CHAPTER 11

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SIMULATION UNCERTAINTY AND THE CHALLENGE OF POSTNORMAL SCIENCE

INTRODUCTION

On January 20, 1999, Hans de Kwaadsteniet, a senior statistician at the Netherlands National Institute for Public Health and the Environment (*Rijksinstituut voor Volksgezondheid en Milieu*, RIVM), made news in the Netherlands. After years of trying to convince his superiors that the environmental assessment branch[1] of the institute leaned too much toward computer simulation at the expense of measurements, he went public with this criticism by publishing an article on the op-ed page of the national newspaper *Trouw* (de Kwaadsteniet 1999). His article was supplemented with an interview that resulted in the headline "Environmental Institute Lies and Deceives" on the newspaper's front page. His specific claim was that the RIVM was suggesting an excessive accuracy for environmental figures published yearly in its *State of the Environment* report. According to him, too many model results were included that had not been compared rigorously with observational data – mostly because of the lack of sufficiently detailed data to do the necessary comparisons. He pointed out that living in an "imaginary world" was dangerous. He thought that if the institute spent more time and energy on testing and developing computer-simulation models in a way that were to make more use of existing and newly performed observations, it would become more careful in the way it presented its results to policy makers. De Kwaadsteniet identified the deceiving speed, clarity, and internal consistency of the computer-simulation approach as the main causes of the claimed bias toward computer simulation at RIVM.

The institute responded immediately to the publication by suspending de Kwaadsteniet from his job and stating in an official reaction that a significant fraction of its environmental research budget was spent on observations, that no policy recommendations were given when uncertainties were too large, and that the uncertainties were not left out of the *State of the Environment* reports on purpose. The institute promised to publish information on the uncertainties in next editions. In a later reaction, the institute's Director of the Environment, Klaas van Egmond (1999), argued that simulation models must be viewed as "condensed knowledge" and that they are

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indispensable in environmental assessment, since, without them, it would be impossible to determine cause-effect relationships between sources and effects of pollution. Thus, models give meaning to measurement results. And they are needed in environmental policy making. Furthermore, he observed that policy makers often are confronted with incomplete knowledge, and that the institute regards it as its task to report on the current state of affairs in the environment, including the uncertainties involved. He gave the example that it will take many more years before climate research reaches the 'ultimate truth' about what is happening to the climate. However, on the basis of currently available knowledge and its uncertainties, politicians have to decide whether to take measures now already. Finally, the Director added that the most important conclusions contained in the summaries for policy makers of the *State of the Environment* reports are carefully crafted, taking all relevant uncertainties into account.

Soon after the publication by de Kwaadsteniet, an intense and long-lasting media debate ensued in the Netherlands.[2] The affair reached the floor of the Dutch Parliament within a matter of days. Facing Parliament, the Minister of the Environment, Jan Pronk, defended the integrity of the institute. In return for an agreement to organize more regular external reviews of its environmental assessment activities and improve its communication of uncertainty, the Minister granted the institute additional funding for its monitoring activities.

The episode of de Kwaadsteniet's questioning of the role of scientific simulation in politics is by no means unique in the world. Controversies like that in the Netherlands surface regularly in many countries. In such discussions, general questions arise about the role of simulation in science as well as its role in policy making. The latter question constitutes the subject of this chapter. It focuses particularly on the reliability of simulation for political uses.

Since World War II, computational approaches in science have emerged and expanded – not in isolation, but often in strong contact with experimental and observational fields in the natural sciences, and aided by developments in mathematics and computer science.[3] Outside science as well, simulations have become important tools in, for instance, providing scientific advice to policy makers.[4] In highly politicized cases, such as climate change, methodological questions about what constitutes 'good' or 'sound' science, often left implicit in scientific practices, are brought into the open. The characteristics of 'sound' science on which policies can be based are contested in political forums. Typically, the issue of the reliability of computer simulation plays an important role in these debates. The state of affairs in which there are high political stakes in conjunction with high systems uncertainty has given rise to normative appeals for systematically dealing with uncertainty in scientific policy advicing. Funtowicz and Ravetz's (1991) proposal for a "post-normal science" problem-solving strategy constitutes a prominent example.

This chapter first discusses the use of scientific simulation for policy. Subsequently, after treating general issues related to the science–policy interface and the challenge of postnormal science, it presents a case study on simulating climate change along with a new methodology for assessing and communicating uncertainty in science-for-policy developed by RIVM and external uncertainty experts in response to the media affair. Finally, it outlines the implications of this new methodology for managing the use of simulation in science-for-policy.

SIMULATION UNCERTAINTY IN SCIENCE-FOR-POLICY

Scientific simulation models are not just used within science. The results of scientific simulation models are frequently employed in public policy making as well.[5] How important it is to assess computer-simulation uncertainty, as part of the process of providing scientific advice to policy makers and politicians, depends on the questions asked of science. In cases in which policy makers ask questions "which cannot be answered by science" (Weinberg 1972) – that is, even though the questions are scientifically formulated, the uncertainties are too large to answer those questions unequivocally – it is typical that many different answers can be produced by applying different simulation models to the policy issue. In this chapter, it is argued that, in such cases, computer-simulation uncertainty must be assessed thoroughly – and that this must be done in a way that is appropriate to the decision-making context.

Similar arguments were developed by the philosophers of science Silvio Funtowicz and Jerry Ravetz (e.g., 1990, 1991, 1993). The aim of Funtowicz and Ravetz's work is to improve the decision-making process by introducing into the policy-advisory process appropriate information about the uncertainty and quality of the underlying science ("science providing advice to policy" can be called "science-for-policy" in short). In the Prologue to their book, this aim is set in the following context:

> There is a long tradition in public affairs which assumes that solutions to policy issues should, and can, be determined by 'the facts' expressed in quantitative form. But such quantitative information, either as particular inputs to decision-making or as general purpose statistics, is itself becoming increasingly problematic and afflicted by severe uncertainty. Previously it was assumed that Science provided 'hard facts' in numerical form, in contrast to the 'soft', interest-driven, value-laden determinants of politics. Now, policy makers increasingly need to make 'hard' decisions, choosing between conflicting options, using scientific information that is irremediably 'soft' (Funtowicz and Ravetz 1990: 1).

In Funtowicz and Ravetz's analysis, the stated "softness" of the scientific information relates mainly to their claim that for many pressing policy problems, we cannot draw on the reliable knowledge that can be gained from experiments, but instead must use much less reliable knowledge from simulation. Even though one cannot make the general statement that all simulations are less reliable than laboratory experiments, nor that simulations are in all respects untestable, the question of the reliability of simulation is indeed pressing for the particular cases discussed by Funtowicz and Ravetz – that is, very complicated and complex environmental issues.

Especially in simulation studies of the future, we must recognize our ignorance about the complex systems under study. Verification and validation of these computer models is impossible, and confirmation is inherently partial. Furthermore, since models are products made by scientists, we must always be aware of the possible presence of personal, institutional, or ideological dimensions – their potential 'value-ladenness.' Knowledge claims based on simulation should be tailored to be insensitive to artifactual aspects of models and precise about real effects (Norton and Suppe

2001: 84). In order to be able to tailor these claims to such requirements, simulationists must, on the one hand, do much practical work to determine the sensitivity of their model results to all sources of uncertainty. It is often not feasible, however, to establish the reliability of a simulation in quantitative terms. Therefore, one has to also assess the reliability of a model in a qualitative manner, for which a thorough review of the model is usually helpful. But even then, the quality of the simulation is only established according to the scientific community's methodological standards. Finally, the scientists must think about remaining uncertainties that have not been estimated (yet) and determine what they can say about them. All these steps require a substantial amount of work. Since policy makers are usually not able to judge the reliability of scientific simulation-model outcomes themselves, scientific policy advisers must carefully assess the reliability of their simulations and be aware of the uncertainties in the presentation of their conclusions.[6]

Simulation models of ecological systems, for example, although they may give an impression of the scope of behavioral possibilities of such systems and, as such, may contribute reasons for taking policy measures, cannot predict the future states of these open and unpredictable systems. If modeling assumptions were made in a more transparent manner, and if, in concrete problem contexts, all relevant policy actors were involved in the framing of the models (what questions to address, where to locate the system boundaries, etc.), the choice of the models, and the evaluation of the models, then

> [m]odelling could … contribute to the organization of knowledge, e.g. it could catalyze mutual learning processes and it could contribute to the integration of scientific and non-scientific knowledge and of exo- en endo-perspectives [perspectives from respectively outside or within the system studied] (Haag and Kaupenjohann 2001: 57).

This is proposed as an ideal situation. Current practice is far from this ideal, however. Leaving aside the question of whether the ideal can ever be reached, we can observe that simulation uncertainties do not often get the airing they may well deserve. Sometimes, policy makers, politicians, and other actors do not see a need to dwell on the uncertainties and treat them explicitly. Policy decisions are just taken without being explicit about the level of uncertainty of the risk involved. A concrete example from the area of international environmental policy making is the formation of the *Mediterranean Action Plan* (Med Plan), a regional environmental cooperation for dealing with the issue of marine pollution in the Mediterranean that arose in the 1970s. The uncertainty in this example is related to uncertainties in ecotoxicological simulations. The main scientists and policy makers involved in the Med Plan "shared an abiding belief in ecological principles and were committed to preserving the physical environment, which they thought was threatened by pollution" (Haas 1990: 74–75). These ecological principles were partly derived from theoretical ecological computer simulations used to study the behavior of complex ecological systems. These simulations are relatively unreliable. This did not seem to hinder the main policy actors. The uncertainties in ecological computer simulations were dealt with only implicitly, not explicitly, by the actors involved in the Med Plan and remained at an unreflective level while decisions were being taken. Increased transparency about simulation uncertainties need not have changed the same policy outcomes, but would have made the decisions more robust against these uncertainties. An explicit precautionary approach could have been used, for instance.

Recently, however, national and international governmental bodies have undergone a reflective transition in their attitudes toward scientific uncertainty. At the end of the 1980s, when environmental policy makers were faced with significant scientific uncertainties surrounding large-scale and high-impact environmental problems such as biodiversity loss and climate change, they started referring more and more often to the "precautionary principle," for instance. Loosely formulated, the principle states that if there is evidence that a certain activity may be harmful to humans or the environment, that activity should be abandoned. The principle provides politicians with the possibility to install measures even when uncertainty still exists about a problem.[7]

Thus, scientific simulation models are often used in providing policy advice, and they typically have significant uncertainties attached to them. In practice, it turns out that many experts still find it difficult to deal with these uncertainties when providing their policy advice. Within their own disciplines, they typically do not learn the skills needed to deal adequately with these uncertainties when providing advice (van Asselt and Petersen 2003: 144–145). There is clearly a need for including these issues in core academic curricula.

THE CHALLENGE OF POSTNORMAL SCIENCE

Many social scientists who have studied the relationship between science and decision making have concluded that these two activities cannot be separated neatly in practice. One way to phrase this conclusion is the following: "Natural knowledge and political order are co-produced through a common social project that shores up the legitimacy of each" (Jasanoff and Wynne 1998: 16). An example may serve to illustrate this point.

A much-discussed, though exceptional, coproduction of natural knowledge and political order is the ongoing assessment process conducted by the Intergovernmental Panel on Climate Change (IPCC), which receives questions from and feeds back into the United Nations Framework Convention on Climate Change. Due to widely publicized warnings from scientists in the 1980s, the public in Western democracies became interested in the risks involved in an enhanced greenhouse effect induced by anthropogenic emissions of CO_2 leading to a human-induced global warming – and its associated effects, such as sea-level rise. The attribution of climate change to human influences and the projections of climate change into the future have made heavy use of climate simulations. Since the societal changes implied by the different solutions proposed for solving the global warming problem are quite drastic, one of the first steps politicians took to address the problem was to ask scientists to regularly assess the state of climate science as well as the possibilities for adaptation to climate change and mitigation of the problem by reducing anthropogenic greenhouse gas (mostly CO_2) emissions. This led to the establishment of the IPCC in 1988.[8] The advisory process involving the IPCC is regarded by many social scientists as being a 'co-production' of, on the one hand, our knowledge about the climate system and, on the other hand, the international political order:

> The IPCC's efforts to provide usable knowledge resonated with the belief of sponsoring policy organizations that climate change is a manageable problem within the framework of existing institutions and cultures (Jasanoff and Wynne 1998: 37).

The alignment of scientific and political views seems to be a common feature of environmental assessment (see, e.g., Haas 1990 for a similar analysis of science and policy involved in the Med Plan). From these and other examples, one may conclude that the knowledge used in scientific assessments for policy purposes, often largely based on computer simulations, is potentially 'value-laden.'

Already earlier in the 1980s, before the IPCC was established, the special challenges facing experts under conditions of potential alignment of scientific and political views became evident in the area of risk assessment. Recognizing that the interactions between science and policy making on risks were often unproductive in cases in which the decision stakes and system uncertainty are very high, Funtowicz and Ravetz proposed to distinguish a new type of risk assessment called "total-environmental assessment" (Funtowicz and Ravetz 1985: 228). This is a form of risk assessment in which the "total environment" – that is, the complete context – of a risk issue is taken into account. This kind of risk assessment is appropriate for cases with high decision stakes and system uncertainty.[9] In very polarized settings, the least one can hope for, according to Funtowicz and Ravetz (1985: 229), is a "consensus over salient areas of debate."

According to Funtowicz and Ravetz, structural changes in the direction of enhanced participation are needed in order to democratize scientific advisory proceedings. For this reason, they have generalized their original normative view on risk assessment into a sweeping normative statement on the future of science-for-policy:

> Now global environmental issues present new tasks for science; instead of discovery and application of facts, the new fundamental achievements for science must be in meeting these challenges. … In this essay, we make the first articulation of a new scientific method, which does not pretend to be either value-free or ethically neutral. The product of such a method, applied to this new enterprise, is what we call 'post-normal science' (Funtowicz and Ravetz 1991: 138).

When Funtowicz and Ravetz first wrote about "risk assessment," they subsequently generalized their analysis to "problem-solving strategies." The problem-solving strategy of "postnormal science" (or 'second-order science') corresponds to the "total-environmental" type of risk assessment discussed above (Funtowicz and Ravetz 1991: 137, 144–145).[10]

Whether or not one agrees with Functowicz and Ravetz's statement that "science" as a whole has to tackle the "new tasks," whoever takes up the challenge has the responsibility to conscientiously (a) assess the issues, which may involve building very complicated computer simulations; (b) assess the uncertainties; and (c) communicate the policy-relevant findings of both these assessment activities.

ASSESSING AND COMMUNICATING SIMULATION UNCERTAINTY IN SCIENCE-FOR-POLICY

How should we deal with the challenge that postnormal science poses to the use of computer simulation in policy making? Let us take a look at a specific example, that of climate simulation and climate policy. Climate simulations play an important role in climate science. These simulations involve mathematical models that are implemented on computers and imitate processes in the climate system. Like the history of numerical weather prediction, the history of climate science is strongly related to the history of the computer. There are two main reasons why simulation is so important in climate science. First, computers removed an actual barrier in meteorological practice: They greatly enhanced the speed with which calculations could be done. The calculations in climate simulations cannot be done practically without the use of computers. Second, simulation is an important ingredient of climate science, because real experiments with the climate as a whole are impossible. If we want to manipulate climate 'experimentally,' we need to perform such manipulations on a digital representation of the climate system.

It must be borne in mind here that climate science is an observational science in which the scientific activities encompass much more than performing computer simulations. In fact, climate observations are of pivotal importance – also for climate-simulation practice. From climate observations, the world's climate scientists have concluded that it is very likely that the earth's climate has changed over the last 100 years. In 2001, the *Third Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC) concluded that the global average surface temperature has increased by 0.6 ± 0.2°C (95% confidence range) over this period (IPCC 2001: 2). The uncertainty is expressed here as a range of temperature change (from 0.4 to 0.8°C) together with the probability that the real value lies within this range (that is, 95%). For the Northern Hemisphere, it is considered likely (a judgmental estimate of confidence that there is a 66 to 90% chance) that current temperatures are higher than historic temperatures over the last millennium (IPCC 2001: 2).

Alongside temperature, precipitation is also a component of climate. It is considered very likely that precipitation has increased by 5 to 10% during the twentieth century over most mid- and high latitudes of the Northern Hemisphere continents (IPCC 2001: 4). Furthermore, in the mid- and high latitudes of the Northern Hemisphere it is likely, according to the climate experts, that there has been a 2 to 4% increase in the frequency of heavy precipitation events over the latter half of the twentieth century (IPCC 2001: 4). Also such extreme events are typically included in the description of climate.

The above statements about observed climate change have been obtained without the use of climate simulations. This means that the sources of uncertainty are of a different kind to those encountered in simulation practice. For example, for global average surface temperature, the sources of uncertainty on the 100-year timescale are located in data and (statistical) model assumptions made in data processing: "data gaps, random instrumental errors and uncertainties, uncertainties in bias corrections in the ocean surface temperature data and also in adjustments for urbanisation over the land" (IPCC 2001: 3). For the Northern Hemisphere temperature on the 1,000-year timescale, the sparseness of 'proxy' data[11] is the main source of uncertainty (IPCC 2001: 3), besides the unreliability of proxies for determining local temperatures in the past.

It is not possible, however, to deduce the *causes* of the observed changes in climate directly from the observations. When climate scientists want to attribute climate changes to causes or make future projections, they need to make use of climate simulations. One of the most important conclusions of the IPCC (2001) is that “most of the observed warming over the last 50 years is likely [between 66 and 90% chance] to have been due to the increase in greenhouse gas concentrations” (IPCC 2001: 10). In order to arrive at this conclusion, climate simulations have been performed as a substitute for experiments. This function of simulation is crucial in climate science, because there is only one historical manifestation of the system under study. Real (in the sense of controlled and reproducible) experiments on the scale of the whole climate system are impossible.

The roles of climate simulation in climate science are manifold. Furthermore, climate models of varying levels of concreteness exist and are valued differently by different groups of climate scientists. On the one hand, we find relatively simple climate models that do not require huge computational resources but can be used for genuine climate-scientific research. On the other hand, we encounter very comprehensive climate models that demand high-end supercomputers in order to be able to work with them. For this latter category of climate models, computing power is currently a bottleneck. This situation will remain unchanged for at least the next decade (the demand for computational power will keep growing faster than what can be delivered). The IPCC reports have taken a pragmatic stance in this matter and acknowledge that both comprehensive and simple models have important roles to play in climate science (see, also, Petersen 2000). The observed plurality at the methodological level is correlated with a plurality of aims and goals held by climate-simulation practitioners in their scientific practice. The social context of climate-simulation practice has a significant influence on this practice. Thus, in evaluating climate simulations, the potential value-ladenness of choices should not be overlooked.

Even though all climate models contain ad hoc ‘parameterizations’ and can be criticized methodologically for that reason, climate scientists generally feel confident about using these models for climate-change studies. However, the IPCC lacks a methodology for uncertainty assessment and a typology of uncertainty that can be used to assess uncertainties more systematically. The challenge to postnormal science is for the IPCC to become even more rigorous and transparent in its treatment of uncertainty.

The MNP faces a similar challenge. In the year 2000, the MNP identified the lack of systematic treatment of uncertainty in the area of environmental policy making as one of the causes of the media affair reported at the beginning of this chapter. In order to help environmental assessors to deal with uncertainty and frame policy problems in a more appropriate way, the Netherlands Environmental Assessment Agency (*Milieu- en Natuurplanbureau*, MNP), then part of RIVM, together with Utrecht University and an international team of uncertainty experts, developed the *RIVM/MNP Guidance for Uncertainty Assessment and Communication* (Petersen et al. 2003; Janssen et al. 2003; van der Sluijs et al. 2003; van der Sluijs et al. 2004).

The *RIVM/MNP Guidance for Uncertainty Assessment and Communication* (www.mnp.nl/guidance) offers assistance to employees of the Netherlands Environmental Assessment Agency in mapping and communicating uncertainties in environmental assessments.[12] It was judged that the Guidance should facilitate dealing with uncertainties throughout the whole environmental assessment process and not be limited to applying ready-made tools for uncertainty analysis and communication, because choices are made in all parts of environmental assessments that influence the way uncertainties are dealt with. The way in which the perspectives of other scientists and stakeholders are treated is particularly crucial when assessing relatively unstructured policy problems.

The Guidance identifies six parts of environmental assessments that have an impact on the way uncertainties are dealt with. These parts are:

1. problem framing;
2. involvement of stakeholders (i.e., all those involved in or affected by a policy problem including experts);
3. selection of indicators representing the policy problem;
4. appraisal of the knowledge base;
5. mapping and assessment of relevant uncertainties;
6. reporting of the uncertainty information.

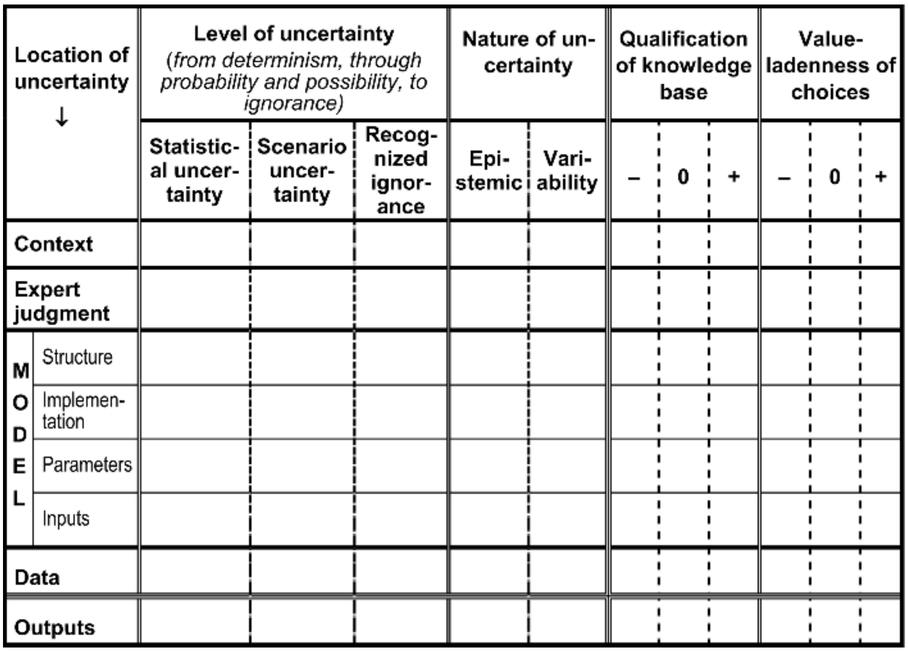
A focused effort to analyze and communicate uncertainty is usually made in parts 5 and 6. However, the choices and judgments made in the other four parts are also of high importance for dealing with uncertainty.

The Guidance is not set up as a protocol. Instead, it aspires to stimulate reflection on the choices made in different parts of environmental assessments, in order to make them more conscious and produce a better way of dealing with uncertainties. Aside from stimulating reflection during the execution of environmental assessments, the Guidance is intended to signal in a timely way which bottlenecks might occur when dealing with uncertainties (and what additional effort should perhaps be made in the field of uncertainty assessment). The Guidance offers advice on the selection of methods and tools for adequately estimating uncertainties in the given context and communicating them to scientific researchers, the ‘clients’ (usually ministries), other actors in the policy process, and the broader public. The group of envisaged users of the Guidance comprises a large fraction of the employees of the Netherlands Environmental Assessment Agency (among others, those who fulfill the roles of project leader, project-team member, researcher, or policy adviser).

The Guidance can be used in different phases of a project (at the beginning, during, after). *At the beginning* of a project, it can play an important role in designing and elaborating the way uncertainty will be dealt with during the project. *During* a project, the Guidance can be of assistance in performing the uncertainty assessment and communicating the results. *After* a project, it can be of use in reviewing and evaluating the project.

The most important function of the instrument is to make the practitioners reflect on the importance of uncertainties and on the way they should communicate these uncertainties to stakeholders (including policy makers). Table 1 shows the uncertainty typology used in the Guidance.[13] The Guidance typology is presented as a matrix. This ‘uncertainty matrix’ is based on five dimensions of uncertainty. In the Guidance, it is used as an instrument for generating an overview of where one expects the most important (policy-relevant) uncertainties to be located (the first dimension), and how these can be further characterized in terms of four other uncertainty dimensions.

Table 1. Uncertainty matrix[14]



Location of uncertainty ↓		**Level of uncertainty** (*from determinism, through probability and possibility, to ignorance*)			**Nature of uncertainty**		**Qualification of knowledge base**			**Value-ladenness of choices**		
		Statistical uncertainty	**Scenario uncertainty**	**Recognized ignorance**	**Epistemic**	**Variability**	**–**	**0**	**+**	**–**	**0**	**+**
Context												
Expert judgment												
MODEL	Structure											
	Implementation											
	Parameters											
	Inputs											
Data												
Outputs												

Using the matrix can serve as a first step toward a more elaborate uncertainty assessment in which the size of uncertainties and their impact on the policy-relevant conclusions is assessed explicitly.[15] For further details about the Guidance, the reader is referred to the Guidance website and publications.

This typology of simulation uncertainty can be applied fruitfully in the analysis of climate-simulation uncertainty, as is shown for the simulation-related sources of uncertainty in climate-change attribution studies by Petersen (in preparation). By applying the typology, it becomes immediately obvious that only part of the uncertainty can be expressed statistically. Additional qualitative judgments on the methodological quality of the climate-simulation models (qualification of the knowledge base) are needed – and indeed played an important role in the production of the IPCC (2001) report. Since the vocabulary needed to explicitly distinguish between the two uncertainty sorts of statistical uncertainty ("inexactness" in the vocabulary of Funtowicz and Ravetz 1990) and qualification of the knowledge base (methodological "unreliability" according to Funtowicz and Ravetz 1990) was not available to the lead authors, the influence of their qualitative judgments on reaching their final conclusion remained largely invisible to outsiders.

Since the Guidance was released in December 2002, it has become part of the agency's system of quality assurance for all projects including those making heavy use of simulations. Through teaching courses, an increasing proportion of scientific advisers have become acquainted with the new methodology. Specific tools for uncertainty assessment that are presented in the Guidance have demonstrated their usefulness for prioritizing research activities in simulation modeling, for instance, the research on the global energy simulation model TIMER (van der Sluijs et al. 2002).

Even though the Guidance is only an instrument for reflection, a change in simulation practice can be observed within the agency in the sense that modeling choices are made more reflectively and reports pay more attention to uncertainties. It remains to be seen whether the institute has become less vulnerable to media affairs such as the one caused by de Kwaadsteniet, but my contention is that the answer will be positive.

CONCLUSION

The facts that science and policy cannot be separated neatly and that experts provide policy advice under conditions of high political stakes and high system uncertainty pose a severe challenge to those expert advisers who use scientific simulation models that have significant uncertainties attached to them. From their own disciplines, experts typically do not gain the necessary skills to adequately deal with these uncertainties when providing their advice. By making systematic use of an instrument such as the RIVM/MNP Guidance on Uncertainty Assessment and Communication, experts are better able to meet the challenge of the postnormal science problem-solving strategy.

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NOTES

[1] Over the years, this branch has become an independent part of the RIVM: The Netherlands Environmental Assessment Agency (*Milieu- en Natuurplanureau*, MNP).

[2] See, for more information about this debate, van Asselt (2000) and van der Sluijs (2002).

[3] Computer simulation as a scientific approach is not limited to the natural sciences, however. Simulation is gaining ever more prominence in, for example, psychology, sociology, political science, and economics. The recent rise in the amount of work on simulation in these fields may be partly related to the wide applicability of the concept of 'complex systems' (see Casti 1997, who provides a popularized account of the use of simulation to study complex systems in the natural and social sciences). Many simulations in both the natural and social sciences share system-theoretical concepts.

[4] Other examples of the use of simulation techniques outside science are flight simulators for training pilots and simulations used in technology development as tools to design and 'test' new technologies, be they in automobile design (simulations of aerodynamics or crashes) or nuclear weapons design (simulation of stockpile safety or explosions).

[5] Not all scientific simulation models find their application in policy making. This chapter only deals with those models that do.

[6] Obviously, there is also a more general need to provide insight into the uncertainties involved in policy advice, and not just in the case of scientific computer simulation. Whereas the main emphasis of this chapter is on simulation-model uncertainty, the general discussion on the science–policy interface and assessing uncertainty in science-for-policy does not just apply to scientific simulation.

[7] Many references can be given to literature on the precautionary principle. Petersen and van der Zwaan (2003) offer a concise introduction to the principle and how it relates to the responsibility of scientific advisers to communicate about uncertainties.

[8] The IPCC consists of three working groups. Currently, Working Group I deals with the (natural) scientific basis of climate change; Working Group II addresses issues of impacts, adaptation, and vulnerability; and Working Group III assesses mitigation options. The analysis presented in this chapter focuses on Working Group I.

[9] These two variables are not totally independent, in the sense that the recognition of system uncertainty is typically enhanced if the decision stakes are high (see Jasanoff and Wynne 1998: 12).

[10] The other two types of problem-solving strategies are applied science (low systems uncertainty and/or low decision stakes) and professional consultancy (medium-level systems uncertainty and/or medium-level decision stakes) (e.g., Funtowicz and Ravetz 1991, 1993).

[11] 'Proxies' such as tree rings, corals, ice cores, and historical records are "interpreted, using physical and biophysical principles, to represent some combination of climate-related variations back in time" (IPCC 2001: 795).

[12] Only some elements of the Guidance are specific to environmental assessment, however. With only some minor changes, the Guidance can be used in any science-for-policy activity. Furthermore, although a strong emphasis is placed on assessing simulation uncertainty, the methodology encompasses all sources of information used in science-for-policy.

[13] This uncertainty typology is based partly on a paper by Walker et al. (2003). That paper was the result of a process involving some of the uncertainty experts who also participated in developing the *Guidance*. In Walker et al. (2003), uncertainty is classified according to three dimensions: its 'location' (where it occurs), its 'level' (where uncertainty manifests itself on the gradual spectrum between deterministic knowledge and total ignorance), and its 'nature' (whether uncertainty primarily stems from knowledge imperfection or is a direct consequence of inherent variability). Janssen et al. (2003) have extended this typology by adding two additional dimensions (represented by two columns on the right-hand side of the uncertainty matrix) denoted 'qualification of knowledge base' and 'value-ladenness of choices.' In order to make the uncertainty matrix more widely applicable than in model-based decision support studies, two location categories have been added, namely 'expert judgment' and 'data.'

[14] Table adapted from Janssen et al., 2003, with permission from *The Netherlands Environmental Assessment Agency, National Institute for Public Health and the Environment RIVM.*

[15] This is done by directly linking the different cells in the matrix to a list of uncertainty-assessment tools (van der Sluijs et al. 2004).

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