Uncertainty in Texts about Climate Change: A Critical Mathematics Education Perspective

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Skovsmose's concept of the formatting power of mathematics refers to the power of mathematics to influence our reality. The way uncertainty is formatted in mathematized problems influences our perception of the limits of such quantifications. In this paper, we apply concepts from post-normal science to analyse how uncertainty is described and constructed in texts on climate change. We have chosen texts that all refer to a figure developed by the Intergovernmental Panel on Climate Change (IPCC) showing projections of temperature changes, including the source document, a newspaper report and a discussion involving master's students. Uncertainty is addressed quite differently in each of these texts. We discuss how insights into such differences can be valuable for developing critical citizenship.

Introduction

Climate change is one of the most urgent global issues of the 21st century. Despite the huge amount of scientific research on climate change, it is full of uncertainty. There is uncertainty in predictions of how climate change will progress, in predictions of the impacts it will have, and in foreseeing the possible effects of any measures we may take to reduce or mitigate the effects. Mathematics is used to describe climate change, to predict climate change and to communicate climate change (Barwell, 2013). Uncertainty has been identified as a significant mathematical problem in climate change research (Nychka, Restrepo & Tybaldi, 2009). Our attention in this paper is on both the prediction and communication of climate change, with a particular focus on the treatment of uncertainty. We examine how a small sample of texts communicates the projections of the future increase in global temperatures produced by the Inter-governmental

Panel on Climate Change (IPCC, 2013a; 2013b). We trace how information presented in one graph, along with the accompanying text, is taken up in a set of related texts. Uncertainty is a key feature in each of the texts, but is treated in subtly different ways.

Deciding how to tackle climate change requires the engagement of all citizens. To participate in the necessary discussion and debate, however, requires some level of understanding of the mathematics of climate change, as well as, crucially, the role of mathematics in shaping our understanding of climate change and in contributing to the causes of climate change. Mathematics education has an important part to play in preparing citizens for this participation. Based on our analysis, we consider how mathematics teaching might address uncertainty in the future.

Literature Review

Uncertainty is related to the mathematical topics of probability, statistics and mathematical and statistical literacy. Research in mathematics education on these topics is extensive and diverse. For this paper, we highlight a few key points. Research on the critical interpretation of graphs has been interpreted as an important aspect of mathematical and statistical literacy, including in relation to understanding publicly available information:

Several researchers emphasise the importance of a critical approach to interpreting data and graphs. In particular, Monteiro and Ainley (2004) proposed the notion of critical sense, to highlight the importance of relating information in a graph to the context in which it is used. Critical sense can be facilitated by students' existing expertise in the subject of the graph (Langrall et al., 2011).

There are few specific mathematics education studies that consider uncertainty. Pratt et al. (2011), however, reported on their development of a software environment in which students could explore and learn about aspects of risk and uncertainty, although their emphasis was more on risk than uncertainty. Nevertheless, they highlight some important points. They refer to research, for example, that shows that lay people tend to over-estimate risk and suggest that this may be because they draw on contextual information that scientific analyses would not consider:

> Estimations of impact are subjective and may be based on sources of information that are unknown to the expert and these, in a rational way, lead to different reasoning about risk. Real problems are extremely complex in their context-dependence, and generally dependent in reflexive ways on the subjective perceptions of different participant groups. It is often not possible to develop comprehensive quantitative analyses. Nevertheless, the scientific/mathematical viewpoint has tended to dominate over the intuitive and informal viewpoint (p. 328).

Pratt et al. found that participants' reasoning about risk in realistic situations with which they had some familiarity not only drew on mathematical inferences (e.g. of probability); they also drew on personal experience of similar situations and affective responses to the situations.

These findings echo research on the public understanding of climate change. Again, there is research that suggests that lay people have a poor understanding of climate change, but this work often examines strictly scientific understanding and can be characterised as deficit-oriented. Bulkeley (2000), however, in a study involving parents and children, found that:

> …public understandings of global environmental risks involve local knowledges, personal values, and scientific information. In these understandings both the social relations surrounding the issue and the physical risks of climate change are important. Despite the scientific uncertainty and claims and counter-claims that have surrounded the issue of climate change, survey respondents and focus group participants continued to place faith in science and education as the most reliable sources of climate change information (p. 329).

This picture is further complicated by the involvement of multiple actors even in the communication of climate change. Weingart et al. (2000) examined scientific, political and media discourses of climate change in Germany, drawing on texts collected from 1975 until 1995. They observed significant differences in these different domains.

In particular, they noted "scientists politicized the issue, politicians reduced the scientific complexities and uncertainties to CO2 emissions reduction targets, and the media ignored the uncertainties and transformed them into a sequence of events leading to catastrophe and requiring immediate action" (p. 280).

Theoretical Framework

Environmental issues where "facts are uncertain, values in dispute, stakes high and decisions urgent" are referred to as post-normal situations (Funtowicz & Ravetz, 1993, p. 86). Climate change matches this description. Funtowicz and Ravetz (1993) point out that post-normal situations are about socio-political and ethical issues rather than problems which scientists can solve alone (p. 99). Post-normal science includes uncertainty and values as new dimensions of science. They argue that uncertainty and values are interlinked and should be brought to the centre of debates.

In traditional science, uncertainty has been seen as something to control, either by reducing it or by quantifying it through statistical measures. Funtowicz and Ravetz (1993) argue that in a policy situation, the nature of uncertainty is crucial. They divide uncertainty into three forms: inexactness, unreliability and ignorance. Inexactness denotes uncertainty that can be controlled by quantification (e.g. error bars, probabilities). Unreliability refers to uncertainty where interactions of concern are known, but where its quantification is associated with uncertainty. Ignorance is the most severe form of uncertainty, since the unknown cannot be controlled in terms of quantities. These three forms of uncertainty do not denote the 'size' of uncertainty, but rather the degree of the ability to control uncertainty with quantification. In practice, uncertainty can be seen as a combination of these three forms.

Funtowicz and Ravetz also highlight the significance of values in post-normal science. Their significance is also apparent in some of the work reviewed in the previous section, including Bulkeley's (2000) and Weingart et al.'s (2000), which showed that people draw on different forms or sources of information (e.g. personal experience, emotional response, media, etc.). In post-normal situations, then, uncertainty may not be controllable through quantities (e.g. in the case of climate change, there are things that are not known about the climate system). Moreover, the way in which uncertainty is handled may relate to particular value perspectives (e.g. scientists prefer mathematical treatments). Funtowicz and Ravetz, (1993) therefore propose the idea of extended peer review. That is, they argue that the scientific process needs to involve a wider range of participants in order to ensure the inclusion of a range of value systems, sources of knowledge, treatments of uncertainty etc. Extended peer review is a form of quality control performed by non-expert citizens, to review the definition of the problem and the quality of expert advice. This approach presumes that multiple views, interests and knowledge bases are valued. This idea implies a role for education to prepare citizens to participate in this process.

Our thinking about how mathematics education can take up this role is informed by critical mathematics education. Skovsmose (1994) introduced the concept of the formatting power of mathematics, to account for the way mathematics shapes reality. He further argued that the ability to recognize this formatting power and reflect on it is an essential democratic competence in order to balance the experts' influence on politics and society. Barwell (2013) proposed the use of a critical mathematics education perspective to theorise the role of mathematics in conceptualising climate change. In particular, climate change can be understood as what Skovsmose calls a 'realised abstraction': that is, the political response is based on a mathematical version of climate change, developed through the collection and analysis of statistical data, and through the production and use of complex mathematical models. In producing these models, of course, choices are made, based in part on the values of science which privilege some kinds of information (e.g. measurements) over others (human experience). A critical mathematics education involves students engaging with the way mathematics is used to shape our world, as well as engaging with the often hidden human choices that go into this mathematical work. This kind of work prepares them to be critical citizens who can engage in the extended peer community posited by post-normal science.

Research Design

The research we report in this paper was inspired by the study of Weingart et al. (2000) of climate change in different discourse domains. Specifically, we wanted to examine how uncertainty is constructed in a range of discourse domains. For this present study, our research questions were: How is uncertainty in climate change constructed in different discourse domains? What differences are there across different domains?

We began with a particular figure from the recent IPCC (2013a) report, which Hauge had already used in a master's course in mathematics education at Bergen University College (see Figure 1). The figure shows projections for temperatures until 2300 based on four different emissions scenarios (RCPs). We sought texts with explicit reference to this figure. We therefore included: the original presentation of the figure in the IPCC report on the physical basis for climate change, the technical summary of the same report, the IPCC's Summary for Policymakers, a news report that refers to the figure and includes a simplified version of the graph, and a transcript of the master's students' discussion.

In our analysis, we differentiated between explicit uncertainty statements and implicit uncertainty statements. The former include assessed uncertainty, either quantitative or qualitative, and statements where uncertainty is otherwise addressed. Assessments include spread

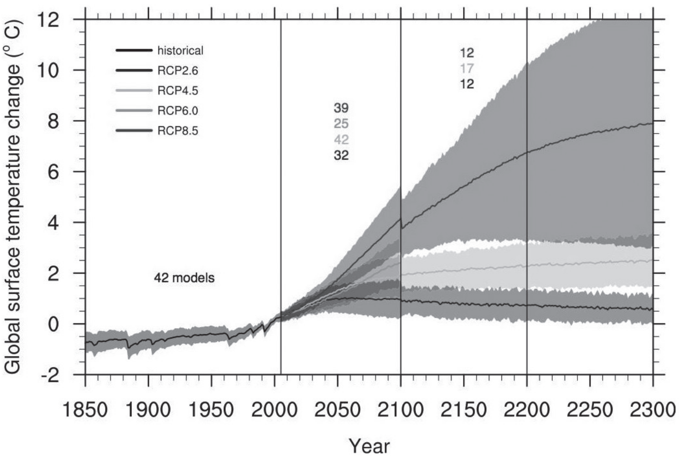

Figure 1: Our selected graph (IPCC, 2013a, p. 1054; original is in colour)

and probabilities, but also qualitative categories for describing uncertainty. Explicit uncertainty statements also include comments on uncertainty or statements on unknown features. Implicit uncertainty statements cover statements where the uncertainty is not explicitly addressed, but the reader can infer that there is associated uncertainty from the context. These uncertainties were then assessed according to the sort of uncertainty the text communicates them to be, based on the forms of uncertainty proposed in post-normal science. Since, however, it can be difficult to distinguish unreliability and ignorance, we merged them into a single form: epistemic uncertainty.

Results

In this section, we present the main patterns observed for each text.

IPCC Working Group Report on the Physical Basis for the Climate Assessment

The IPCC working group explicitly communicates uncertainty in three ways: by quantitative assessments, qualitative assessments and statements about uncertainty. The graph contains quantitatively assessed means and 90% uncertainty ranges related to the predicted scenarios for temperature changes. These intervals are also qualitatively assessed in the text. The following paragraph contains a number of uncertainty statements:

> For these long-term projections, the 5 to 95% ranges of the CMIP5[1] model ensemble are considered the likely range, an assessment based on the fact that the 5 to 95% range of CMIP5 models' TCR[2] coincides with the assessed likely range of the TCR […]. Based on this assessment, global mean temperatures averaged in the period 2081–2100 are projected to likely exceed 1.5°C above 1850-1900 for RCP4.5, RCP6.0 and RCP8.5 (high confidence) (IPCC, 2013a, p. 1055).

The "5 to 95% ranges" refers to quantitative uncertainty measures, while "likely" represents a qualitative uncertainty measure, although it can be linked to quantities. The IPCC applies a likelihood scale for assessing the certainty in results, ranging from "virtually certain", "very likely", down to "exceptionally unlikely" (IPCC, 2013a, p. 36). Each element corresponds to a probability range; for example "likely" represents a probability between 50 and 100%. These probabilities are either based on statistical analysis or expert judgement (p. 36). The 5 to 95% ranges in Figure 1, and described in the cited paragraph, can thus be associated with a probability of 50–100%. This likelihood seems to be based on judgment since it makes little sense to statistically assess the likelihood of an interval. "Confidence" is a qualitative measure of the validity of a finding, based on the degree of evidence combined with the degree of agreement between experts (IPCC, 2013a, p. 36). For example "high confidence" can either refer to high agreement and medium evidence or to medium agreement and robust evidence (p. 36). The two metrics of confidence and likelihood provide a way to communicate that there is uncertainty in the temperature projections, and imply that uncertainty cannot be fully controlled through quantification. Epistemic uncertainty is thereby implicitly communicated, and differentiated through the degrees of confidence and likelihood.

The IPCC offers several explicit statements related to uncertainty in addition to the two certainty metrics. For example: "The likely ranges for 2046–2065 do not take into account the possible influence of factors that lead to near-term (2016–2035) projections of global mean surface temperature [...] that are somewhat cooler than the 5 to 95% model ranges [...] because the influence of these factors on longer term projections cannot be quantified" (IPCC, 2013a, p. 1057). This statement also expresses the factors as the origin of uncertainty.

Uncertainty is also suggested implicitly. From Figure 1, a reader can see that the mean is constructed from up to 42 models, which means that the models do not necessarily produce the same results or the same uncertainty measures. Indeed, the report states: "some CMIP5 models have a higher sensitivity to GHGs[3] and a larger response to other anthropogenic forcings (dominated by the effects of aerosols) than the real world (medium confidence)" (p. 1055). This suggests that because mathematical models are constructed in different ways (different data, different variables, different computation techniques, different statistical approaches, different drivers), they behave differently and produce different results. Other examples of implicitly addressed uncertainty include statements that justify findings by comparing them to previous studies. This implies that "facts" are constructed and settled when there is consistency in findings across research communities. All the implicit references to uncertainty suggest the presence of epistemic uncertainty and that part of the uncertainty cannot be controlled through quantities.

Technical Summary of the IPCC Report on the Physical Basis

The IPCC report described above has a summary section where Figure 1 is also included and accompanied with a brief text. The technical summary presents the main findings in a similar manner to the first excerpt from the report, presented in the previous subsection. The qualitative descriptors of confidence and likelihood are frequent, but implicit uncertainty statements as exemplified above are not included. Neither are sources of uncertainty an issue in the summary, apart from the reference to the number of models in the figure caption. The figure caption in the summary (which is not the same as the caption in the main report) makes an explicit comment about the graph that is not in the main report:

> Discontinuities at 2100 are due to different numbers of models performing the extension runs beyond the 21st century and have no physical meaning (IPCC, 2013a, p. 89).

The discontinuity is thus presented as an artefact (without a physical meaning) resulting from a reduced number of models and model output. Drawing attention to this artefact makes the implicit uncertainty clearer.

The figure is also referred to in the Summary for Policymakers (IPCC, 2013b), when considering the effect of making future energy use within transport more efficient:

> Projected energy efficiency and vehicle performance improvements range from 30 – 50% in 2030 relative to 2010 depending

> on transport mode and vehicle type (medium evidence, medium agreement). Such mitigation measures are challenging, have uncertain outcomes, and could reduce transport GHG emissions by 20 – 50 % in 2050 compared to baseline (limited evidence, low agreement) […] [Figure] 12.5 (IPCC, 2013b, p. 23; Figure 12.5 is shown as Figure 1 in this paper).

The figure is treated as a baseline without supporting uncertainty statements. Rather, the paragraph emphasises uncertainties associated with mitigation measures. This represents another layer of uncertainty, as the uncertainty associated with the figure relates to the effect of emissions on temperature change, while the citation addresses uncertainty related to the effect of mitigation measures on emissions. How uncertainty from one layer affects the other is not addressed in this text.

Newspaper Report

The news text was published in the UK's Guardian newspaper[4] shortly after the IPCC's report was released. It provides a summary of the key points in the report. The language of the report includes little that explicitly indicates uncertainty. Indeed, much of the language implies certainty: for example, "without 'substantial and sustained' reductions in greenhouse gas emissions we will breach the symbolic threshold of 2C of warming". In this kind of expression, 'will' is an expression of certainty. Much of the report follows the same tone, although in one place, 'could' is used rather than 'will'. The report also includes a graph derived from Figure 1. It shows only the range RCP6 until 2100, labelling RCP6 'business as usual'. By stopping at 2100 and only showing one scenario, the graph removes much of the implicit uncertainty in Figure 1, including the 'break' at 2100, and the presence of multiple scenarios. Finally, a section of the report addresses the idea that warming has slowed in recent years, stating that the IPCC report "rebuffed the argument made by climate sceptics that a 'pause' for the last 10-15 years […] was evidence of flaws in their computer models." In this case, the possibility of uncertainty is 'rebuffed' with a defence of the models. Overall, it is noticeable that there is much less indication of uncertainty in the report and the expression of uncertainty is largely not mathematical, although the graph does include temperature ranges and the report includes the statement "global temperatures are likely to rise by 0.3C to 4.8C by the end of the century depending on how much governments control carbon emissions." This statement echoes in simplified form similar statements in the IPCC report.

Students Discussing Temperature Change

In the master's course, the students did not read the report or the summary where the figure is presented. Kjellrun Hiis Hauge briefly explained the meaning of RCP and that the figure represented future global temperature projections related to four RCP scenarios. Previous to the following excerpt, the students were trying to make sense of the figure and the meaning of the coloured shading.

TOR INGE: Where is the limit for where the measurements fall within?

MARIA: It depends on which scenario is taken into account. If you - if they have calculated with an RCP value of 8.5, and that resulted in - those who achieved the lowest values at the … lowest one, right? And then they calculated with the same model with a value of 2.6. And that could have resulted in one of the lowest values there, and - so - while some with a high value could have ended down there. But - what … you can see here is that there's a lot of variation here. That here it seems that they disagree much more.

TOR INGE: More uncertain?

MARIA: Yes, while at the blue, they quite agree all the way, in a way. They are more certain.

Maria is referring both to RCP values and to models, so she seems to have understood that each colour represents one RCP scenario, and that the consequence of each scenario is predicted through a combination of models. Her use of "disagree" indicates that she pictures that at least some of the models do not produce the same predictions. It is not clear whether she pictures stochastic or deterministic models, but in any case she characterises the uncertainty derived from the deviating results as disagreements. She thereby expresses an awareness of an uncertainty that is not controlled.

In the next excerpt, Hauge draws the students' attention to the sudden break in the graph.

KJELLRUN: But if we look at year 2100, what is happening there?
[pause 16 sec.]
ELISABETH: [inaudible] is a break?
KJELLRUN: Yes, why is that?
ELISABETH: At least the red one.
KJELLRUN: Yes, at least the red one, that's very distinct.
ELISABETH: There are fewer models, you know.
[…]
TOR INGE: I'm thinking that the most critical until 2010 do not continue further in the models.
KJELLRUN: Yeah, well that's true.
TOR INGE: So that the curve isn't as steep when it continues.

Elisabeth explains the break by stating that "there are fewer models". By that she indicates that the number of models influence the features of the graph. Tor Inge stresses that the break is a drop by saying "the most critical until 2010 do not continue". He thereby indicates that the projections could have been more severe. Both indirectly express that uncertainty is not controlled and Tor Inge also suggests that uncertainty can influence our understanding of the severity of the situation.

Discussion and Conclusions

The four main texts (including the students' discussion) display some differences in how they treat uncertainty. In the IPCC report, there is much technical uncertainty in highly mathematized form, with some indications of epistemic uncertainty. In the technical summary and the summary for policy-makers, some of the detailed mathematical treatments of uncertainty are reduced. In the news report, there is much less evidence of technical uncertainty in mathematical form, or indeed of epistemic uncertainty. Finally, in the class discussion, the students show some awareness of epistemic uncertainty in their interpretations of the graph. These differences are consistent with the findings of Weingart et al. (2000).

The shifts that occur from the original IPCC report to the summary texts and the news reports suggest that the mathematical treatment of uncertainty in climate science becomes much less visible in texts meant for more general audiences. We suggest that uncertainty is itself formatted by mathematics; it is constructed and interpreted by scientists in largely mathematical terms, which then become much less visible and much less human in subsequent reporting. The effect of this formatting is to construct uncertainty as controllable, while de-emphasising epistemic uncertainty. Thus the news report only really indicates uncertainty implicitly and gives no hint of epistemic uncertainty. Interestingly, in their discussion of the original graph, the students seem able to identify possibilities for epistemic uncertainty.

Acknowledgments

We would like to thank IPCC for granting permission to reprint the figure.

Notes

1. CMIP5: Coordinated Modelling Intercomparison Project phase 5, a joint activity of scientists at a certain stage.

2. TCR: Transient Climate Response: the temperature rise at the time of CO_2 doubling.

3. GHG: Greenhouse gases.

4. "IPCC: 30 years to climate calamity if we carry on blowing the carbon budget." The Guardian, 27 September 2013.

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