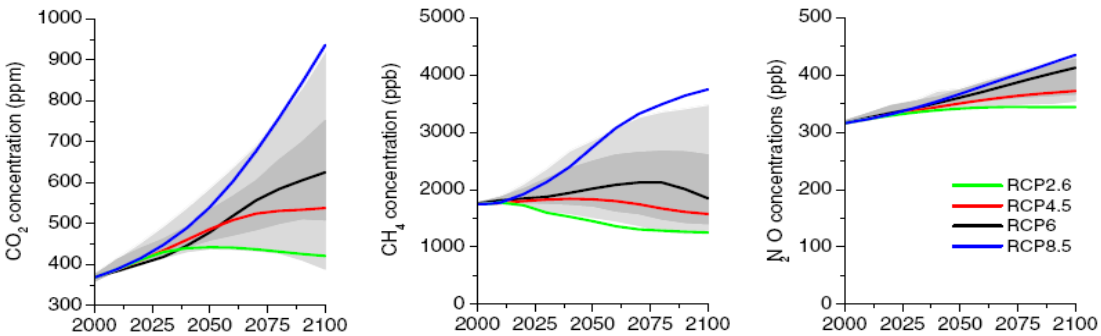


***Figure 9: Trends in concentrations of greenhouse gases (van Vuuren 2011)****. Grey area indicates the 98th and 90th percentiles (light/dark grey) of the recent EMF-22 study (Clarke et al. 2010)*

"The greenhouse gas concentrations in the RCPs closely correspond to the emissions trends discussed earlier . For CO2, RCP8.5 follows the upper range in the literature (rapidly increasing

concentrations). RCP6 and RCP4.5 show a stabilizing CO2 concentration (close to the median range in the literature). Finally, RCP2.6 has a peak in CO2 concentrations around 2050, followed by a modest decline to around 400 ppm CO2, by the end of the century. For CH4 and N2O, the order in which the RCPs can be placed are also a direct result of the assumed level of climate policy. The trends in CH4 concentrations are more pronounced, as a result of the relatively short lifetime of CH4. Emission reductions, as in the RCP2.6 and RCP4.5, therefore, may lead to an emission peak much earlier in the century. For N2O, in contrast, a relatively long lifetime and a modest reduction potential imply an increase in concentrations, in all RCPs. For both CH4 and N2O, the concentration levels correspond well with the range in the literature. Further information on the calculations of concentration can be found in Meinshausen et al. (2011b)*" **(van Vuuren et.al. 2011).***

## Atmospheric Air Pollutants

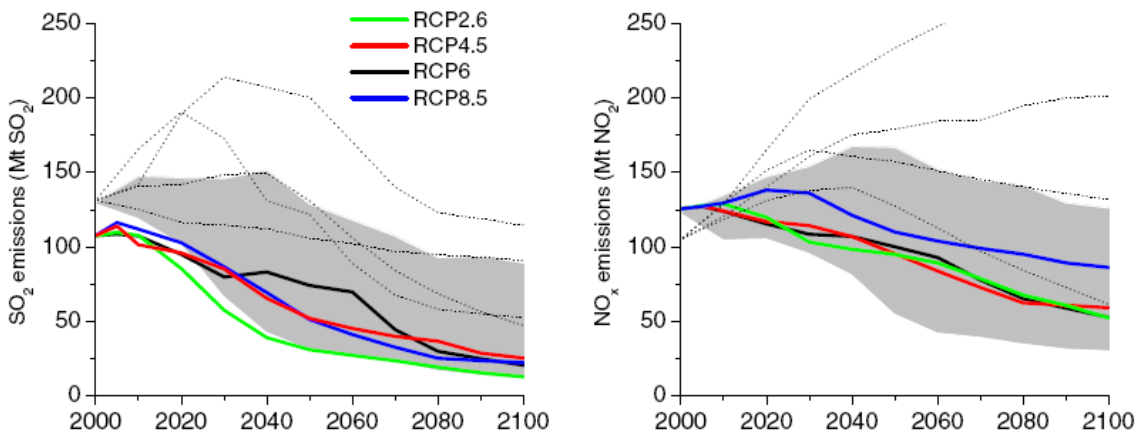


***Figure 10: Emissions of $SO_2$ and $NO_X$ across the RCPs**. Grey area indicates the 90th percentile of the literature (only scenarios included in Van Vuuren et al. 2008b, i.e. 22 scenarios; the scenarios were also harmonized for their starting year—but using a different inventory). Dotted lines indicate SRES scenarios. The different studies use slightly different data for the start year. (van Vuuren et.al. 2011)*

"The RCPs generally exhibit a declining trend of air polluting emissions. The emission trends for air pollutants are determined by three factors: the change in driving forces (fossil- fuel use, fertilizer use), the assumed air pollution control policy, and the assumed climate policy (as the last induces changes in energy consumption leading to changes (generally reductions) in air polluting emissions). We have illustrated the trends in air pollutants by looking at SO2 and NOx (Fig. 10). In general, similar trends can be seen for other air pollutants.

"All RCPs include the assumption that air pollution control becomes more stringent, over time, as a result of rising income levels. Globally, this would cause emissions to decrease, over time—although trends can be different for specific regions or at particular moments in time. A second factor that influences the results across the RCPs is climate policy. In general, the lowest emissions are found for the scenario with the most stringent climate policy (RCP2.6) and the highest for the scenario without climate policy (RCP8.5), although this does not apply to all regions, at all times". ***(van Vuuren et.al. 2011).***

## Radiative Forcing Trends

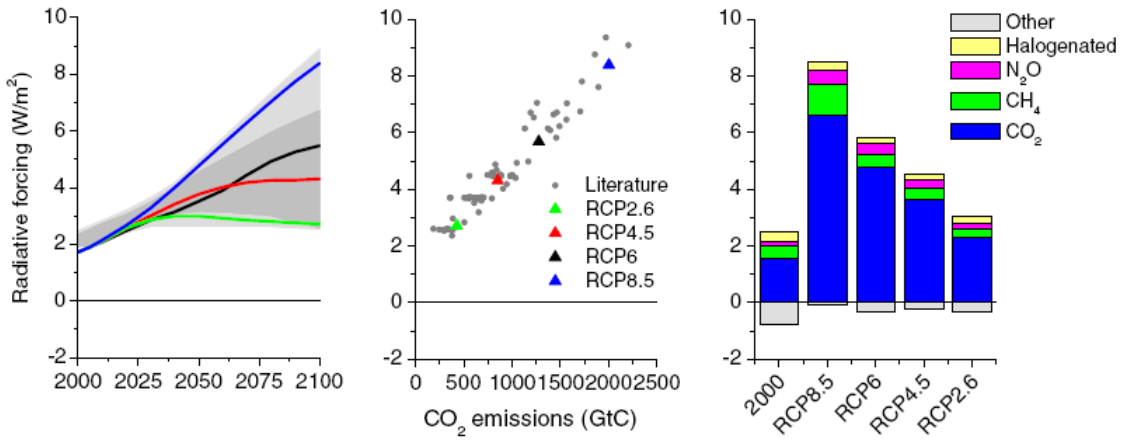


***Figure 11: Trends in radiative forcing (left), cumulative 21st centuryCO2 emissions vs 2100 radiative forcing (middle) and 2100 forcing level per category (right).*** *Grey area indicates the 98th and 90th percentiles (light/dark grey) of the literature. The dots in the middle graph also represent a large number of studies. Forcing is relative to pre-industrial values and does not include land use (albedo), dust, or nitrate aerosol forcing (van Vuuren 2011).*

## Population and GDP

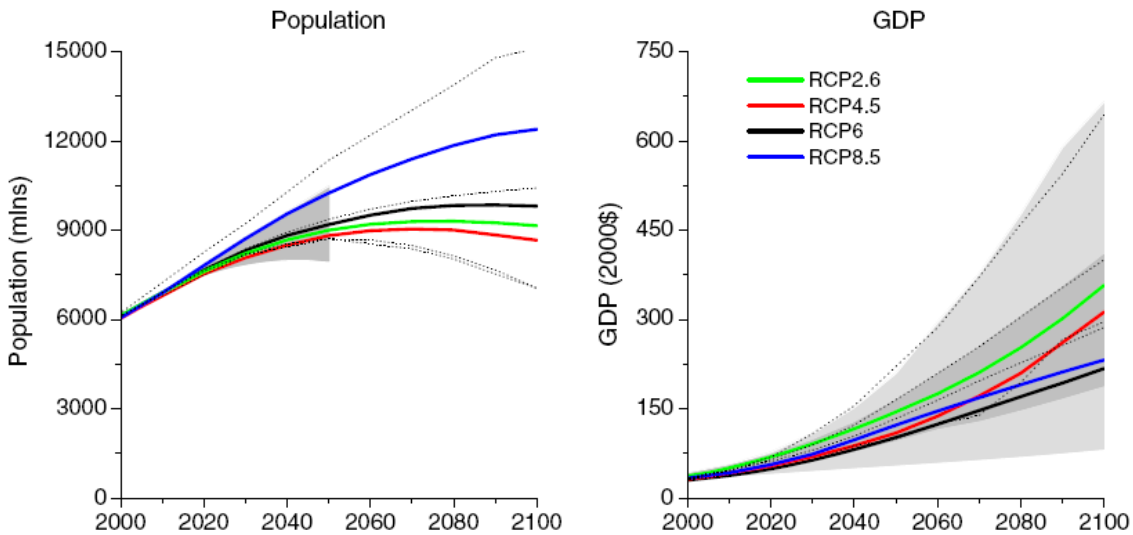


***Figure 12: Population and GDP projections of the four scenarios underlying the RCPs (van Vuuren et.al. 2011).*** *Grey area for population indicates the range of the UN scenarios (low and high) (UN 2003). Grey area for income indicates the 98th and 90th percentiles (light/dark grey) of the IPCC AR4 database (Hanaoka et al. 2006). The dotted lines indicate four of the SRES marker scenarios*

"The population and GDP pathways underlying the four RCPs are shown in Fig. 12. The figure also shows, as reference, the UN population projections and the 90th percentile range of GDP scenarios in the literature on greenhouse gas emission scenarios. Figure 12 shows the RCPs to be consistent with these two references. It should be noted that, with one exception (RCP8.5), the modeling teams deliberately made intermediate assumptions about the main driving forces (as illustrated by their position in Fig. 12)…In contrast, the RCP8.5 was based on a revised version of the SRES A2 scenario; here, the storyline emphasizes high population growth and lower incomes in developing countries". ***(van Vuuren et.al. 2011).***

## Energy and oil consumption

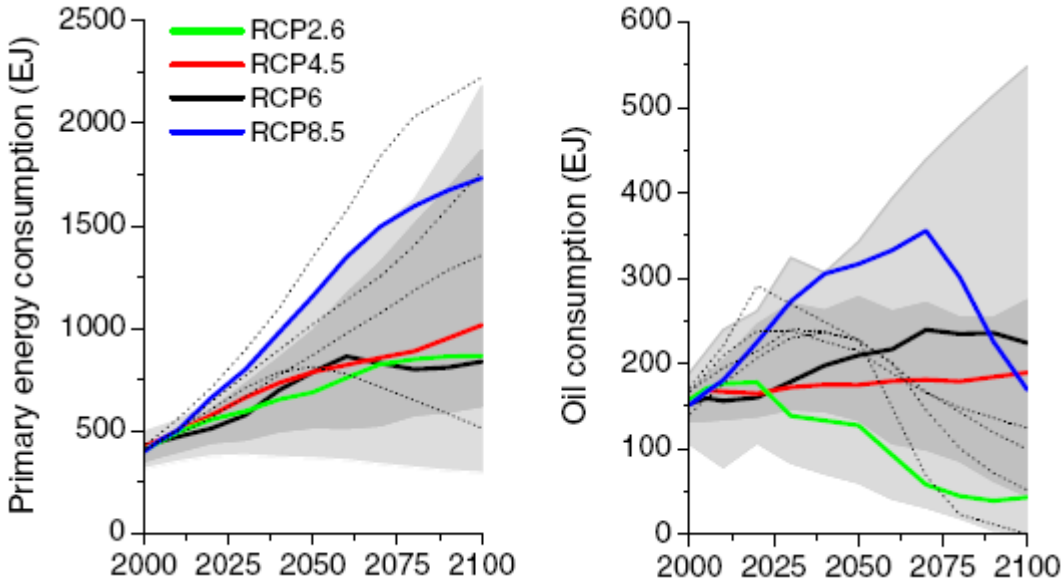


***Figure 13: Development of primary energy consumption (direct equivalent) and oil consumption for the different RCPs (van Vuuren et.al. 2011).*** *The grey area indicates the 98th and 90th percentiles (light/dark grey) (AR4 database (Hanaoka et al. 2006) and more recent literature (Clarke et al. 2010; Edenhofer et al. 2010). The dotted lines indicate four of the SRES marker scenarios*

"For energy use, the scenarios underlying the RCPs are consistent with the literature— with the RCP2.6, RCP4.5 and RCP6 again being representative of intermediate scenarios in the literature (resulting in a primary energy use of 750 to 900 EJ in 2100, or about double the level of today). The RCP8.5, in contrast, is a highly energy-intensive scenario as a result of high population growth and a lower rate of technology development". ***(van Vuuren et.al. 2011).***

## Energy sources at years 2000 and 2100

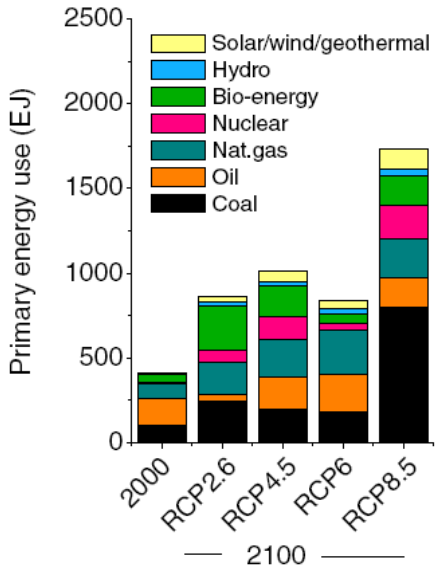


***Figure 14: Energy sources by sector (van Vuuren et.al. 2011)***

"In terms of the mix of energy carriers, there is a clear distinction across the RCPs given the influence of the climate target. Total fossil- fuel use basically follows the radiative forcing level of the scenarios; however, due to the use of carbon capture and storage (CCS) technologies (in particular in the power sector), all scenarios, by 2100, still use a greater amount of coal and/or natural gas than in the year 2000. The use of oil stays fairly constant in most scenarios, but declines in the RCP2.6 (as a result of depletion and climate policy).

The use of non-fossil fuels increases in all scenarios, especially renewable resources (e.g. wind, solar), bio-energy and nuclear power. The main driving forces are increasing energy demand, rising fossil-fuel prices and climate policy. An important element of the RCP2.6 is the use of bio-energy and CCS, resulting in negative emissions (and allowing some fossil fuel without CCS by the end of the century)". ***(van Vuuren et.al. 2011).***

## Land Use

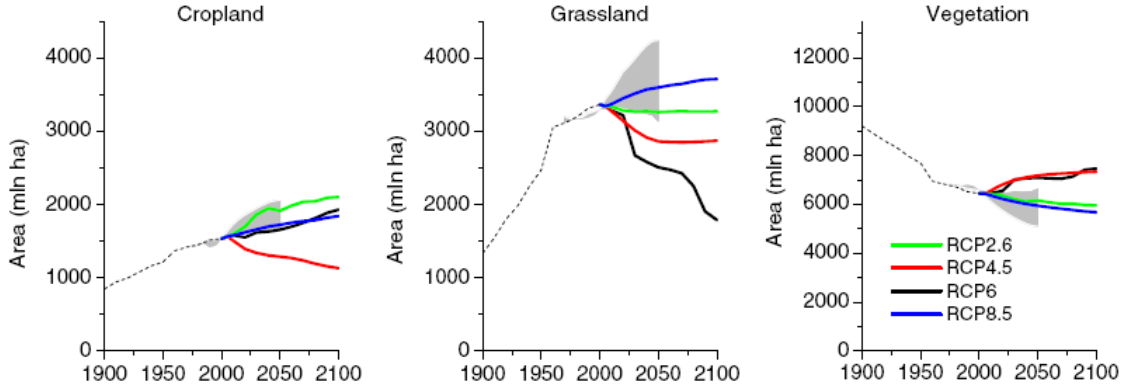


***Figure 15: Land use (crop land and use of grass land) across the RCPs.*** *Grey area indicates the 90th percentile of scenarios reported in the literature (taken from Smith et al. 2010). Vegetation is defined as the part not covered by cropland or anthropogenically used grassland. (van Vuuren et.al. 2011)*

"A crucial element of the new scenarios is land use. Land use influences the climate system in many different ways including direct emissions from land-use change, hydrological impacts, biogeophysical impacts (such as changes in albedo and surface roughness), and the size of the remaining vegetation stock (influencing CO2 removal from the atmosphere). Historically, cropland and anthropogenic use of grassland have both been increasing, driven by rising population and changing dietary patterns. There are far fewer land-use scenarios published in the literature than emission or energy-use scenarios. Moreover, far less experience exists with scenario projections (Rose et al. 2011; Smith et al. 2010). Most projections focus on a shorter time period (up to 2030 or 2050) and show an increasing demand for cropland and pasture.

"The limited experience in global land-use modeling as part of integrated assessment work is also reflected in the RCP development process. Compared to emission modeling, definitions of relevant variables and base year data differ more greatly across the IAMs for the land use components.

"The RCPs cover a very wide-range of land-use scenario projections. This is illustrated by the trends shown in Fig. 15 (i.e. after harmonization). The use of cropland and grasslands increases in RCP8.5, mostly driven by an increasing global population. Cropland also increases in the RCP2.6, but largely as a result of bio-energy production. The use of grassland is more-or-less constant in the RCP2.6, as the increase in production of animal products is met through a shift from extensive to more intensive animal husbandry. The RCP6 shows an increasing use of cropland but a decline in pasture. This decline is caused by a similar trend as noted for RCP2.6, but with a much stronger implementation. Finally, the RCP4.5 shows a clear turning point in global land use based on the assumption that carbon in natural vegetation will be valued as part of global climate policy. As a result of reforestation programs, the use of cropland and grassland decreases, following considerable yield increases and dietary changes". ***(van Vuuren et.al. 2011).***

## Comparisons with SRES equivalents

| Main similarities and differences between temperature projections for SRES scenarios and RCPs. | | |
|---|---|---|
| **RCP** | **SRES scenario with similar median temp increase by 2100** | **Particular differences** |
| RCP3PD | None | The ratio between temperature increase and net radiative forcing in 2100 is 0:88 $C(Wm^{-2})^{-1}$ for RCP3-PD, whereas all other scenarios show a ratio of about 0:62 $C(Wm^{-2})^{-1}$; that is, RCP3-PD is closer to equilibrium in 2100 than the other scenarios. |
| RCP4.5 | SRES B1 | Median temperatures in RCP4.5 rise faster than in SRES B1 until mid-century, and slower afterwards. |
| RCP6 | SRES B2 | Median temperatures in RCP6 rise faster than in SRES B2 during the three decades between 2060 and 2090, and slower during other periods of the twenty-first century. |
| RCP8.5 | SRES A1FI | Median temperatures in RCP8.5 rise slower than in SRES A1FI during the period between 2035 and 2080, and faster during other periods of the twenty-first century. |

***Table 5: From Rogelj et.al. 2012***

## Extended Concentration Pathway Emissions and Forcing

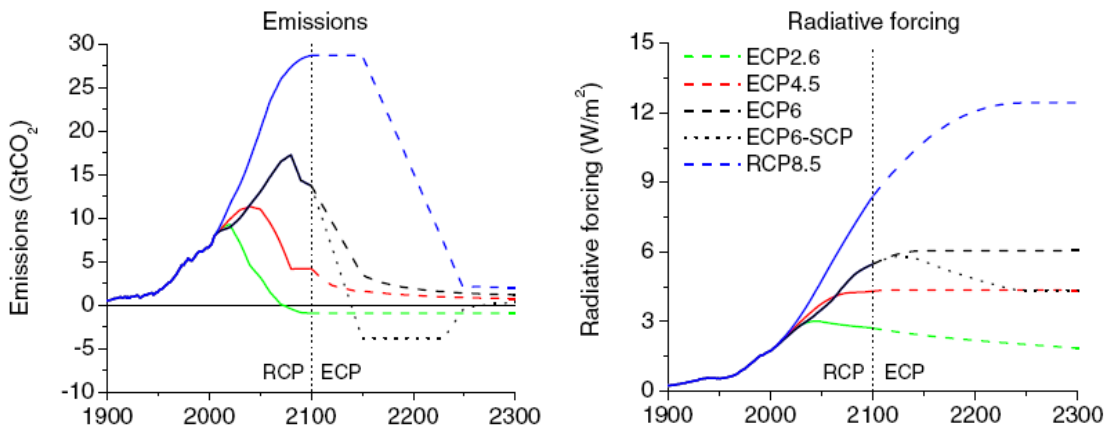


***Figure 16: Extension of the RCPs (radiative forcing and associated CO2 emissions) from van Vuuren 2011.*** *(ECP is Extended Concentration Pathway). The SCP6to4.5 (supplementary concentration pathway) shows an alternative extension for RCP6…(Meinshausen et al. 2011b)*

Figure 16 shows the CO2 emissions and radiative forcing trajectories for each of the four extensions of the RCPs (ECPs). These extensions have not been based on integrated assessment modeling, but on simple extension rules consistent with the rationale of each of the RCPs to which they connect. This has resulted in a set of extended concentration pathways to be used for climate model runs.

# Further Reading

## Summary Publications

**Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies**, IPCC Expert Meeting Report, 19–21 September, 2007

**The representative concentration pathways**: an overview, van Vuuren et. al 2011, Climatic Change (2011) 109:5–31, DOI 10.1007/s10584-011-0148-z

**The next generation of scenarios for climate change research and assessment**, Moss et.al. 2010, Nature, doi:10.1038/nature08823

**Global warming under old and new scenarios using IPCC climate sensitivity range estimates**, Rogelj, Meinshausen and Knutti 2012, Nature Climate Change, DOI: 10.1038/NCLIMATE1385

**IPCC Data Distribution Centre on-line documentation of the scenario process, including documentation of narrative development and usage**: http://sedac.ipcc-data.org/ddc/ar5_scenario_process/index.html

## RCP8.5 specific papers (MESSAGE):

**Scenarios of long-term socio-economic and environmental development under climate stabilization.** Riahi K, Grübler A, Nakicenovic N (2007) Technol Forecast Soc Chang 74:887–935

**RCP-8.5: exploring the consequence of high emission trajectories.** Riahi K, Krey V, Rao S, Chirkov V, Fischer G, Kolp P, Kindermann G, Nakicenovic N, Rafai P (2011) Climatic Change. doi: 10.1007/s10584-011-0149-y

## RCP 6 specific papers (AIM):

**Multigas mitigation analysis on stabilization scenarios using aim global model.** Fujino J, Nair R, Kainuma M, Masui T, Matsuoka Y (2006) The Energy Journal Special issue #3:343–354

**A emission pathway to stabilize at 6 W/m2 of radiative forcing.** Masui T, Matsumoto K, Hijioka Y, Kinoshita T, Nozawa T, Ishiwatari S, Kato E, Shukla PR, Yamagata Y, Kainuma M (2011) Climatic Change. doi: 10.1007/s10584-011-0150-5

**Global GHG emission scenarios under GHG concentration stabilization targets.** Hijioka Y, Matsuoka Y, Nishimoto H, Masui T, Kainuma M (2008) J Glob Environ Eng 13:97–108

## RCP 4.5 specific papers (GCAM):

**RCP4.5: a pathway for stabilization of radiative forcing by 2100.** Thomson AM, Calvin KV, Smith SJ, Kyle GP, Volke A, Patel P, Delgado-Arias S, Bond-Lamberty B, Wise MA, Clarke LE et al (2011) Climatic Change. doi: 10.1007/s10584-011-0151-4

**Scenarios of greenhouse gas emissions and atmospheric concentrations**. Clarke LE, Edmonds JA, Jacoby HD, Pitcher H, Reilly JM, Richels R (2007) Sub-report 2.1a of Synthesis and Assessment Product 2.1. Climate Change Science Program and the Subcommittee on Global Change Research, Washington DC

**MultiGas forcing stabilization with minicam.** Smith SJ, Wigley TML (2006) The Energy Journal Special issue #3:373–392

**Implications of limiting CO2 concentrations for land use and energy.** Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith SJ, Janetos A, Edmonds J, (2009) Science 324:1183-1186

## RCP 2.6 (RCP3-PD) specific papers (IMAGE):

**RCP2.6: Exploring the possibility to keep global mean temperature change below 2°C.** Van Vuuren DP, Stehfest E, Den Elzen MGJ, Deetman S, Hof A, Isaac M, Klein Goldewijk K, Kram T, Mendoza Beltran A, Oostenrijk R et al (2011a) Climatic Change. doi: 10.1007/s10584-011-0152-3

**Long-term multi-gas scenarios to stabilise radiative forcing—exploring costs and benefits within an integrated assessment framework.** Van Vuuren DP, Eickhout B, Lucas PL, den Elzen MGJ (2006) Energ J 27:201–233

**Stabilizing greenhouse gas concentrations at low levels: an assessment of reduction strategies and costs.** Van Vuuren DP, Den Elzen MGJ, Lucas PL, Eickhout B, Strengers BJ, Van Ruijven B, Wonink S, Van Houdt R (2007a) Clim Chang 81:119–159

## RCP Development papers:

**Evolution of anthropogenic and biomass burning emissions at global and regional scales during the 1980–2010 period.** Granier C, Bessagnet B, Bond T, D'Angiola A, van der Gon HG, Frost G, Heil A, Kainuma M, Kaiser J, Kinne S et al (2011) Climatic Change. doi: 10.1007/s10584-011-0154-1. (An assessment of a range of historical emissions data as context for the harmonized emissions used as a common starting point for the future trajectories of the RCPs.)

**Global and regional evolution of short-lived radiatively-active gases and aerosols in the Representative Concentration Pathways.** Lamarque JF, Page Kyle G, Meinshausen M, Riahi K, Smith S, van Vuuren DP, Conley AJ, Vitt F (2011) Climatic change. doi: 10.1007/s10584-011-0155-0. (Describes how information on air pollutant emissions was used for deriving future concentration and forcing scenarios for aerosols and ozone).

**Land use Change and earth system dynamics.** Hurtt G, Chini L, Frolking S, Betts R, Edmonds J, Feddema J, Fisher G, Goldewijk KK, Hibbard KA, Houghton R et al (2011) Climatic Change. doi: 10.1007/s10584-011-0153-2. (The paper by Hurtt et al. (2011) is the first to harmonize land-use history data with future scenario data from multiple IAMs to form a single consistent, spatially gridded, set of scenarios on land-use change, to study human impacts on the past, present, and future Earth system).

**The RCP greenhouse gas concentrations and their extensions from 1765 to 2300.** Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque J-F, Matsumoto K, Montzka SA, Raper S, Riahi K et al (2011b) Climatic Change. doi: 10.1007/s10584-011-0156-z . (Describes how the IAM's emission projections of long-lived greenhouse gases were harmonized and used for calculating concentration trajectories for these gases, including the Extended Concentration Pathways (ECPs) from 2100 to 2300.

# Acknowledgements

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This guide quotes extensively from **The representative concentration pathways: an overview**, van Vuuren et. al. 2011, a special report first published by Climatic Change, and made available through Springerlink.com as an Open Access document, distributed under the terms of the Creative Commons Attribution Non-commercial License which permits any non-commercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

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**Written by Graham Wayne (http://gpwayne.wordpress.com) for Skeptical Science, August 2013.**
**PDF Cover artwork by John Cook.**