Climate Change Economics, Vol. 7, No. 1 (2016) 1640003 (30 pages)

DOI: 10.1142/S2010007816400030

IS THE IPCC's 5TH ASSESSMENT A DENIER OF POSSIBLE MACROECONOMIC BENEFITS FROM MITIGATING CLIMATE CHANGE?

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Accepted 21 October 2015
Published 10 December 2015

This review summarizes what we know about the macroeconomics of mitigating climate change over the period 2010 to 2100 as presented in the 2014 IPCC Working Group III report. The review finds that little more, if anything, has been learned about the macroeconomics of mitigating climate change over the long run since the 2007 IPCC report. Furthermore, while the 2014 report is quite self-critical about the serious weaknesses in its methodologies, the self-criticisms are not explicitly taken into account when the net macroeconomic costs of mitigation are reported. Nor do the research teams that run the integrated assessment models relied on in the report utilize any systematic methodology for assessing the inherent uncertainty in the macroeconomic results reported. Thus, the basic quantitative "findings" are misleading — and, perhaps, even deceptive — in part because they appear to preclude the possibility of large macroeconomic benefits from mitigating climate change.

Keywords: Economics of mitigation; critique of 2014 IPCC report; Integrated Assessment Models; economics of climate change.

1. Introduction

Now that the Working Group III report on mitigating climate change from the IPCC's Fifth Climate Assessment has been published, it is time to reflect on what has been learned about the macroeconomics of mitigating climate change over the long run since the IPCC's Fourth Climate Assessment in 2007, and on what we now know overall about this very important topic (IPCC, 2014). Of course, the macroeconomics of the mitigation of climate change is a fairly broad issue which includes many sub-issues, such as the impact of uncertainty on what one can know over relevant time frames; how the various costs and benefits to society of really slowing down climate change are conceptualized, weighed, discussed, and analyzed; and how the choices and policy options for mitigation facing humanity are integrated into and flow from the macroeconomic analyses on which the Fifth Assessment (AR5) relied.[1] Much of the

[1]This paper will focus on reviewing the material on integrated assessment models and their use for analyzing the macroeconomics of mitigation scenarios that appears in the WGIII report in Chapter 2 (the "Uncertainty Assessment" portions), Chapter 3 (Aggregation of costs and benefits), and Chapter 6 ("Assessing Transformation Pathways").

material on the macroeconomics of mitigation discussed in the 2014 WGIII report is based on dozens of research articles that rely in whole or in part on the running of integrated assessment models (IAMs). The results of more than 1180 scenarios run on these models were collected into a database used for the Fifth Assessment. This review will focus on the question of the scientific adequacy of the IAMs relied on, how they are used, and to what extent they are appropriate for the purpose of assisting policy makers in understanding the key macroeconomic trade-offs through 2100 involved in trying to mitigate climate change.[2]

One of the main issues regarding the use of IAMs is the fact that the results of the 20 major IAMs that underpin most of the analytical literature (published in a group of about 10 major journals from 2007 to 2014) cannot easily be compared. Each IAM not only has a different mathematical structure from others, but also optimizes or computes one of the five different economic indices such as GDP or consumption.[3] It is thus unclear how the results of different models can be compared or used to complement each other, even in theory. These five indices are also the basis for the decisions of the WGIII authors as to whether or not one scenario is "better" for society than another. Overall, the WGIII report authors conclude that there will likely be "costs", not benefits, to society over the long run if it attempts to mitigate climate change, even if the "costs" are fairly small. However, the analytical and conceptual basis for this major conclusion which was the main focus of much media attention is not well grounded in science and logic. Unfortunately, the authors of the WGIII report do not seem to understand how important it is politically to the world to make it clear that large macroeconomic benefits might result from mitigating climate change.

Alternative IAMs also have different strengths and weaknesses because their structures differ, but this issue never seems to be explored in the articles written by the research groups that have developed the models, not even in the published many "multi-model comparison studies" referenced in the WGIII report. Similarly, based on my review of existing documentation, the models appear to utilize different numerical values for dozens of the most important input assumptions needed by all the models for quantifying what are considered to be the "same" scenarios. While this may not be surprising, what is surprising is that the WGIII report does not really try to understand or communicate the consequences of these differences. In fact, the report completely ignores the implications of the fact that different IAMs utilize different numerical values for hundreds of their same inputs.[4] Such omissions raise questions about the scientific basis for any conclusions regarding the macroeconomics of mitigating climate change reached in the 2014 WGIII report, especially in Chapter 6, and about

[2]I will discuss the relevant issues for the period 2010–2100, since that is the period covered by the 2014 WGIII report. Note that the timeframe covered in the earlier Fourth Assessment was only 2005–2050, a much short time period.
[3]See Annex II.3.2 for a discussion of these indices.
[4]It is important to understand that each model has hundreds, if not thousands, of input assumptions since most model at least 10 separate regions of the world. In general, input assumptions for the same variable should vary somewhat between regions, but not always.

what, in fact, we actually know about the macroeconomics of mitigating climate change in the long run to 2100.

Since, the existing IAMs have proven to be inadequate for the purpose of quantifying the macroeconomics of mitigation, this review develops suggestions for how they might be further improved to better aid policy makers in devising solutions for the mitigation of climate change.[5] This review considers not just the adequacy of the models themselves, but the appropriateness of how they have actually been used in the process of attempting to educate these policy makers. The adequacy of the IAMs from a theoretical economics perspective is arguably less important than how they have been actually utilized in the peer-reviewed research papers to create the scenarios relied on by the IPCC WGIII authors. This review will elaborate on some of the arguments made in a very comprehensive book on climate change issues by Mike Hulme, who was head of the Tyndall Centre for Climate Change Research (Hulme, 2009).

2. What are the Basic Economic Findings of the WGIII Report?

The most basic finding of the WGIII report regards what it calls the "costs" of mitigating climate change. In fact, the WGIII report never mentions the real possibility that mitigating climate change could yield substantial macroeconomic *benefits*. Since the WGIII report focuses on the "cost" of achieving various scenarios for mitigating climate change globally over the next 90 years, it begins with a discussion of the various base cases, which are then compared to various levels of mitigation achieved in a wide range of "mitigation" cases or scenarios. The absolute value of the "costs", or really "net costs", of mitigation is computed by simply subtracting the "cost" index, such as GDP, calculated by a particular IAM in each year in the mitigation case, from the value of the same cost index calculated by the same IAM in the relevant base case. For some purposes, these "cost" differences are then present-valued using a discount rate and are reported as a change in the cumulative present value through 2100 for certain mitigation cases relative to others.

The WGIII report states its main macroeconomic findings relevant to mitigating climate change as follows, with "global consumption loss" considered to be the "cost" of mitigation:

> According to the idealized implementation scenarios collected in the WGIII AR5 Scenario Database (Annex II.10), the central 70% (10 out of 14) of global consumption loss estimates for reaching levels of 430-480 ppm CO2eq by 2100 range between 1% to 4% in 2030, 2% to 6% in 2050, and 3% to 11% in 2100 [median of 0.06% per year reduced

[5]In all scientific fields, there is always a debate as to whether it is worth reporting the results of certain models that may not be very good, but are considered the "state-of-the-art" in the field. While the weaknesses of IAMs will be discussed further below, it is always worth remembering that in some fields the "state-of-the-art" models may be so inadequate as not to be worth using in many circumstances. For example, weather forecasting models are fairly reliable for five day forecasts, and even ten day forecasts are routinely published, but no one would give them any credence for 30 days.

growth] relative to consumption in the baseline (p. 449, and Figures 6.22 on 6.23 on p. 452).[6]

Of course, these results are highly sensitive to the cost and other input assumptions for each major energy sector technology, as well as to the structure of each IAM. In particular, the costs of the mitigation scenarios modeled are dependent on the costs of the base cases to which they were compared. Yet, as I argue below, even base case costs are far too uncertain over a period of 90 years to be knowable.[7] Several other types of potential costs or benefits were also omitted from the models and calculations, leaving a very incomplete picture of the possible total costs or benefits of mitigating climate change. This is especially true in the report's Summary for Policy Makers, where the simplest, clearest, and most inclusive statement of the macroeconomic "big picture" for mitigating climate change should be presented.

Unfortunately, there is also no way of knowing whether the input assumptions for either the base cases or the mitigation cases relied on were reasonable, nor what costs or benefits other sets of reasonable input assumptions would imply for the overall economics of mitigating climate change. This is because the numerical values of most input assumptions for IAMs are never included as part of the published research articles, even when Supplementary Materials accompany the main articles. Furthermore, the WGIII authors do not appear to have made the effort to request the input assumption values from each IAM research team, since very few input assumptions used for generating the scenarios relied on were included in the 2014 WGIII report.

Table SPM.2 shows the results for two of the main sensitivity analyses performed for the most stringent mitigation case (reducing atmospheric concentration levels of greenhouse gases to 430–480 ppm CO2eq by 2100). The cumulative discounted costs from 2010 to 2100 increase substantially, namely by 64% and 138%, respectively, when there is "limited bioenergy" and no carbon capture and storage technologies available to mitigate CO_2 emissions. However, given the huge uncertainties involved, these incremental cost results, as in Chapter 6 to three significant figures, are perfect examples of "undue precision" in policy science. And whether these overall incremental "cost" increases due to mitigation are good or bad depends on further conceptual analysis of the economic indices relied on. As emphasized above, the magnitude of the cumulative cost increases cited is obviously dependent on the costs of and constraints on the availability of all the energy supply technologies assumed in each IAM in each scenario run. However, since no cost sensitivity analyses for these

[6]Page numbers in parentheses refer to the 2014 WGIII report unless otherwise stated.

[7]It is quite strange that there is no discussion of the issue of the inherent uncertainties of long-range economic forecasts or projections from any kind of economic models in Chapter 6, since all the results of Chapter 6 are affected by this generic issue. As is well-known today, especially after the recent world financial crisis, even 10-year macroeconomic forecasts are highly uncertain. Furthermore, there is no discussion in Chapter 6 of how relatively small differences between two long-range forecasts, such as between a base case and a mitigation case forecast, could possibly be sufficiently accurate for the purposes of the WGIII report, given that hundreds of parameter values may differ between these two types of scenarios in unknowable ways.

technologies were run or reported on in the WGIII report, it is impossible for policy makers to tell how much these additional percent increases might vary if reasonable ranges of all the relevant technology costs over the period 2010–2100 had been analyzed.

Regardless of how the basic macroeconomic "cost" results for mitigating climate change over the long run are cited numerically, or how large they are, they are deceptive in several ways. Firstly, there is no discussion for each of the five indices that are utilized to compute "costs" in different IAMs as to whether a higher or lower value is better or worse for society. It is implicitly assumed, however, that lower values for most of the five indices, such as GDP, are always worse. Secondly, there is no quantitative discussion of the fact that many of the various uncertainties involved in making such long-term projections of "costs" could be far bigger than the result reported itself. Thirdly, the reader is not clearly informed that the 5% real discount rate used to report the present value results for the sensitivity analyses is inconsistent with the internal discount rates used in some of the models. The 5% figure is also very high for a long-run discount rate and, therefore, very controversial; however, the report neither thoroughly discusses this issue nor provides results using alternative discount rates (Stern, 2007; Nordhaus, 2013).

Fourthly, and most importantly, the reader is not clearly informed that the potentially very large avoided damages to the global economy and ecosystems due to mitigating climate change are not included at all in the key results cited for the costs of mitigation.[8] The avoided damage costs, which are clearly net benefits to society of mitigation, could easily be of the same order of magnitude, if not even greater, than the other "costs" of mitigation. Moreover, other costs and benefits of mitigating climate change have also been omitted from the macroeconomic analysis presented, such as the investments needed to enhance the energy efficiency of end-use technologies in the mitigation scenarios. Thus, the up-front summaries of cost results for policy makers, as well as analysts, should have been clearly described by WGIII authors as based on only a partial analysis of some components of the costs and benefits of mitigating climate change, but not others. Of course, doing this would have indicated to policy makers that the WGIII report had not provided them with a complete and balanced look at the full range of all major costs and benefits, of mitigation.

Thus, there is no serious and comprehensive discussion in the entire WGIII report of the circumstances under which mitigating climate change could yield substantial "net macroeconomic benefits" to the global economy, yet there are surely many plausibly different sets of input assumptions for the various base cases and mitigation cases for which this would be so. In particular, if the costs of new renewable energy resources were much lower in the mitigation case, and if the prices for fossil fuels were much higher in the base case (where demand for them would be high) than in the mitigation case (where demand for them would be much lower), then substantial net benefits

[8]This fact is buried in Chapter 6.

would likely be found for mitigating climate change using any common sense definition of "net benefits". This would especially be the case when estimates of avoided damages were included in the analysis as both Stern and Nordhaus did, even though they disagreed about the magnitude of these possible benefits (Nordhaus, 2013; Stern, 2007).

The remainder of the main findings claimed in the 2014 WGIII report are listed below[9]:

(1) "A robust result across studies is that aggregate global [net] costs of mitigation tend to increase over time and with stringency of the concentration goal" (p. 449). This finding may be true for some of the mitigation scenarios modeled, but it is probably not valid for many other mitigation scenarios that could have been seen with alternative sets of input assumptions, even for the most stringent RCP2.6 scenarios. Since almost no sensitivity analyses seem to have been performed involving major changes in key input parameters like fossil fuel prices, renewable technology capital costs, and the costs of enhanced energy efficiency, we do not know if there would be large net economic benefits, rather than costs, from mitigation in many plausible scenarios. In fact, if economic and ecological damage caused by climate change had been included in the WGIII total cost or benefit results, then mitigation scenarios that met more stringent climate goals might have seen net benefits increase, not decrease, with the degree of stringency. Of course, all these results would be highly dependent on how net economic damages were estimated, among other assumptions. Either way, this claimed "robust result" is primarily a simple mathematical characteristic of these kinds of optimization models given the value of the input assumptions used. One does not need to run an IAM to "discover" this result.

(2) "To a first-order, mitigation involves reductions in the consumption of energy services, and perhaps agricultural products, and the use of more expensive [energy supply] technologies. This first-order effect is the predominant feature and focus of the integrated modeling estimates discussed in this chapter and will lead to aggregate economic losses" (p. 448). Besides the question of whether or not the major implicit assumption that renewable energy technologies will be more expensive than fossil fuel-based energy supply technologies is true, this statement raises two key issues. The first is whether a reduction in the consumption of energy services (especially if primarily due to greater efficiency on the demand side) would be a good thing for the economy. Thus, if greater energy efficiency leads to lower values of GDP, or another economic index, because less money is spent on energy, this should not automatically be considered an "economic loss", for the term "economic loss" connotes a negative outcome for society. A narrowly

[9] These findings are described in more detail in Section 6.3.6, which has the appropriate title "The aggregate economic implications of transformation pathways."

defined "economic loss" might, in some situations, be a "social gain". In theory, aside from what the existing IAMs may compute, greater energy efficiency should allow the money that would otherwise have been spent on energy supplies to be spent on other goods and services, *if* the IAMs are flexible enough to allow for this kind of trade-off between consumption in the energy sector and other sectors. Either way, though, a lower GDP or lower level of consumption might be good for society if the reduction is simply due to consuming less energy.

The second issue, then, is whether or not the models relied on by WGIII are flexible enough to freely allow the substitution of one kind of product for another, such as in the case of energy consumption. However, in the example cited above, the consumption of more expensive energy supply technologies would seem to work in the other direction by increasing GDP, which is not necessarily good for society. The statement made by the WGIII authors implying that a higher value of GDP or consumption is always good requires much further analysis and explanation before it can be accepted as a valid basis for making sound policy to mitigate climate change.

Contrary to much economic dogma, one cannot tell which future scenario is better simply from looking at the magnitude of its GDP or consumption. One needs to analyze the composition of the GDP or consumption to make this determination, as many reports have indicated in the last 10 years, the most prominent of which was Stiglitz (2009). Unfortunately, the authors of the WGIII report never even raise this issue to determine which changes in the GDP or consumption represent something that ordinary people and policy makers would call "economic losses" or "economic gains". A similar analysis needs to be performed for each of the other three economic indices used to measure economic "costs" in the report. (Again, see Annex II for a discussion of these indices.)

(3) "Mitigation will affect economic conditions through several avenues, only some of which are included in estimates from integrated models" (p. 448). This claimed finding hardly seems to be a legitimate finding since the modeling teams knew this from the beginning from the known weaknesses and lack of completeness of their models.

(4) "A major advance in the literature since AR4 is the assessment of scenarios with limits on available technologies or variations in the cost and performance of key technologies" (p. 445). Unfortunately, no references were cited to support the second part of this claimed finding, and it is a very dubious claim given the flaws and limitations of all the scenarios run by IAMs relied on in this report. Again, I could not find any material in Chapter 6 which showed results when the cost and performance of key technologies was varied.

(5) There are many mitigation scenarios produced by IAMs that can reduce greenhouse gas emissions enough to meet the lowest emissions target typically modeled, namely the RCP 2.6 emissions trajectory (Figure 6.7). These mitigation scenarios may allow the average global surface temperature increase to remain

under 2°C by 2100, depending on the "climate sensitivity" assumed. This is the global temperature impact due to a doubling of CO_2 concentrations relative to pre-industrial times, assumed in the physical climate modules (Figure 6.13). The main economic results reported in the 2014 WGIII report all assume a climate sensitivity equal to 3.0°C in spite of the fact that the climate sensitivity ranges from about 1.5°C to 4.5°C (IPCC, 2013). Note, again, that none of the so-called "probability" estimates in the text represent knowable probabilities of being able to meet any given temperature target. These "probabilities" only represent distributions of temperature results from several dozen physical climate models, which are not a reflection of real-world probabilities for climate change outcomes, as the report acknowledges.[10]

(6) "Research has consistently demonstrated that delaying near-term global mitigation as well as reducing the extent of international participation in mitigation can significantly affect [increase] economic costs of mitigation" (p. 453). This "finding" again appears to be based on a simple quantitative mathematical truth, because when any IAM that relies on an optimization process is run, any additional constraints on the solution, such as delaying the willingness of various nations to participate in mitigating climate change, will automatically increase costs or lower the economic benefits of mitigation when expressed in terms of the economic index being optimized. The quantitative results are new.

(7) "Mitigation scenarios indicate that meeting long-term goals will most significantly reduce coal use, followed by unconventional oil and gas use, with conventional oil and gas affected the least" (p. 443 and Figure 6.15 on p. 442). This "finding" is, of course, not new, and it is fairly obvious to all experts in the energy economics field, since it is consistent with the idea of prioritizing the reduction of the use of fossil fuels in order from highest carbon content to the lowest carbon content. Of course, the relative costs of different fossil fuels would alter these qualitative results somewhat.

(8) The carbon intensity of primary energy resources will, on average, decrease faster over the long run than the energy intensity of final energy demand in the stronger mitigation scenarios (p. 443 - Figure 6.16). This would be an interesting finding if it were always true. I assume that what is meant by this finding is that it is economically more cost effective, in general, to move towards an energy supply mix with lower CO_2 emissions faster than it is to move to higher levels of energy efficiency on the demand side of the economy. However, since the IAMs relied on by the WGIII authors do not, in general, allow for cost effectiveness tests to be run for enhanced energy efficiency technologies, there does not appear to be sufficient evidence presented in the WGIII report to justify this conclusion. I believe the

[10]The range of climate sensitivity results reflects what physical and chemical effects, and interactions, different research teams decided to include in their models. Often, these choices were constrained in order to allow the climate models to run on a computer in a reasonable amount of time, and thus did not even reflect the full range of knowledge of climate scientists about climate change.

> levels of enhanced energy efficiency assumed in the mitigation scenarios relative to the base case scenarios are "hardwired" into those scenarios, and no incremental investment costs are included. The more rapid trend towards lower carbon intensity on the supply side compared to higher energy efficiency on the demand side appears to be simply a function of the limited sets of assumptions made by the modeling teams, rather than a result of careful and comprehensive economic analysis.

Given all the work that went into running the roughly 1180 scenarios and more than 30 models over the previous seven years since the AR4 reports, most in the course of performing multi-model comparison studies, the very limited set of findings listed above might be described as rather anticlimactic to experienced modelers. In particular, some of these findings do not depend on running scenarios through models at all. Similarly, some of the "findings" either are incorrect or unknowable, as indicated above, since many of the claimed results would be swamped by the relevant uncertainties in the model results, if the relevant uncertainties had been properly addressed.

In summary, the main finding on the macroeconomic "costs" of mitigation through 2100 is the one on which both the IPCC and the media have put the most emphasis. Namely, if society wants to try to keep the average global temperature increase to 2°C or lower, then society will have to incur small but significant levels of "costs", in contrast to experiencing significant economic benefits. One major reason why the existence of benefits has almost never been calculated and highlighted in WGIII reports is that each IAM run for a mitigation scenario has been run under very narrow (often only one) sets of most input assumptions. Thus, in general, the IAM research teams have never used their models to systematically explore the question of which realistic sets of input assumptions would yield economic benefits to society if mitigation is implemented, versus which sets of input assumptions would yield net economic costs for mitigation, even if possible avoided damage costs are not included in the total.

3. The Structure of the Models

In order to determine what macroeconomic insights arise in the AR5 WGIII report, it is important to first understand some aspects of the structures of the models used. Section 6.2.1 of Chapter 6 provides a very brief (1.5 page) overview of the types of IAMs on which all the basic global macroeconomic results for mitigating climate change depend in all the scenarios analyzed. More specifically, Chapter 6 "relies heavily" on IAM results from a set of inter-model comparison studies listed in Table 6.1 (p. 421).[11] These inter-model comparison studies were carried out by about 20 research teams, depending on the study, between 2008 and 2014. Clearly, given the major importance

[11]The complete list of IAMs relied on that appears in Table A.II.14.

of the models used in these inter-model comparison studies, a 1.5 page summary is not nearly sufficient to provide clear insights into the structures and the strengths and weakness of about 20 models'. Moreover, the scientific basis for any of the IAMs is never discussed in the WGIII report, nor are any references provided which explicitly document the scientific basis for the models. Despite such major omissions, Chapter 6 describes five key generic features of the models.

First, the models "represent many of the most relevant interactions among important human systems (e.g., energy, agriculture, the economic system), and often represent important physical processes associated with climate change..." (p. 422).

Second, the models are "simplified, stylized numerical approaches to represent enormously complex physical and social systems." Chapter 6 explains further,

> "They take in a set of input assumptions and produce outputs such as energy system transitions, land-use transitions, economic impacts, and emissions trajectories. Important input assumptions include population growth, baseline economic growth, resources, technological change, and the mitigation policy environment. In creating mitigation scenarios, the models attempt to minimize the aggregate economic costs of achieving the specified mitigation outcome by assuming fully functioning and competitive markets, but the same type of minimization process is used for the base or reference cases as well" (p. 422).

The underlying macroeconomic models within IAMs do not model financial crises or business cycles because they omit most social and political forces.

Third, for those IAMs which attempt to optimize or minimize various measures of aggregate costs, such as GDP, over the time period for which they are run, some include all the information available for the entire time period (2005–2100) in their optimization procedures (perfect foresight models), whereas some only take into account the information that is available as of the year for which they are computing results (myopic models). These differences in computational methodology often translate to the use of a different economic metric for stating results (p. 449 and Annex II).

Fourth, all the major IAMs divide the world into about 10–20 regions and include some forms of trade between these regions, especially in fossil fuels. But each model handles trade differently from other models. Different models also have different built-in degrees of "flexibility" in terms of "how easily capital can be reallocated across sectors [of the economy], including the premature retirement of capital stock, how easily the economy is able to substitute across energy technologies, whether fossil fuels and renewable resource constraints exist, and how easily the economy can extract resources" (p. 423).

Fifth, models "differ dramatically in terms of the detail at which they represent key sectors [of the economy] and systems" (p. 423). Different models even include different sets of energy supply technologies, which are central to modeling climate change. Most sectors of the economy are represented in an extremely aggregate way in most IAMs, such that more types of industry, transportation, and commercial and residential buildings may all be modeled using a single equation each, in each region of the world, depending on the model. Within each sector, the costs of some technologies, especially energy supply technologies, change over time based on exogenous input assumptions, and some models calculate changes in technology costs over time endogenously based on sets of equations developed for this purpose. Also, different models even include different sets of greenhouse gases in their emissions inventories, and some models did not include emissions from all the most common greenhouse gases, another important structural difference.

One consequence of this very high degree of aggregation is that most IAMs cannot directly and explicitly model the costs and benefits of improvements in the energy efficiency of end-use technologies within each economic sector. For example, changes in the energy efficiency of lighting in buildings cannot be distinguished from changes in the efficiency of air conditioning, because there is usually one equation that includes both. Similarly, efficiency improvements in the chemical industry cannot be distinguished from efficiency improvements in the iron and steel industry in most, if not all, IAMs. This lack of disaggregation implies that capital investments in enhanced energy efficiency technologies on the demand-side are not typically included, even though these investments may add significantly to the costs of mitigation (Fujimori *et al.*, 2014). Similarly, the energy flow implications of possible changes in the product mixes of each major industry cannot be determined, which makes lifestyle or culturally induced changes impossible to model, especially in the long run when they are likely to be quite substantial.

A lot more can also be learned about the general structure and capabilities of the IAMs relied on from the report's description of what the models cannot do, or do not include. As noted above, "the majority of these scenarios [relied on] were produced as part of multi-model comparisons." (p. 423). This implies that Chapter 6 the 2014 WGIII report is basically one very large and complex multi-model comparison study which depends on the results of about 1180 base case or mitigation scenarios run at different times since the AR4 report, and by different models, or by different versions of the same model. These scenarios were amassed into a large database maintained by IIASA.[12]

Here is a partial list of what the report explicitly says was not done or could not be done using these IAMs.[13] Some of these points further amplify the presentation above.

(1) The "cost" calculations generally do not include the economic benefits to the world of avoiding climate change-caused damage to the global economy

[12]IIASA is the International Institute for Applied Systems Analysis in Austria. The database and models from which scenarios were included are described in Annex II.

[13]This list is primarily taken from the sections of the WGIII report 6.2 and 6.3.6 entitled "Tools of analysis" and "The aggregate implications of transformation pathways," respectively.

(p. 448). Yet, these might be so large in the future as to exceed the direct costs of climate mitigation itself.

(2) The "cost" calculations generally do not include many economic co-benefits of mitigation such as the health benefits of lower air pollution levels and adverse side-effects from mitigating climate change (p. 448).

(3) The "cost" calculations generally do not take into account the impact of mitigating climate change on "pre-existing distortions in labor, capital, energy, and land markets, and failures in markets for technology adoption and innovation, among other things" (p. 448). This limitation probably means that mitigation scenarios cannot be the economic benefit of eliminating these distortions where appropriate, but a more complete discussion of these issues would have been helpful.

(4) The "cost" calculations are directly and especially sensitively affected by each of the large set of energy sector supply technologies included in each model. Different models include different sets of such technologies and, presumably, different physical constraints on when and how much of each technology can be implemented in a scenario depending on the relevant economic trade-offs and other unspecified factors relevant to the affected region. In addition, assumptions about the future cost and performance of these technologies "vary across models, even within a single multi-model study" (p. 451). This almost certainly implies that fundamental input assumptions such as the costs of fossil fuels for each future year also vary between IAMs for what is called the "same" base case or mitigation scenario. Unfortunately, as noted above, most of these important assumptions are never presented in the relevant published research papers, and do not even appear in the model documentation that currently exists on research team websites in a comprehensive format.[14]

(5) Model results vary substantially due to "differences in assumptions about driving forces such as population and economic growth and the policy environment in the baseline, as well as differences in the structures and scopes of the models" (p. 449). These so-called "driving forces" are often the most important characteristics of either a base case or mitigation scenario, but there are hundreds of other important exogenous or endogenous parameters, the values of which the models need to run. The values of these assumptions were not varied in a systemic way to help quantify uncertainty. Thus, the cost results "do not capture uncertainty in model parameter assumptions" (p. 449). This is a vast understatement of the problems caused by uncertainty. An example of a key model parameter assumption is the price of oil until 2100. Obviously, no one knows what that price in 2100 is likely to be, yet the impact of parameter uncertainty on IAM results for the future is barely discussed in the WGIII report. Again, there are hundreds of parameter values for the future in each model that are all very uncertain (Rosen

[14]This claim is based on the author's extensive review of IAM website documentation.

and Guenther, 2015). Since many of the equations in each model have to be econometrically estimated from historical data, the values of these internal equation parameters, as well as the structure of the equations themselves, will also likely change in indeterminate ways over such a long period of time as from now to 2100. There is even a lot of uncertainty associated with values used for base year data, given the well-known problems associated with global data collection.

(6) The final energy demand per unit of GDP is assumed to be able to drop by as much as 50% relative to 2010 levels by 2030 in some 430–530 ppm CO2eq mitigation scenarios (Figure 6.16), and by 90% by 2100.[15] But, there is no information provided as to how this is possible from an engineering perspective, and what the gross cost of accomplishing these substantial reductions would be. Yet, the costs and benefits of achieving these incremental energy intensity reductions relative to the base case are needed in order to properly compute the net costs of these mitigation scenarios relative to the base cases on a consistent basis.

(7) The IAMS used to compute the costs of mitigating climate change, and particularly the macroeconomic sub-modules used to forecast the economy, "do not structurally represent many social and political forces that can influence the way the world evolves (e.g., shocks such as the oil crisis of the 1970s)" (p. 422). In other words, they are simplified macroeconomic models.

(8) The IAMs "typically assume fully functioning markets and competitive market behavior, meaning that factors such as nonmarket transactions, information asymmetries, and market power influencing decisions are not effectively represented" (p. 422). Unfortunately, when dealing with energy markets, which are one of the major foci of climate change IAMs, the assumption of competitive market behavior is far from the truth. For example, it is well known that all societies, even those in energy-efficient Europe, have underinvested in more efficient energy end-use devices (Grubb, 2015). This is especially true in the transportation sector, but it is also true for buildings and industry.

(9) "The models do not generally represent the behavior of certain important system dynamics, such as economic cycles or the operation of electric power systems important for the integration of solar and wind power, at the level of detail that would be afforded by analyses that the focus [sic] exclusively on those dynamics" (p. 422).

(10) Chapter 6 further acknowledges that "integrated modeling approaches can be very different, and these differences can have important implications for the variation among scenarios that emerge from different models" (p. 422). Even though the 2014 WGIII report briefly acknowledges that various differences in model structures will lead to very different model outcomes, the report never discusses this issue in appropriate detail. This is, in part, because the

[15]"Ppm CO2eq" means "parts per million of CO_2 equivalent for all greenhouse gases in the atmosphere."

peer-reviewed literature basically makes no credible attempt to analyze the scientific basis for different results from different models for the "same" scenario, where all values of inputs have been harmonized for the same input parameters wherever possible in order to allow for such an analysis.

(11) "Models differ dramatically in terms of the detail at which they represent key sectors [of the economy such as buildings, transportation, land-use, and industry] and systems" (p. 423). While this may be true, all the IAMs represent the economy in far too aggregate a fashion to allow for many possible changes in the mix of goods and services in the future to be explicitly represented, as noted above. Furthermore, because of the highly aggregated representation of the economy, many interesting mitigation policy options cannot be modeled at all, thus greatly limiting the usefulness of these models for policy makers, contrary to the basic intention of the entire IPCC report process.

(12) "Some models include only CO_2 emissions [excluding other greenhouse gas emissions], many do not treat land-use change (LUC) and associated emissions, and many do not have sub-models of the carbon cycle necessary to calculate CO_2 concentrations [in the atmosphere]" (p. 423). These structural differences between models make it very difficult, in principle, to compare model results in terms of their likely impact on climate change, and in particular to analyze the incremental role of bioenergy in mitigative scenarios. Only modeling CO_2 emissions is not nearly sufficient when trying to predict climate change, since other greenhouse gas emissions contribute significantly to total global temperature changes. It is difficult to accurately correct for the omissions of other greenhouse gases.

(13) Some models rely on exogenous inputs for describing technical and cost changes for energy supply technologies from 2010 to 2100, and other models endogenously compute changes in technology cost and operating parameters, usually as a function of "deployment rates or investments in research and development" (p. 423). These limitations would have several implications for doing proper cross-model comparisons of scenario results, if they had been attempted. Firstly, if certain parameter values are calculated endogenously, it is difficult to ensure that they can be set to equal to the same inputs to other models in order to be able to run different models for the same exact scenario. Secondly, endogenously calculated parameter values are typically much less transparent in that it is also often difficult to even "pull" them out of model runs in order to inform the reviewers of research papers what their values were. This is likely one reason why it is almost impossible to find these endogenously determined parameter values in the literature relied on by the WGIII report, either in the research papers themselves, or in the partial documentation of the models available on research team websites.

(14) "There is an unavoidable ambiguity in interpreting ensemble results in the context of uncertainty.... [T]he scenarios assessed in this chapter do not represent a random sample that can be used for formal uncertainty analysis"

(p. 423). This sentence, with which I agree, implies that it is impossible to development any probabilities for any particular economic scenario results from IAMs, in spite of the fact that the 2014 WGIII claims to report such probabilistic results (Meinshausen *et al.*, 2011).

(15) "While all models assume increasing per capita income and declining energy intensity [in both the base and mitigation cases], broad ranges are projected and high uncertainty [emphasis added] remains as to what rates might prevail" (p. 426).

4. How were the Models Used to Compute the Costs of Mitigation in AR5 Compared with AR4?

Section 6.2.3 provides a discussion of how the results of many of the multi-model studies, such as those listed in Table 6.1, were interpreted and used in the 2014 IPCC analysis of the macroeconomics of mitigating climate change (pp. 423–424). But first, it is appropriate to describe what was new about the mitigation scenarios analyzed for AR5 relative to AR4. What progress was made in designing useful scenarios? As section 6.1.2 describes, what was new in AR5 was fairly limited.

Firstly, what is not even mentioned in the IPCC report is that base year data for the models was generally claimed to be updated to 2005, and some scenarios appear to have been normalized to an even more recent base year such as 2010.[16] In addition, for AR5, the "long run" became through 2100, whereas in AR4 the model results were only reported through 2050. This extension of the economic analysis to 2100 in AR5 introduced another large "dose" of uncertainty into the results and, therefore, was completely unnecessary and unhelpful for enhancing policy analysis. The degree of uncertainty in model results through only 2050 is, though, still overwhelming.

Secondly, the mitigation scenarios for AR5 were generally grouped into four categories, i.e., four resource concentration pathways (RCPs) that reflected four different levels of radiative forcing that could be achieved in the year 2100, the endpoint of the economic analysis. These four different levels of radiative forcing were assumed to bracket the full range of reasonable outcomes of both base case and mitigation scenarios by 2100. Thus, to facilitate the comparison of the economic results from different models for all scenarios, it made sense to at least have the different models attempt to replicate approximately the same results for climate change by the same year (2100), since these levels of radiative forcing fairly directly correlate with the incremental average global temperature changes due to human-caused climate change.

Thirdly, many more scenario runs were developed for the lowest level of climate change (RCP2.6) than had been done in AR4 (section 6.1.2, pp. 420–422). Many more

[16]While the claim has been made at meetings of the Integrated Assessment Modeling Consortium, namely that all models used by its members have been updated to a base year of at least 2005, what this means in practice is not clear. For example, it is not clear how internal model parameters have been re-estimated for this period of historical data ending in 2005, assuming that they have been. It is impossible to find any quantitative description of the parameter estimation process for most if not all the models on which the 2014 WGIII report has relied.

scenarios were also developed in which action to mitigate climate change was delayed relative to a more economically optimal pathway of earlier mitigation in various regions of the world.

Finally, mitigation scenarios were run with different constraints on the types of low or negative carbon emissions technologies that were assumed to be available for implementation globally or regionally. Note, however, that these changes reflect very few differences in the mitigation policy options that were modeled and analyzed in AR5 relative to AR4, primarily because representation of the economy in the IAMs remained extremely aggregate. In fact, the basic structures of the various IAMs used in both AR4 and AR5 seem to have changed fairly little. This high degree of aggregation prevented the various IAM development teams from modeling many important and interesting policy options, such as regulations on the efficiency of end-use technologies, which are common throughout the world already. There are also dozens of additional climate change-related policy options, such as the electrification of vehicles, that cannot typically be modeled by IAMs because they are not sufficiently disaggregated to include different end-use technologies.

Another change between AR4 and AR5 was the way results were collected and presented. Results from "multi-model comparison studies" were fed into a large standardized database of scenarios maintained by IIASA in Austria. Section 6.2.3 of Chapter 6 begins, "The interpretation of large ensembles of scenarios from different models, different studies, and different versions of individual models is a core component of the assessment of transformation pathways in this chapter. Indeed, many of the tables and figures represent ranges of results across all these dimensions" (p. 423). However, what this description omits is that even for what was often considered to be the "same scenario", almost all the input assumptions for critical variables like technology costs, operating parameters, and fossil fuel prices were also different in different IAMs. Thus, to the extent that a few input variables were occasionally "harmonized" across all models for a particular scenario, the harmonization usually only included population, GDP growth, and carbon dioxide allowance prices.

While the issue of uncertainty of results was discussed more in Chapter 2 than it was in Chapter 6, the authors of Chapter 6 conclude, "[T]here is an unavoidable ambiguity [emphasis added] in interpreting ensemble results in the context of uncertainty" (p. 423). By "uncertainty", I assume the authors are referring to the uncertainty in the values of hundreds of input assumptions, internal model parameter values, and model equations across all the regions modeled. This uncertainty exists both in the base year (since the data on which models are built is highly imperfect), and in each future year until the end of the study period. Thus, relative to considerations of uncertainty and its impact on all model results, the situation seems to be basically the same for the AR5 model runs as it was for the AR4 model runs.

But does the WGIII report provide an honest and complete assessment of the problem of how to interpret the new ensemble of over 1100 scenarios from the various IAMs collected for analysis in AR5? Unfortunately, the authors' use of the word "ambiguity" above does not fully capture the analytical challenge presented here. In fact, the scientific challenge of comparing and interpreting the results of over 1100 scenario runs by different IAMs utilizing different input parameter values is an impossible challenge to carry out. Under these conditions, each IAM is like a "black box" which produces various outputs for each scenario modeled, but where neither the equations nor the input assumptions are known. In such circumstances, it is scientifically meaningless to compare the results of the different models in various figures and tables as is done extensively in Chapter 6.[17] There are no possible scientifically valid insights that can be learned from the type of scatter or ranges of results shown because the cause of that scatter cannot be understood.

Even the authors of the 2014 WGIII report conclude section 6.2.3 by saying, "The synthesis in this chapter does not attempt to resolve the ambiguity associated with the ranges of scenarios, and instead focuses simply on articulating the most robust and valuable insights that can be extracted given this ambiguity" (p. 424). However, as this review has already argued, no "robust and valuable insights" can be extracted from this mass of results at all in light of the way in which the scenarios were created.

5. What are the Main Uncertainties Cited in the WGIII Report that Affect its Macroeconomic Analysis of Mitigating Climate Change?

Chapter 2 of the 2014 WGIII report does a fairly good job of laying out many of the relevant uncertainties that affect the macroeconomic analysis described later in Chapter 6. Unfortunately, the analysis in Chapter 6 ignores the warnings implied by the discussion of uncertainty in Chapter 2, and is presented as if that discussion did not even exist (Funtowicz and Ravetz, 1990). Of course, there was a different set of authors for Chapter 2 than for Chapter 6, so it may not be surprising if these authors did not check each other's work for consistency. Some of the key aspects of uncertainty discussed in Chapter 2 were the following:

(1) The Executive Summary stresses that "the social benefit from investments in mitigation tends to increase when uncertainty in the factors relating GHG emissions to climate change impacts are considered." This also implies that "investments in mitigation measures should be accelerated" (p. 154).

(2) With respect to the probabilities of achieving various temperature targets by a given year that are cited throughout the WGIII report, section 2.5.7.2 explains that "there is no established formal method to generate PDFs [probability density functions] based on results from different published studies" (p. 175). In other words, while running different physical climate models gives different results for temperature increases for the same level of GHGs in the atmosphere, one cannot take those results, which exist for an ensemble of about 40 or so models, and turn

[17] Examples of such misleading figures and tables include almost all the figures and tables in section 6.3, even when one of the five cost indices is not explicit in the figure or table.

the range of the results into a probability distribution for the likelihood of achieving a specified temperature target in a given future year. Those actual "real-world" probabilities are unknowable, and, therefore, all the "probabilities" or "likelihoods" cited throughout the WGIII report are incorrect and misleading.[18] This limitation on the usefulness of the physical climate models for computing probabilities of specific outcomes would also apply, of course, to economic model results, in that distributions of economic results from different IAMs cannot be translated into the probabilities of certain economic outcomes either. Nor can one even know the probability of any particular future value for any particular input parameter, or estimated parameter in an IAM, such as the price of oil or photovoltaic cells in 2050 (Rosen and Guenther, 2015).

(3) "Climate policy assessment should be considered in light of uncertainties associated with climate or damage response functions, the costs of mitigation technology and the uncertainty of climate change" (p. 179). In light of this admonition in Chapter 2, it is instructive to repeat the fact that the results as reported in Chapter 6 for the macroeconomics of mitigating climate change in the long run do not take into account damage response functions at all, they do not consider the results of sensitivity analyses based on varying the future costs of mitigation technologies over reasonable ranges of assumptions, and they do not directly consider the potential impact on the macroeconomics of mitigating climate change of uncertainty in the physics of climate change itself. This is, in part, because the basic GHG constraint scenarios, known as the RCP scenarios, assume the mid-range climate sensitivity of 3°C for all the results from IAMs relied on in the 2014 WGIII report.[19] In particular, no scenarios were run looking at the economic implications and risks of climate change scenarios with higher levels of climate sensitivity, such as a 4.5°C level, or examining low probability but high impact climate damage scenarios (Weitzman, 2009; Pindyck, 2013).

(4) Enhanced energy efficiency and behavioral change as potential aspects of mitigation scenarios were discussed briefly in section 2.6.5.3. This section focuses on the economic and cultural impediments to a greater rate of implementation of various higher energy efficient technologies. However, the macroeconomic analysis presented in Chapter 6 fails to analyze the long-run macroeconomic benefits to society from the introduction of higher levels of efficiency. This issue introduces costs and new elements of uncertainty, thus policy makers are left in the dark about what kinds of economic incentives for comprehensive new investments in efficiency would be cost effective and, therefore, which incentives could easily be

[18]Note that the original papers by Meinshausen during 2011 that developed the set of MAGICC models used in the IAMs relied on by the WGIII authors of Chapter 6 also acknowledged that the MAGICC models only represented distributions of physical science model results, and not true probabilities that apply to the real physical world.

[19]Only the so-called "probability" of achieving various temperature increases was calculated based on the MAGICC6 model, but other implications of different climate sensitivities were not modeled.

justified to promote greater levels of enhanced energy efficiency in each of the four basic RCP scenarios.

(5) Another overwhelming source of uncertainty is that inherent in forecasting the underlying economic growth for the next 90 years for all scenarios. Obviously, the uncertainty in the forecasted economic growth rates assumed are huge, but this issue is never mentioned in the technical analysis presented in Chapter 6 (Saltelli and Funtowicz, 2014; Saltelli *et al.*, 2015; Hulme, 2009). This implies that no attempt was made to analyze how long-run mitigation costs or benefits might vary with changes in the underlying economic growth assumptions. This alone is a glaring omission in the economic analysis. And while, technically, the authors of Chapter 6 could only rely on the published literature for their analysis, many of these authors were also responsible for designing and publishing the research papers that led to many of the scenarios input to the IIASA scenario database. Thus, they could have performed these important sensitivity analyses in their original research programs.

(6) The authors themselves state that "policies to mitigate emissions are extremely complex and arise in the context of many different forms of uncertainty. While there has been much public attention to uncertainties in the underlying science of climate change... profound uncertainties arise in the socioeconomic factors addressed here in Working Group III. Those uncertainties include the development and deployment of technologies, prices for major primary energy sources, emissions patterns.... In general, these uncertainties and complexities multiply those already identified in climate science by Working Groups I and II" (p. 114). This set of admissions by the authors makes it all the more inexplicable why any macroeconomic results were published for the "costs" of mitigation for as long a time period as through 2100 (Hulme, 2009).

(7) Similarly, there are uncertainties due to the structure of the various models falling short of an "ideal" model structure, uncertainties due to data quality problems in most of the world, uncertainties due to the methodologies used for making statistical estimates for the values of parameters internal to the model equations, uncertainties due to not knowing how model equations and parameter values should change in the future as economies grow and change, and uncertainties as to how future technologies of all types would perform in the conditions that they face in various regions of the world. None of these uncertainties were either mentioned or analyzed relative to the long-run impact they might have on the economics of mitigating climate change. Yet many analysts have pointed out that the more society attempts to change a business-as-usual technology development trajectory in order to strongly mitigate climate change, the more the structure of the rest of the economy and human behavior will likely change (Stern, 2007).

(8) Similarly, determining the exact cost required to achieve any particular climate change goal is difficult because the models that are used to analyze emissions must contend with many uncertainties about how the real world will evolve (p. 422).

> In addition, the authors acknowledge that "the scenario literature does not systematically explore the full range of uncertainty surrounding development pathways and the possible evolution of key drivers such as population, technology, and resources" (p. 418). This is a serious understatement. For example, the scenario literature relied on here does not even systematically explore the impact on the cost of fossil fuels of the uncertainty in the amount of fossil fuel resources that exist, or on the demand for fuels, a topic that one would think economists would be eager to research for both baseline and mitigation scenarios.

Aside from large uncertainties that affect most input assumptions over 90 years, the nonlinearity of the macroeconomic equations within each IAM also plays a very significant role in determining severe limits on the time period over which macroeconomic forecasts might be reasonably accurate. It is my hypothesis that this limit is at most 10–20 years, not 90 years[20] (Hulme, 2009). A good analogy can be drawn to the physical climate models themselves. For these models, as stated earlier, a mere doubling of CO_2 in the atmosphere yields a range of climate sensitivities that vary by a factor of 3 depending on the model used, even though the physical parameters in the equations do not change over time, because the laws of physics and chemistry do not change. In contrast, the parameter values in economic models do, in general, change over time in unpredictable ways because human behavior is involved. Another modeling analogy with regard to the time limits for valid projections comes from daily weather forecasting, as mentioned in footnote 5.

6. What are Some of the Questionable Aspects of the Base and Mitigation Cases Relied on in the WGIII Report?

After describing the "tools of analysis", Chapter 6 presents a discussion of the base cases from the literature on which it relied. Then, these base cases are compared to a wide range of mitigation cases generally separated into the four RCP types, from weakest degree of mitigation to strongest: RCP8.5, RCP6.0, RCP4.5, and RCP2.6. The numbers in the four RCP names refer to the radiative forcing levels in watts per square meter that the mitigation scenario was designed to match in the year 2100, above the pre-industrial radiative forcing level. This radiative forcing level is due to the amounts of all greenhouse gases, not just CO_2, residing in the atmosphere in 2100.[21]

[20]Note that it is up to the authors of Chapter 6 to provide documentation and argumentation that longer forecasts than 10–20 years can be reasonably accurate and useful for policy makers, not for me to disprove this possibility (Saltelli and Funtowicz, 2014).

[21]The term "radiative forcing" is a physics term that refers to the measure of the total amount of radiation trapped in the atmosphere on an average annual basis by the various greenhouse gases, such that this amount of radiation can no longer escape back out into outer space from the Earth. In other words, it is a measure of how much the Earth system will warm on an incremental basis above the pre-industrial period because this incremental amount of radiation is trapped. Once the Earth system reaches equilibrium with a specific radiative forcing level, the radiative forcing level would correspond to a unique rise in the average temperature of the air, water, and land around the globe, but this equilibrium takes hundreds of years to reach.

Since most realistic mitigation scenarios involve fairly slow changes to greenhouse gas concentrations in the atmosphere over the next 90 years, all mitigation scenarios that have the same concentrations of these gases by 2100 will not necessarily have identical air temperature increases by 2100, although the increases will be very close. For an exact temperature equilibrium to be achieved, all the water in the oceans needs to warm up sufficiently by the mixing of deep and surface layers, and the water needs to absorb its equilibrium level of CO_2, which takes a very long time. In addition, equilibrium needs to be achieved between higher air and water temperatures, the amount of ice stored in glaciers and ice caps, and the amount of CO_2, methane, and other greenhouse gases stored in the soil and biomass.

Section 6.3.1 presents the results of base case scenarios taken from the IAM database assembled at IIASA. Most scenarios are based on a fairly narrow (+/− 10%) range of global population forecasts through 2100 (p. 425). In contrast, even for these baseline forecasts, the most important driver of growth in GHG emissions, namely GDP growth per capita, has a huge spread between different IAMs of about +/− 40%. Some of these GDP forecasts are input exogenously to the models, and some are endogenously generated. Figure 6.1.b illustrates this wide range. Since the focus of this review paper is on methodology, I will not focus much attention on actual numerical assumptions and results, but it is very strange that almost the entire range of GDP per capita forecasts through 2100 is far above what this figure reports as the historic global growth rate from 1970 to 2010, which was only 1.4% per year. The median GDP per capita forecast is almost twice as high as this historic average.[22] This leads to a global average level of GDP per capita in 2100 almost a factor of 6 higher than in 2010, a seemingly implausible result which requires rigorous justification, especially in light of recent economic history (Hulme, 2009). However, there is no such justification provided in Chapter 6. (And, of course, higher GDP growth implies higher costs of mitigation, everything else being equal, because the marginal costs of mitigation increase as more mitigation is required.[23])

Obviously, then, higher projected GDP growth rates in base cases relative to past history tend to imply higher energy consumption, which implies greater consumption of fossil fuels in the absence of mitigation for climate change. In fact, while even in the base cases, where the energy intensity of GDP continues to fall at an average rate of

[22]This fact is most likely due to some unrevealed bias towards high growth in the average IAM macroeconomic module. It is very strange, and a real scientific weakness in the 2014 WGIII report, that these high GDP per capita forecasts compared with the historical level did not lead to a comprehensive review of their underlying causes and a public discussion of their justification, since they directly lead to the emissions forecasts for the base cases in 2100 which received wide-scale publicity in the media. All that is mentioned in the text is that these growth rates have "high uncertainty" and that "most models describe income growth as the result of exogenous improvements in labor productivity" (p. 426). However, this statement raises the additional question of the justification for those forecasts for labor productivity for 90 years.

[23]Even though the marginal costs of mitigation will increase, they might still average a negative number (net benefits), but the negative average will become less negative as more mitigation is required.

about −1.2% per year, a bit more strongly than the long run historical average, the carbon intensity is not projected to decline at all in the average base case model result due to market forces (Figure 6.1.d). This leads to a median increase in global GHG emissions for all baseline scenarios (Figure 6.5) of almost a factor of 2.0 by as early as 2070. But, again, this median result for large increases in GHG emissions requires firm scientific justification, which is not forthcoming in the WGIII report. This median emissions increase leads to a radiative forcing level for the baseline cases of about 7.7 W/m^2 by 2100, making it much closer to the generic RCP8.5 scenario than to the RCP6.0 scenario.

Presumably, these results imply that the RCP8.5 scenario is very unlikely to occur given how much above the historical average the baseline GDP growth rates were projected to be. This likelihood can also be seen in Figure 6.7.a. The strongest set of mitigation scenarios (the RCP2.6 scenarios) require that the average radiative forcing level drop from about 7.7 in the baseline to 2.6 in the strong mitigation cases by 2100, a decrease of approximately two-thirds in W/m^2. Again, this is the change in *incremental* forcing, namely a change in the increases from pre-industrial levels. In addition, the bad news is that the incremental forcing level for 2010 was already up to about 2.2 according to the WGIII report, so very little growth can occur in GHG concentrations in the atmosphere between now and 2100, so as not to exceed 2.6 in that year. To achieve this, emissions of GHGs have to begin declining rapidly as soon as possible, hitting zero net emissions globally as early as 2070 in some RCP2.6 mitigation scenarios, as presented in Chapter 6.

Another important point given a lot of stress in Chapter 6 that is not adequately discussed is the fact that "many models could not produce scenarios leading to about 450 ppm CO2eq by 2100 with limited technology portfolios" (p. 451). This illustrates the fact that some of the IAMs are so highly constrained by assumptions internal to the models that are not revealed to the scientific community that they cannot produce some of the strong mitigation scenarios (RCP2.6) even at infinite cost, even though these scenarios are likely to be perfectly possible to achieve in the real world. The internal model constraints that cause this problem may, therefore, artificially inflate the costs of the mitigation scenarios that those models can achieve. Furthermore, the existence of these severe internal constraints in certain models may imply that there are serious weaknesses and problematic with the methodologies and results from these models, even for the weaker mitigation scenarios they could successfully run.

7. Summary of Conclusions — Are the Key Macroeconomic Findings of the WGIII Report Scientifically Valid?

It is fairly obvious that if any policy maker who is not an expert on IAMS were to actually read the numerous caveats listed throughout this paper, it is very unlikely that she would have confidence in any of the claimed findings on the macroeconomics of mitigating climate change.[24] However, in spite of the numerous caveats and descriptions of what was done or not done when running the models, is there a firm scientific basis for believing any of the eight main findings cited in Sec. 2 *based on the numerous IAM runs relied on*?[25] Unfortunately, my answer is "no". Again, some of these findings are correct, but they did not require IAM runs to demonstrate their correctness, so these findings do not count.

This review found that there are four major reasons why the claim that society will have to suffer net macroeconomic "costs" to mitigate climate change may not be correct. The first is that the avoided damage costs that mitigating climate change would prevent were not included in the WGIII analysis.[26] It is important to note what the authors of Chapter 6 of the WGIII report surely know, namely that other well-known climate/economic studies, such as the Nordhaus and Stern research, have integrated estimates of future damage costs into their overall macroeconomic analysis of mitigating climate change (Nordhaus, 2013; Stern, 2007). Of course, as estimates of climate change-caused damages have increased over the years, it is quite possible that these could exceed many of the other components of the costs of mitigation as reported in Chapter 6. Not including damage costs in the IAMs relied on in the WGIII report was, thus, a major omission, as was the failure to include all the economic co-benefits of mitigation that the authors themselves list. It was also very problematic not to highlight these omissions to policy makers in the relevant Summaries for policy makers, both for the entire Synthesis Report, as well as for the WGIII report. The second is that the IAMs were not run with a realistically wide range of input assumptions in order to discover mitigation scenarios with large net macroeconomic benefits, not costs. If a reasonable broad range of realistic input assumptions had been utilized for each mitigation scenario, as well as for the base case to which it is related, it is quite unlikely that net macroeconomic costs would result for all sets of reasonable input assumptions, even without considering avoided damage costs. The third is that, depending on the particular economic or cost "index" that each IAM calculated as the bottom line representing a so-called "cost" to society, having a lower number over time may actually be better for society for several indices such as GDP, changing a so-called net "cost" into a net benefit. It seems to be common sense, as many analysts have now concluded, that a single index like GDP or "consumption" cannot possibly measure whether absolute economic changes from one scenario to another are good or bad (Stiglitz, 2009). Policy makers and the public would need to have a much more detailed analysis of the changes in the composition of each index between base case

[24]See also Schwanitz (2013) on issues relevant to evaluating the usefulness of IAMs.

[25]In addition to the numerous caveats listed in this paper, there are also numerous such reasons cited in Rosen and Guenther (2015). This paper describes why considerations of uncertainty, by themselves, imply that the findings listed in the text, could not possibly be knowable for a period as long as 50–100 years into the future, just as the underlying base case economic forecast could not be known to any reasonable degree of accuracy for that far into the future.

[26]See the fairly good discussion of the problems with including the impacts (damages) due to climate change in IAMs in section 6.3.3 in pages 441–443. This section provides a weak reason why impacts were not included in most IAMs, especially those used to compute results included in the IIASA database.

and mitigation scenarios in order to determine which scenario is better for society on the whole. Similarly, none of the IAMs relied on in the WGIII report seem to allow analysts to model the impacts of changes in lifestyles and values, yet these will obviously need to be included in any thorough analysis of the feasibility, as well as costs and benefits, of mitigating climate change.

The fourth is that all the layers of uncertainty and unknowability that affect long run projections such as those relied upon in the WGIII report imply that relying on projections for more than about 10–20 years is meaningless anyway (Stern, 2013).

Furthermore, there is no coherent methodology for including the investment costs of enhanced energy efficiency technologies in a self-consistent way with the investments for new supply-side energy technologies. Enhanced energy efficiency should be assumed to be invested in at much higher rates per year in the mitigation cases than in the base cases, especially when avoided damage costs are taken into account. What rates should be assumed for such investments is, in part, a policy issue, since it is well known that underinvestment in energy efficiency occurs when the matter is left to "markets". In fact, there are many social, political, and financial constraints to achieving "optimal" levels of energy efficiency, many of which are discussed in Chapter 6.[27] But the "bottom line" is that very different levels of investments in energy efficiency technologies are likely to occur between the base and mitigation cases which will strongly impact the net economic benefits of mitigation.

As Chapter 6 also discusses, because the IAMs have different structures for the overall economy represented in their macroeconomic modules, some do not even include some land-use activities and functions as part of the economic modeling. Land use is, of course, very important because the proper kinds of land are essential for food production, paper and pulp production, wood and lumber production, and, potentially, for biomass solid and liquid fuel production. Land can also potentially be used to reabsorb CO_2 back into the soil as a means of decreasing atmospheric concentrations of CO_2. This omission in some of the IAMs seriously limits whatever value the main findings may have for policy makers.

My main conclusion regarding the WGIII report, then, is that there is no transparent, well-documented, and sufficiently comprehensive set of methodologies that have been used to integrate all the most important phenomenon relevant to the macroeconomics of mitigating climate change into a coherent set of readily understandable results that would be useful to climate change policy makers, even for only the next 10–20 years. Relying on the current large set of IAMs, with their piecemeal and partial approach to the issues, is of little use, especially in light of the multiple layers of uncertainties that overlay all of their results over the long run. This is especially true since, whether one agrees with the theoretical economic basis for their structures or not, the existing IAMs are not even used in sensible ways to address the issue of uncertainty. They are run with whatever sets of input assumption values each research

[27]For example, see section 6.8.4.

team decides to use independent of each other, without any team performing sensitivity runs over reasonable ranges of values, in spite of the large uncertainties involved for the hundreds of key inputs to each model. Ultimately, then, there is no sound scientific basis for most, if not all, of the numerical results reported either in Chapter 6 on the macroeconomics of mitigating climate change, or in the relevant summaries for policy makers. Economists must learn to be much more transparent and honest with policy makers about what can and cannot be known about the macroeconomics of mitigating climate change, especially over the long run to 2100 (Hulme, 2009).

8. Recommendations

The scientific community needs quality, not quantity, when it comes to providing policy makers concerned about climate change with appropriate macroeconomic analyses. Having large numbers of IAM-produced scenarios of any type produced using multiple models does not overcome the fundamental problems that exist with the set of scenarios produced by each model separately on which the WGIII report relied. This should be obvious, but what is equally obvious is that the IAM research community has not agreed upon what is the acceptable or best use of each model. The community tries to develop and run too many different models instead of focusing its time, money, and understanding on constructing fewer but higher quality and more comprehensive models. Furthermore, since the IAMs that produced the majority of the mitigation scenarios for the 2014 IPCC WGIII report were not significantly changed or upgraded since they were used roughly seven years earlier to produce similar scenarios for the 2007 IPCC WGIII report, the policy world has learned very little new from the most recent report. This lack of progress implies that the many issues raised in this review need to be addressed before it is decided to include a similar kind of macroeconomic analysis of the mitigation of climate change in the next WGIII report, if there is to be one.

Given the numerous uncertainties involved, all of which get worse over time within any given scenario, any economic analysis for a proposed AR6 report should probably be done for a maximum of 20 years. This would still be a sufficiently long period of time to help inform policy makers and the public as to what should be done beginning now to address climate change issues for the next decade or so. Modelers tend to forget that by focusing on economic analysis over the very long run, policy makers can become distracted from the decisions they need to make now, not 25 or 50 years from now. The whole point of creating periodic updates, such as the IPCC reports, is to allow previous actions and investment plans to be revised appropriately. And macroeconomic analyses of mitigating climate change have been underway for a couple of decades now, we know by now that the world needs as much cost effective energy efficiency-oriented investment as soon as possible, combined with massive investment in renewable energy supplies. We also know that the world is behind in making these investments, so there is no danger that it will overinvest in these areas for decades, if ever. To fine-tune this overall strategy, more regional mitigation plans are needed to be created and carried out (Carraro *et al.*, 2015). In fact, it is the lack of commitment to actually invest sufficient amounts of money in the technologies described above that seems to be the major problem preventing sufficiently rapid mitigation of climate change, not being unsure as to what to tell policy makers at this time.

In addition, there needs to be serious conceptual discussion, and eventual agreement, on what the "bottom line" for the basic cost/benefit calculations should be. What is the appropriate economic/social policy index that would allow direct comparison between models, or which small number of indices would at least allow for different but important insights to be learned about the macroeconomics of mitigating climate change? What social and economic phenomena should be included in a policy index? How should damage calculations as well as other social and economic co-benefits be included in IAMs for determining an economic "bottom line" to report to policy makers? Clearly, just computing GDP or consumption figures for different scenarios is insufficient and/or outright deceptive. We must focus our attention of the composition on GDP or consumption to determine which scenarios are "better" or "worse" for society. In some scenarios, more GDP might be better, and in some other scenarios, less GDP might be better for the achievement of a wide range of social goals, such as those cited in the new Sustainable Development Goals. But until we know specifically which kinds of "bottom-line" numbers we need to compute instead of GDP or consumption, the improved IAMs of the future cannot be created.

The IAM research community also finally needs to sponsor public peer reviews of its models and input assumptions. Without these expert reviews being made public and debated publicly, as scientific issues should be, policy makers can have little confidence in the results of running the models. This is especially true when results from so many different models, using different input assumptions, which yield very different results, are relied on.[28] Publishing articles based on secret peer reviews is no longer adequate for establishing the scientific credibility of IAM-based research for journals, when so much is at stake for the world. The names of the authors of these public peer reviews of the IAMs themselves do not have to be publically released, but their reviews certainly must be available to the public so that their content can be discussed and, potentially, refuted. All actors in this key policy area will learn more from an enhanced review process like the one proposed above.

Again, all IAMs cannot be equally good at everything they need to do, and policy makers need to have a better understanding of which models or kinds of models are better or worse for various purposes. This is especially important now, since over the last 10 years, or more, many economists have written very damning critiques of neoclassical economic theory on which many, if not most, of the IAMs are based. Not having public reviews available makes it seem like model developers are trying to hide

[28]It is important to note that there is no evidence of which the author of this review paper is aware that any publically available peer reviews have ever been done for any of the IAMs relied on in the 2014 IPCC WGIII report.

key information from the public and from policy makers, while at the same time expecting the public to trust their expertise. The IAM research teams cannot have it both ways.

In brief, then, my recommendations for the future development and use of IAMs for the purpose of informing policy makers on the macroeconomics of mitigating climate change are the following:

(1) All IAM research teams should agree to focus their future research efforts on enhancing and running no more than three or four IAMs, perhaps focusing more on bottom-up nonoptimization models that allow for greater disaggregation of the economy, then on top-down optimization models. The degree of disaggregation should be guided by the need to analyze more types of mitigation policies. But since the economic analysis of investments for enhanced energy efficiency is crucial, more disaggregation is required for each sector of the economy. Furthermore, the models should not assume that at any point in time we have perfect knowledge of the future, since we do not, nor do human beings optimize their behavior. Damage estimates resulting from future incremental climate change, as well as other major costs and benefits of mitigation currently missing from the models, must be included. The same land-use interactions with the economy and atmosphere should also be included in each model, along with the same fairly complete set of greenhouse gas emissions. The economic indices quantified as the result of each model should attempt to take the new Sustainable Development Goals into account to the extent possible, and should not simply rely on an aggregate measure of economic activity such as GDP or consumption.

(2) This focus on just a few models should be facilitated by detailed public expert reviews of the candidate models that are put forward for consideration by research teams. These reviews should be funded, and reviewers paid, by a pooling of a percentage of the research budgets of the research teams that put forward candidate models, or some similar process. These expert reviews should be published in part to help elucidate past research products and published articles, since this has never been done before (Rosen, 2015; Schwanitz, 2013).

(3) Uncertainty in scenario outcomes must be quantified for a comprehensive range of sets of input assumptions and internal parameter values, even if some analysts might deem some of the assumptions to be too extreme. History has been full of surprises, and the future will be, too (GEC, 2007).[29]

(4) A professional technical writer should be employed to write all the summaries for policy makers of the products of an AR6. Currently, these summaries are difficult for even experts in the field to understand clearly, and they do not include all relevant information for policy makers.[30]

[29]For a similar critique of the presentation of the WGI report findings, see Jefferson (2014).

[30]Even the journal *Nature Climate Change* has published articles recently that were critical of these summaries for policy makers (Hollin and Pearce, 2015; Black, 2015).

(5) The new and improved IAMs should only be run for a maximum of 10–20 years into the future in order to provide policy inputs for the next set of national and regional mitigation plans. Beyond 20 years, all relevant uncertainties are just too big for model results to be taken seriously. Furthermore, by only running IAMs for a maximum of 10–20 years, the computer running time freed up can be used to accommodate more disaggregated model structures, especially on the demand side of the energy economy.[31]
(6) If there is to be a new AR6 IPCC WGIII report, its timeline for completion should be lengthened to accommodate the model review, development, and enhancement process described above. Climate change mitigation policy experts already know most of what needs to be done for the next 10 years. Thus, no new analyses are really required to inform policy at the level of the past WGIII assessment reports on the macroeconomics of mitigating climate change for at least 10 years, if waiting that long would produce more useful guidance for policy makers beyond that time frame.
(7) All new research results must include extensive tables and figures providing all key assumptions and results on which the analyses are based, both qualitative and quantitative. All controversial issues relevant to these analyses, such as the determination of the discount rate, must also be addressed in a way relevant to the results and findings cited (NCC, 2015).
(8) The authorship policy of a new AR6 should prohibit obvious conflicts of interest, such as where members of major IAM research teams were allowed to be lead or contributing authors of the key Chapter 6 of the 2014 WGIII report. This conflict of interest involved at least 10 such authors of the 2014 WGIII report who were reviewing and writing about their own research work that had appeared in the peer-reviewed literature over the previous seven years, or about research published by their close colleagues. Major climate change assessments, with their great importance to the world, should recruit independent expert authors, even if they must be paid for their work and travel costs to meetings, or future IPCC assessments should not be done. With fewer models being seen, it will not be difficult to find relevant experts who are not members of these modeling teams.

There is no rush to perform a similar analysis of the long-run macroeconomics of mitigating climate change as contained in the 2014 IPCC WGIII report for an AR6. Little new would likely be learned from repeating past analyses utilizing existing IAMs. A major change needs to be undertaken starting now to enhance the capabilities of IAMs, if they are ever to be of any substantial use to climate change policy makers in the future. Any further research which utilizes the existing IAMs should be

[31]Another good way of reducing computer running time would be to stop modeling GHG emissions for each grid square by eliminating local air pollution impacts from the analysis.

immediately redirected towards analyzing lessons to be learned for a new generation of many fewer but better models, not 20, as currently exist.

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