Climatic Change (2010) 103:635–642
DOI 10.1007/s10584-010-9940-4

LETTER

What do near-term observations tell us about long-term developments in greenhouse gas emissions?

A letter

Detlef P. van Vuuren · Jae Edmonds · Steven J. Smith · Kate V. Calvin · Joseph Karas · Mikiko Kainuma · Nebojsa Nakicenovic · Keywan Riahi · Bas J. van Ruijven · Rob Swart · Allison Thomson

Received: 29 July 2010 / Accepted: 1 October 2010 / Published online: 26 October 2010

Abstract Long-term scenarios developed by integrated assessment models are used in climate research to provide an indication of plausible long-term emissions of greenhouse gases and other radiatively active substances based on developments in the global energy system, land-use and the emissions associated with these systems. The phenomena that determine these long-term developments (several decades or even centuries) are very different than those that operate on a shorter time-scales (a few years). Nevertheless, in the literature, we still often find direct comparisons between short-term observations and long-term developments that do not take into

Electronic supplementary material The online version of this article (doi:10.1007/s10584-010-9940-4) contains supplementary material, which is available to authorized users.

D. P. van Vuuren (✉) · B. J. van Ruijven
Netherlands Environmental Assessment Agency, Postbus 303 3720 AH Bilthoven, The Netherlands
e-mail: detlef.vanvuuren@pbl.nl

J. Edmonds · S. J. Smith · K. V. Calvin · J. Karas · A. Thomson
Pacific Northwest National Laboratory, Joint Global Change Research Institute, College Park, MD 20740, USA

M. Kainuma
National Institute for Environmental Studies (NIES), 16-2, Onogawa, Tsukuba, Ibaraki, 305-8506, Japan

N. Nakicenovic · K. Riahi
International Institute for Applied System Analysis, Schlossplatz 1, 2361 Laxenburg, Austria

N. Nakicenovic
Vienna University of Technology, Gusshausstrasse 25-29/37320, 1040 Vienna, Austria

R. Swart
Wageningen University and Research Centre, Earth System Science and Climate Change Group, Droevendaalsesteeg 4, 6708 PB, Wageningen, The Netherlands

account the differing dynamics over these time scales. In this letter, we discuss some of the differences between the factors that operate in the short term and those that operate in the long term. We use long-term historical emissions trends to show that short-term observations are very poor indicators of long-term future emissions developments. Based on this, we conclude that the performance of long-term scenarios should be evaluated against the appropriate, corresponding long-term variables and trends. The research community may facilitate this by developing appropriate data sets and protocols that can be used to test the performance of long-term scenarios and the models that produce them.

1 Introduction

Climate change, with a timescale of centuries or more, casts a long shadow back to present decisions. The long-term character of the climate problem implies the need for analytical tools of commensurate time scales. As a consequence, tools have been developed to examine potential future developments over several decades (up to century scale) with and without climate policy intervention. These tools include both climate models and long-term models of human activities and associated greenhouse gas emissions. The nature of tools to examine global developments over decades or even centuries are different than the tools used to study phenomena with shorter time-scales of a few years. Long-term climate models are different from weather forecasting models. Similarly, integrated system models of long-term human activities are fundamentally different from quarterly economic forecast models.

The integrated system models of long-term human activities (generally called integrated assessment models or IAMs) have been used to develop scenarios to explore long-term trends in the global energy system and land-use patterns—specifically with respect to emissions of greenhouse gases and other air pollutants (Fisher et al. 2007; Moss et al. 2010; Nakicenovic et al. 2000).[1] For projections over such a long time horizon, uncertainties are a critical concern. To deal with these uncertainties, scenarios are developed by combining a set of assumptions that are external to the models, with a set of relationships that constitute the model based on historical transformations, trends and other information. Factors external to the models include assumptions about future population, underlying economic characteristics, the nature and availability of future technology, the scope of available energy and land-use resources—both depletable and renewable—and the policy environment. For each of these factors, the future might not necessarily be the same as the past, nor would it necessarily portray the same dynamics of change. IAMs link these assumptions to produce a set of derived variables, such as greenhouse gas emissions, energy and food prices, the magnitude and composition of the global energy system, the allocation of land, and energy and agricultural trade. As past events (e.g. the energy crises or the current economic crisis) demonstrate, some variables, such as energy prices and financing are subject to large inter-annual variations, while other variables, including those related to demography, energy reserves, available land or the energy intensity of the global economy, may change more slowly.

[1] See for early applications, for instance Edmonds and Reilly (1983).

In other words, long-term scenarios provide an indication of plausible long-term developments under a set of "what-if" assumptions. Long-term scenarios are essential to understanding climate change and informing near-term actions. Because climate impacts depend on cumulative emissions over decades to centuries, long-term scenarios of potential future developments are critical to developing an informed current response to the challenge of climate change.

Typical specific uses for long-term scenarios include: (1) delineating the range of plausible future developments, including their boundaries, in the context of critical uncertainties or policy-decisions today (for instance in terms of temperature increase or climate impacts), (2) identifying the costs of meeting long-term climate targets and the sensitivity of these costs estimates for various assumptions (e.g. technology), (3) identifying different types of technology portfolios that can meet long-term climate targets, (4) identifying key relationships and/or trade-offs for future developments (e.g. bio-energy and its impacts on biodiversity and climate) and (5) more generally, stimulate thinking about a wide range of plausible long-term developments, expanding the time horizon and breadth of strategic decision-making (Godet and Roubelat 1996; Parson et al. 2007; Shell International 2001).

Short- and long-term scenarios require different assumptions and approaches. For example, factors that determine the energy system in the long-term (e.g., technology development and resource depletion), tend to be very different from shorter-term influences, where economic business cycles are more dominant.

Nevertheless, in the literature, we still often find comparisons between short-term observations and long-term developments that do not take into account the different dynamics over short and long time scales. In this brief paper, we indicate how this may lead to incorrect conclusions using the discussion about the IPCC Special Report on Emissions Scenarios as an illustration. Based on this, we discuss the need and possibilities to develop more appropriate tools to evaluate the performance of long-term scenarios and the models that produce them.

2 Evaluation of scenarios

The performance of long-term scenarios has been discussed in several earlier publications. Differences between long-term scenarios and historical data have been reported on long-term (decadal) scales (Craig et al. 2002; Smil 2000). Given the uncertainties involved (including those of human decisions), this is not surprising: scenarios should be regarded as what-if calculations, designed in the context of a specific question and based on limited information available at a specific point in time. However, we also find criticism of long-term scenarios originating from comparison with short-term observations (Mayor and Tol 2010; Raupach et al. 2007; Sheehan 2008). The question of what near-term observations may really tell us about long-term developments should therefore be seen in the context of how scenarios are used. While long-term scenarios are often used as input for long-term climate models, they are sometimes also used as a means to explore medium-term implications (e.g. 2020 to 2030) of long-term targets in mitigation studies. Obviously, the implications of short-term trends can be much more important for such medium term studies.

We can illustrate the issues involved using the debate on the SRES scenarios (Nakicenovic et al. 2000). These scenarios have been frequently subject to criticisms

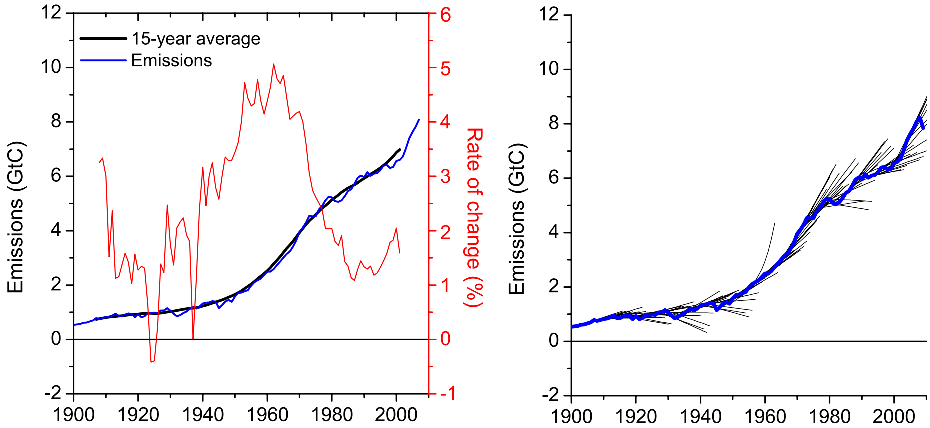

Fig. 1 Historical emissions of fossil-fuel CO_2 emissions (*blue*) and 10-year linear extrapolations based on the emission trends of the proceeding 5-year period. Source: Boden et al. 2010

based on short-term trends. Initially, the SRES scenarios were criticized for overestimating global emissions, which in the period just before 2000 were growing slowly, due in part to the transition process in Eastern Europe and the Former Soviet Union and the economic recession in Asian economies (see Van Vuuren and O'Neill 2006). More recently, the SRES scenarios have been criticized as underestimating observed emissions, as emissions in the 2001–2006 period increased faster than the SRES scenarios projected (Anderson and Bows 2008; Mayor and Tol 2010; Raupach et al. 2007; Sheehan 2008).[2] Several authors emphasized that that emissions were following a trajectory near the upper limit of the SRES range (Richardson et al. 2009), giving rise to the question of whether the SRES scenarios represented an underestimate of necessary emissions mitigation (Pielke et al. 2008).

However, as argued in the introduction, good practice requires that one distinguishes between long-term developments and short-term trends. This is illustrated in Fig. 1 by developing emissions projections based solely on immediate past performance. In Fig. 1a we show the historic development of emissions over the period 1900–2009 (Boden et al. 2010). The average growth rate of global emissions over the whole period was approximately 2.6% per year, but with clear sub-periods exhibiting faster and slower emissions growth rates. Emissions grew particularly fast during the post-World War II decades preceding the recession and "oil crisis" of the early 1970s. The slowdown after the mid-1970s led many of the earlier scenarios to overestimate historical emission growth over the last two decades (see for example, emissions trajectories reported in Edmonds and Reilly 1985). In Fig. 1b, we used the same data to create, for each year, a linear 10-year emission projection based solely on the emission trends over the previous 5 year period. The clear divergence of most "projections" of 10 years from the actual emission trend shows that focusing on short-term trends can lead to very large "forecast" errors (see also Electronic Supplemental

[2]While some studies claimed that recent emissions were outside the SRES range, this was based on an incorrect interpretation of the SRES scenarios (Manning et al. 2010).

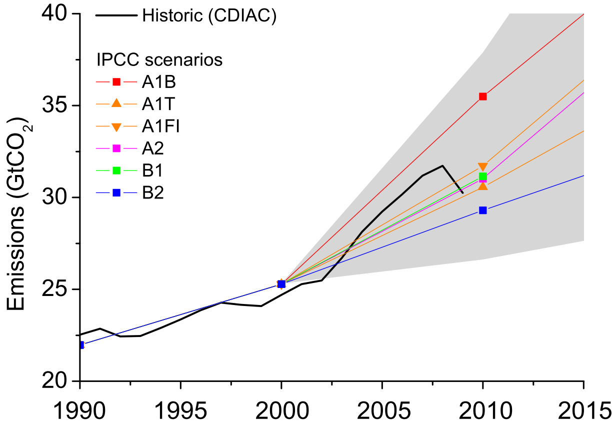

Fig. 2 Comparison of the emission development of the SRES scenarios and the historical emission trend. Sources: Nakicenovic et al. 2000; Boden et al. 2010

Material). This illustrates the point that emissions trend development from short-term (5-year) data forms a poor indicator for long-term trends.

In this context, it should be noted that recent trends have again put the SRES long-term scenarios in a different light. van Vuuren and Riahi (2008) suggested that a possible economic crisis would reconcile the trends over the 2004–2007 period with the long-term developments. In fact, the global economic slowdown is now reflected in estimated emissions for 2008 and 2009. which show a considerable decline (Le Quéré et al. 2009) or very little growth (Olivier and Peters 2010). This brings the observations back to center of the range of SRES projections (Fig. 2). So there is now little support for the proposition that the SRES scenarios systematically underestimate future emissions.

The importance of time-scale in analyzing trends is not unique for the case of emissions estimates. The problem of reconciling short-term and long-term time scales also occurs in other research fields, such as climate modeling. While a severe winter cold period or a summer drought may be cited as evidence for or against anthropogenic climate change, researchers are always quick to point out that climate change is about the forces shaping long-term averages and not specific weather events. Annual temperature, for example, is provided as a 5-year average (NASA 2010), as well as individual annual averages. In other words, short-term observations are not necessarily good indicators of long-term future emissions developments.

3 Updating scenarios and validating models

This does not mean that scenarios should not be checked against observations (Richels et al. 2008). This needs to be done realizing the characteristics of long-term scenarios: scenarios are conditional forecasts created by combining models of human and natural systems with assumptions about future states of the world that reside outside of the models. The external assumptions and the models each have an important and different role to play in creating and evaluating scenarios.

We begin with assumptions that are the external inputs to the models and the external starting point for the scenario—typically such key considerations as demographics, economic growth, and technology availability. Scenario assumptions are often developed to explore the range of future possibilities and focus on long-term trends. Still, scenarios have a limited "shelf life" as new information becomes available over time and that may be inconsistent with the scenario. Such information may simply require a change in the starting point of the scenario (values for historical or current parameters), but could also undermine the original critical assumptions (so-called 'storyline') of the scenario by providing, for example, new information on long-term technology potential. It could also lead to new policy questions that require different scenarios. While the second and third cases require the development of new scenarios, in the first case it might be possible to update the existing scenarios using simple mathematical tools. It should be noted that the different scenario purposes discussed earlier also have implications. When used in support of climate analysis, the long-term developments are the only important factor. When used to explore medium-term implications, short-term trends may have direct implications on the results. For example, the impact of the 2008/2009 economic crisis may be substantial for scenario estimates of 2020 mitigation costs, but less significant for the costs estimates in 2100.

This raises the question of whether there are new methods or tools to increase our ability to project the development of the human systems, and thus also associated emissions, at a time scale of decades, or to provide some level of probability estimation. One element might be that of probabilistic emission estimates that are conditional upon long-term structural assumptions (e.g. O'Neill et al. 2010; Richels et al. 2004; van Vuuren et al. 2008). It would also be useful to regularly evaluate the performance of long-term scenarios, provided that they are evaluated against the appropriate, corresponding long-term variables and trends. The focus should not be on relatively small quantitative deviations—but rather on structural variables and changing dynamics of deeper, underlying processes. In that context, one needs to consider how tests can include long-term measures of both the exogenous assumptions that shape emissions trajectories as well as long-term measures of forecast variables. As a very simple example, a lesson we can learn from climate science is that it is more useful to focus on running averages and structural changes instead of on annual data with considerable fluctuations. Similarly, one could easily develop statistical tests that indicate the position of scenario projections vis-à-vis observed data while accounting for historical short-term variability.

The story is somewhat different regarding the IAMs themselves. To the extent that assumptions about future states of the world that reside outside of the models are correct, it is the job of the IAMs to describe the implications of those events in terms of scenario variables in a credible way. An important task for the IAM community is the development of appropriate data bases and methods for testing, improving and validating the performance of long-term IAMs. The difficulty in validating IAMs arises from the fact that there are many uncertainties that can only be predicted within relatively wide margins and that unlike natural processes, the behavior of human systems tends to change over time, in part through learning from past experiences. Furthermore, IAMs are often used to describe paradigm shifts and measures that would transform the system away from historical trends. For instance, the stabilization of greenhouse gas concentrations involves excursions dramatically outside the bounds of historical experience for key values such as energy prices and technology choice. As a result, the ability of a model to reproduce the past is thus no guarantee that it will be capable of predicting the future: a model might do an admirable job reproducing historical behavior, yet omit key features that could become dominant in the future. Still knowing how model behavior compares to historical trends requires modelers to transparently explain what could cause these differences. It should also be noted that IAMs are also much broader in scope than most models. All of this makes the job of evaluating and validating IAMs a unique, as well as an important challenge for the IAM community.

In addition to the development of appropriate long-term data sets and developing the architecture for a robust program of model intercomparison and validation, one can imagine a number of potentially useful exercises. First of all, some physical elements, such as the behavior of the climate models within integrated assessment models can be validated (van Vuuren et al. 2010). Secondly, it is possible to discuss and test some of the theoretical concepts underlying IAMs (such as trends in energy intensity) and/or to present historical analogies. Examples of this include examination of development concepts (van Ruijven et al. 2008) or technology dynamics (Wilson 2009). Finally, it is possible to compare the behavior of the model under clearly defined assumptions with historical trends as a basis for discussion. For example, while long-term models are not intended to be able to predict the 1970's oil crisis or the collapse of the Soviet Union, insights can be gained from their behavior when these historical events are prescribed (e.g. van Ruijven et al. 2010). These diagnostic experiments would allow for a more explicit and transparent treatment of the deep uncertainties and structural dynamics, as well as scientific assessment processes, that allow for cumulative scenario updates and improvements as new evidence and observations become available.

References

Anderson K, Bows A (2008) Reframing the climate change challenge in light of post-2000 emission trends. Philos Trans Royal Soc A, Math Phys Eng Sci 366:3863–3882

Boden TA, Marland G, Andres RJ (2010) Global, regional, and national fossil-fuel CO2 emissions. Carbon Dioxide Information Analysis Center. Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., USA

Craig PP, Gadgil A, Koomey JG (2002) What can history teach us? A retrospective examination of long-term energy forecasts for the United States. Annu Rev Energy Environ 27:83–118

Edmonds J, Reilly J (1983) A long-term global energy-economic model of carbon dioxide release from fossil fuel use. Energy Econ 5:74–88

Edmonds J, Reilly J (1985) Global energy—assessing the future. Oxford University Press, New York

Fisher B, Nakicenovic N, Alfsen K, Corfee Morlot J, de la Chesnaye F, Hourcade J-C, Jiang K, Kainuma M, La Rovere E, Matysek A, Rana A, Riahi K, Richels R, Rose S, Van Vuuren D, Warren R, Ambrosi P, Birol F, Bouille D, Clapp C, Eickhout B, Hanaoka T, Mastrandrea MD, Matsuoko Y, O'Neill B, Pitcher H, Rao S, Toth F (2007) Issues related to mitigation in the long-term context. In: Metz B, Davidson O, Bosch P, Dave R, Meyer L (eds) Climate change 2007. Mitigation of climate change. Contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, New York, pp 169–250

Godet M, Roubelat F (1996) Creating the future: the use and mis-use of scenarios. Long Range Plan 29:164–171

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely RA, Foster PN, Friedlingstein P, Gurney KR, Houghton RA, House JI, Huntingford C, Levy PE, Lomas MR, Majkut J, Metzl N, Ometto JP, Peters GP, Prentice IC, Randerson JT, Running SW, Sarmiento JL, Schuster U, Sitch S, Takahashi T, Viovy N, van der Werf GR, Woodward FI (2009) Trends in the sources and sinks of carbon dioxide. Nat Geosci 2:831–836

Manning MR, Edmonds J, Emori S, Grubler A, Hibbard KA, Joos F, Kainuma M, Keeling RF, Kram T, Manning AC, Meinshausen M, Moss R, Nakicenovic N, Riahi K, Rose SK, Smith S,

Swart R, Van Vuuren DP (2010) Misrepresentation of the IPCC CO2 emission scenarios. Nat Geosci 3:376–277
Mayor K, Tol RSW (2010) Scenarios of carbon dioxide emissions from aviation. Glob Environ Change 20:65–73
Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, Van Vuuren DP, Carter TR, Emori S, Kainuma M, Kram T, Meehl GA, Mitchell JFB, Nakicenovic N, Riahi K, Smith SJ, Stouffer RJ, Thomson AM, Weyant JP, Wilbanks TJ (2010) The next generation of scenarios for climate change research and assessment. Nature. doi:10.1038/nature08823
Nakicenovic N, Alcamo J, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Yong Jung T, Kram T, Lebre La Rovere E, Michaelis L, Mori S, Morita T, Pepper W, Pitcher H, Price L, Riahi K, Roehrl A, Rogner H-H, Sankovski A, Schlesinger M, Shukla P, Smith S, Swart R, van Rooijen SNV, Dadi Z (2000) Special report on emissions scenarios: a special report of working Group III of the intergovernmental panel on climate change. Cambridge University Press, Cambridge
NASA (2010) http://data.giss.nasa.gov/gistemp/graphs/
O'Neill B, Riahi K, Keppo I (2010) Mitigation implications of midcentury targets that preserve long-term climate policy options. Proc Natl Acad Sci. doi:10.1073/pnas.0903797106
Olivier JGJ, Peters JAHW (2010) No growth in total global CO2 emissions in 2009. Netherlands Environmental Assessment Agency, Bilthoven
Parson E, Burkett V, Fisher-Vanden K, Keith DW, Mearns LO, Pitcher H, Rosenzweig C, Webster M (2007) Global change scenarios: their development and use. Sub-report 2.1B of synthesis and assessment product 2.1 U.S. Climate change science program and the subcommittee on global change research. Department of Energy, Office of Biological & Environmental Research, Washington, DC
Pielke R, Wigley T, Green C (2008) Dangerous assumptions. Nature 452:531–532
Raupach MR, Marland G, Ciais P, Le Quére C, Canadell CG, Klepper G, Field CB (2007) Global and regional drivers of accelerating CO2 emissions. PNAS 104:10288–10293
Richardson K, Steffen W, Schellnhuber HJ, Alcamo J, Barker T, Kammen DM, Leemans R, Liverman D, Munasinghe M, Osman-Elasha B, Stern N, Wæver O (2009) Climate change. Copenhagen 2009, 10–12 March. Synthesis report. University of Copenhagen, Copenhagen
Richels RG, Manne AS, Wigley TML (2004) Moving beyond concentrations: the challange of limiting temperature change. AEI-Brooking Joint Center for regulatory studies, Washington D.C
Richels RG, Tol RSJ, Yohe GW (2008) Future scenarios for emissions need continual adjustment. Nature 453:155
Sheehan P (2008) The new global growth path: implications for climate change analysis and policy. Clim Change
Shell International (2001) Energy needs, choices, and possibilities: scenarios to 2050. Global Business Environment
Smil V (2000) Perils of long-range energy forecasting: reflections on looking far ahead. Technol Forecast Soc Change 65:251–264
van Ruijven B, Urban F, Benders RMJ, Moll HC, van der Sluijs JP, de Vries B, Van Vuuren DP (2008) Modeling energy and development: an evaluation of models and concepts. World Dev 36:2801–2821
van Ruijven BJ, van der Sluijs J, Van Vuuren D, Janssen P, Heuberger P, de Vries B (2010) Uncertainty from model calibration: applying a new method to transport energy demand modelling. Environ Model Assess 15:175–188
van Vuuren DP, O'Neill BC (2006) The consistency of IPCC's SRES scenarios to recent literature and recent projections. Clim Change 75:9–46
van Vuuren DP, Riahi K (2008) Do recent emission trends imply higher emissions forever? Clim Change 91:237–248
van Vuuren DP, de Vries B, Beusen A, Heuberger PSC (2008) Conditional probabilistic estimates of 21st century greenhouse gas emissions based on the storylines of the IPCC-SRES scenarios. Glob Environ Change 18:635–654
van Vuuren DP, Lowe J, Stehfest E, Gohar L, Hof AF, Hope C, Warren R, Meinshausen M, Plattner GK (2010) How well do integrated assessment models simulate climate change? Clim Change. 10.1007/s10584-009-9764-2
Wilson C (2009) Meta-analysis of unit and industry level scaling dynamics in energy technologies and climate change mitigation scenarios. International Institute of Applied System Analysis. IIASA Interim Report IR-09-029. Laxenbourg, Austria