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The Structure of Economic Modeling of the Potential Impacts of Climate Change: Grafting Gross Underestimation of Risk onto Already Narrow Science Models†

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Scientists describe the scale of the risks from unmanaged climate change as potentially immense. However, the scientific models, because they omit key factors that are hard to capture precisely, appear to substantially underestimate these risks. Many economic models add further gross underassessment of risk because the assumptions built into the economic modeling on growth, damages and risks, come close to assuming directly that the impacts and costs will be modest and close to excluding the possibility of catastrophic outcomes. A new generation of models is needed in all three of climate science, impact and economics with a still stronger focus on lives and livelihoods, including the risks of large-scale migration and conflicts. (*JEL* C51, Q54, Q58)

1. *Introduction and Summary*

Scientific evidence over the past decade on the scale and nature of the potential risks from human-induced climate change[1]

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[1] The scale and nature of risks from human-induced climate change have long been a source of deep concern and a critical challenge for public policy. The growing awareness of their possible likelihood and magnitude led to the establishment of the Intergovernmental Panel on Climate Change (IPCC) twenty-five years ago. Its work embodies remarkable international collaboration and its warnings have been consistent and clear.

is becoming still more worrying: rapidly rising emissions and concentrations; impacts appearing more rapidly than anticipated; major features omitted from models, because they are not currently easy to characterize, look still more threatening; the state of oceans more fragile than previously thought and the implications more difficult and complex; interactions between climate change and ecosystems appear to be still more important; and so on. Unless action is greatly strengthened there appear to be substantial probabilities of a world a century or so from now which is 4°C or more warmer[2] than the late nineteenth century (the usual benchmark). Such temperature changes and other related climate effects could transform the relationship between humans and the planet, including where and how they could live.[3]

However, there is a disconnect between the scale of the risks, i.e., the potential consequences from human action, *as described by scientists*, and what many of the formal scientific *models*, (climate and particularly impact models) are telling us about the impacts of a shift to a 4°C or warmer world.[4]

The climate models generally leave out many effects, recognized as potentially very large, which are not easy to make precise or formal enough for integration into the modeling. And the impact models, based on the climate models, fall far short of capturing the scale and nature of what might happen to lives and livelihoods. Scientists are keenly aware of these issues and are actively working on them. This paper is primarily addressed to economists.

The economic models, which build on the science models, are used for cost–benefit analysis or policy assessments of climate impacts and action.[5] The economic models add further underassessment of risk on top of the underassessment embodied in the science models, in particular because they generally assume exogenous drivers of growth, only modest damages from climate change and narrow distributions of risk. The key point in this paper is not that we know what will happen at 4°C or more, but that we have some intimation or notion of what might happen, and we can see that some potential impacts, with probabilities far from remote, look very or catastrophically damaging. Thus models that come close to excluding such risks or assuming they are very small may be profoundly misleading on issues of great significance.

We discuss the science and how to examine and describe the scale of risks in section 2 and economic modeling in section 3. Section 4 concludes, arguing that we need not only a new generation of models, but also a broader and wiser set of perspectives on how to use the models that we have, and that we may have, to examine, discuss and propose policies.

2. *Science—Risk and Uncertainty*[6]

2.1 *What Broad Story Does the Science Tell?*

What is the broad story that the science tells us and why is it so worrying? Put simply,

[2] Temperature here is global average surface temperature, averaged over the surface of the earth and over the year.

[3] This is not the place to deal with the "arguments" of those who would deny the validity of two centuries of climate science and 97 percent of relevant refereed papers in the scientific journals. These arguments are often a tissue of confusions and occasionally of dubious origin (see, e.g., Stern 2009, chapter 2; Oreskes and Conway 2010; Cook et al. 2013).

[4] Climate models usually attempt to make general statements about earth processes such as temperature increases and sea-level rises. On the other hand, impact models, which are based on the climate models, attempt to quantify impacts on lives and livelihoods by extending such broad statements to more regional or local effects such as desertification, rainfall patterns, potential agricultural outputs, etc.

[5] Ackerman et al. 2009; Kopp, Hsiang, and Oppenheimer 2013.

[6] In this paper, I make no distinction between risk and uncertainty. But Knightian uncertainty in terms of our having scant knowledge of key probabilities is an important issue—see also Stern (2007), p. 38.

it goes like this. Current concentrations of carbon dioxide (CO_2) are around 400 ppm, compared with preindustrial concentrations of around 270 ppm. Current concentrations of greenhouse gasses (GHGs), which includes warming contributions from gasses much shorter-lived than CO_2, are now around 445 ppm carbon dioxide equivalent (CO_2e); this includes the six "Kyoto" gasses (EEA 2013).[7] We are adding CO_2e at a per annum rate of around 3 ppm and that rate is rising (EEA 2013; Stern 2009, chapter 2). A century of "business-as-usual" might thus add 300 ppm or more and take us into the region of 750 ppm CO_2e or perhaps much higher. Some climate models suggest a median temperature increase over the next one or two centuries in the region of 4°C or warmer, with substantial probabilities of well above 4°C (see, e.g., IEA 2012, 2013; Rogelj, Meinhausen, and Knutti 2012). Decision making requires some understanding of what could happen during the shift to and at 4°C or warmer and we look to the scientists to paint an informed picture of what might happen. They are surely the best placed to do so.

Here are some ways in which we might begin to appreciate the potentially enormous consequence of such temperatures. The planet has not seen CO_2 levels as high as the current 400 ppm for at least 800,000 years (Lüthi et al. 2008) and likely not for around 3 million years (Pagani et al. 2010). Global mean temperatures regularly exceeding 4°C above preindustrial have likely not been seen for at least 10 million years, perhaps much more (e.g., Zachos, Dickens, and Zeebe 2008). The last time CO_2 levels exceeded 750 ppm, with surface temperatures well beyond 4°C above preindustrial, was likely about 35 million years ago during the Eocene Epoch when the planet was entirely ice-free, which today would drive a sea level rise of 70 meters.

Modern *homo sapiens* is probably no more than 250,000 years old (Stewart and Stringer 2012)[8] and has not experienced anything like this. Our own civilizations, with village and town living, appeared after the last ice age during the Holocene period. The early Holocene, between around 12,000 and 7,000 years ago, saw rapid changes in ice sheets, sea levels and temperature (Stringer 2007; IPCC AR4, 2007a; Törnqvist and Hijma 2012). Following this transition, over the last 7 or 8 millennia, temperatures have been remarkably stable, fluctuating in a range of plus or minus 1 or 1½°C around an average, allowing cereals, sedentary agriculture, and the growth of villages and towns.[9,10]

We are already on the upper edge of that range, in large measure as a result of changes brought about by humans and, at 3°C, will be well outside that range. It seems possible that we have not seen such temperatures, sustained, for around 3 million years. We appear to be embarked on a massive experiment

[7] The equivalence comes from adding, in radiative forcing equivalent, across the GHGs. There are a number of ways to express GHG equivalent concentrations: "Kyoto" GHGs (CO_2, CH_4, N_2O, and three fluorinated gasses (HFC, PFC, SF_6)), which together are currently around 445 ppm CO_2e; "Kyoto" + "Montreal" GHGs (Montreal gasses include the Ozone Depleting Substances, such as CFC gasses) are currently around 470 ppm CO_2e. Aerosols (dirt, particulates, etc.) in the atmosphere can prevent some of the solar energy reaching the earth's surface. The pace of increase of temperature will thus be influenced by the assumptions made about the future of aerosols (EEA 2013). Aerosols and polluted air carry their own problems and it is the concentrations of CO_2 that are crucial to ocean acidification (see Stern 2007, p. 334; Bowen and Ranger 2009).

[8] See also http://www.worldmuseumofman.org/hum.php.

[9] See Marcott et al. (2013) and Stern (2012).

[10] These Holocene temperatures allowed our societies to develop: grasses were cultivated to become cereals, thus requiring sedentary populations to tend and protect crops until harvest, and allowing both surplus and storage. This provided time and opportunity to develop much of the way of life and skills of civilization as we know it.

where the consequences are hard to predict and the effects may be irreversible.[11]

Scientists have indeed been helping us to understand the nature of the risks. Based on the mainstream scientific literature, at 4°C or warmer we might see the following (see Appendix—Part 1 for more detailed descriptions and references). Many of these effects might emerge strongly at 3°C.

- *Desertification, droughts, and water stress*. Much of southern Europe may look like the Sahara desert, much of the snow and ice on the Himalayas gone, and melting of snow and ice on the Andes and Rockies; possibly profound effects on water availability for billions of people.

- *Changing patterns of precipitation and temperature*. The North India monsoon, which shapes the agricultural lives of hundreds of millions, may be radically altered. Severe flooding from intense precipitation and changing river flows, erosion and loss of tree cover. Local heat stress more common as temperatures rise.

- *Collapse of forests and biodiversity*. Rainforests, such as the Amazon, might die back in dramatically altered climates, with the release of huge amounts of CO_2 and the risk of desertification in key regions.

- *Extreme weather events*. Likely to be more intense, e.g., storms, cyclones, etc., with much higher wind speeds.

- *Storm surges from seas/oceans*. Could result in salination of large areas and their effective loss to agriculture.

- *Global sea levels*. Rise slowly with thermal expansion but the effects, such as permanent submergence of land, could be massive. Effects could come through much more quickly if land-based ice slides into the oceans.

It is not easy to predict what would occur when and where but these are examples of what might happen. The reasons for hundreds of millions of people living where they do could be largely rewritten, and so rapidly that adaptation would be very difficult. The risk of vast movements of population could be high.[12] History indicates that this could involve severe, widespread and extended conflict, particularly where migration is across country borders.

The probabilities of eventual warming of 4°C or more, on current emissions paths, may be of the order of 20–60 percent (e.g., IEA 2012, 2013; Rogelj, Meinhausen, and Knutti 2012). Of course, we cannot be highly confident of the probabilities, and the nature, scale and possible location of the effects are difficult to describe with confidence, but the science does seem to indicate that the risks are immense and are not remote.

Scientists are, understandably, professionally cautious. They are being asked to speculate about circumstances that the world has not seen for millions of years and modern *homo sapiens* has never experienced. But if these are the risks that our actions imply then rationality, in a world of irreversibilities where

[11] The magnitude and potential duration of such impacts have led some to suggest we should regard current times as the beginning of the Anthropocene (Crutzen 2002). We are not only contemplating temperature increases which are, in many ways, unknown territory, but also CO_2 is very hard to extract and may last for hundreds of years in the atmosphere. And damage from some impacts, such as desertification or inundation, can be very long lasting.

[12] For recent literature on climate migration see: Gemenne (2011); Royal Society (2011); Steinbruner, Stern, and Husbands (2012) (Box 1-2 and the section on disruptive migration); Licker and Oppenheimer (2013); Oppenheimer (2013); Gilmore et al. (2013); and the January 2012 Special Issue on Climate Change and Conflict in the *Journal of Peace Research*.

wait-and-see may be dangerous, requires us to speculate on their scale and nature.[13] Fortunately some distinguished climate scientists are showing greater willingness to take this responsibility.[14] It is important that this process accelerates given the urgency implied by the scale of the risks, where we are heading, and potential irreversibilities.

2.2 *What Do Science Models Do?*[15]

In the broad context of this description of possible outcomes, we examine both the climate and impact models and argue that it appears likely that they substantially underestimate risks to lives and livelihoods.

2.2.1 *Climate Models: "The Climate We Get If We Are Very Lucky"*[16]

Climate scientists have, of course, long been keenly aware that their models leave out much that may be of profound significance and many have discussed these omissions and their possible consequences. Sometimes such discussions are linked to or expressed in terms of "tipping points".[17] Over the past three decades, many more of these processes, or better representations of them, have been included as climate models have developed. But many are still omitted. It is to these omissions that the word "narrow" in the title of the paper refers.

Leaving something out of a model for reasons of our inability to model it satisfactorily is understandable, indeed reasonable.[18] Thus, drawing attention to the omissions is not to criticize the builders of the models. But omissions from a model should not imply omissions from the argument.

Potentially key factors or effects still generally omitted include:

- thawing of the permafrost and release of methane
- collapse of land-based polar ice sheets;
- release of sea-bed methane
- complex interaction with ecosystems and biodiversity more generally.

Other key factors that are represented in the models, but where the range of risks might be understated, include:

- ocean acidification and associated feedbacks
- collapse of the oceanic thermohaline circulation
- collapse of the Amazon and other tropical forests
- potential for chaotic and unstable behavior of complex dynamical systems.

We cannot say precisely what risks are associated with the omitted factors when they are taken together and combined with those features that are represented, or underrepresented, in the climate models. But it seems reasonable to suggest that they could add greatly to the risks indicated by the existing climate models. And it would seem extraordinary to say that we can be confident that

[13] The 2012 World Bank 4 degrees report, including the 2013 update, is a step in the right direction.

[14] See, e.g., New et al. (2011) and the Royal Society (2011), which examine what a 4°C world might look like, Schellnhuber (2009 and 2013), Lenton et al. (2008) on "tipping points" (nonlinear or irreversible effects), and Rockström et al. (2009) on Planetary Boundaries.

[15] The economic models are examined separately in the next section.

[16] I owe this quote to Sir Brian Hoskins FRS, Professor at Imperial College London, Head of the Grantham Institute for Climate Change at Imperial College London, and Professor of Meteorology at the University of Reading. I chair the Grantham Research Institute on Climate Change and the Environment at LSE.

[17] See, e.g., Lenton et al. (2008).

[18] Indeed the point of using models, that is their essence, is that they leave out many things in order to focus. But we have to ask whether their focus is on what and where matters most.

the risks associated with the omitted factors are negligibly small.[19,20]

It is also of concern that key examples from past climate history generally fail to emerge in current models, e.g., the rapid transformation of the "green" Sahara around 5,000 to 9,000 years ago, and/or require very large disturbances to simulate them, e.g., collapse of the Atlantic Meridional Overturning Circulation during the glacial period 12,000 to 120,000 years ago (Valdes 2011).[21]

There are various research programs that aim to push the models forward, for example, the EU funded EMBRACE project (work package 5), planned modeling work at the UK Met Office Hadley Centre on methane emissions and ice sheets on land, and a range of research on extreme events (see Appendix—Part 2 for examples of research to improve the models).[22]

2.2.2 *Impact Models: More Omissions, Overfocus on the Tractable, Inadequate Focus on Impacts on Lives and Livelihoods*

With impact models and how they tutor policy, the worries are somewhat different to the concerns expressed in the above discussion. With such models, the problem is that the focus has been on the tractable rather than on the effects of climate change likely to be of most importance for people's lives and livelihoods. Factors affecting lives and livelihoods, mostly involving water, or the lack of it, in some shape or form, were described in section 2.1.

Impact models incorporate some of these factors with different degrees of credibility, e.g., heat stress and changes in extreme precipitation have been modeled for some locations. In contrast, other factors are usually missing from models altogether, e.g., nonlinear impacts of temperature on crop yields (see, e.g., World Bank 2012; Rosenzweig et al. 2013). On the whole, I would suggest that the models fail to get to grips with the overall scale of the risks associated with the possible phenomena described at temperature changes of 4°C or more.[23] Key to many of these modeling problems is that the impact is local, yet many climate factors operate at a global level where the links to the local are not easily captured. The resolution necessary for much of the relevant local modeling strains information, modeling capacity and computation beyond their limits. Thus the models are better at simulating large spatial

19 Socolow (2011) recommends that the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) should communicate much more strongly what the science community does and does not understand about high consequence outcomes.

20 A brief comment is in order on the lower rate of surface temperature rise over the last decade, which some in the media, misguidedly in the view of many scientists, have used to suggest the climate problem is much less important than previously thought (e.g., some of the media commentary on Otto et al. 2013). It seems that the slowdown in temperature rise is the combination of a strong rising long-term trend and strong offsetting short-term factors which include: higher absorption of heat in the deep oceans; quiet solar activity; and an increase in volcanic and man-made aerosols in the atmosphere. Many or all of these factors are likely to be temporary and unwind in the short to medium term. Note also that there was a very strong El Niño in 1998, contributing to high global average temperatures in that year. It seems that the pause in the rise in global average temperatures is particularly associated with surface temperature of the Pacific Ocean: land temperatures have continued to rise. Economists, of all people, should understand the difference between trends and oscillations. The presence of such phenomena underlines the importance of recognizing that both human and nonhuman factors influence climate change. The basic physics points to a strong underlying trend from increasing concentrations of GHGs by human action, indeed, as noted above, we have just seen the concentrations of CO_2 rise to around 400 ppm (see NOAA http://www.esrl.noaa.gov/gmd/ccgg/trends/weekly.html).

21 Jason Lowe has pointed out to us that palaeo simulations are often run for much longer periods and the models need to be simplified (e.g., lower spatial resolution) to run in the available computer resources.

22 I am grateful to Jason Lowe of the UK Met Office Hadley Centre for this guidance.

23 The scale of impacts at 4°C or more could make hardship intense and widespread and, in many cases, could imply movement of people in very large numbers.

scales and longer-term averages than local or short-term extremes.

Here are just three examples of the adoption of methods for the estimation of impacts or damages that are likely to yield small results in relation to the scale of possible impacts. One method sometimes used is to estimate the effects of global temperature change by comparing two different places with different average temperatures, say Helsinki and Madrid. That is clearly to miss the basic point that most potential damages are from water-related and extreme weather effects (desertification, storms, floods, etc.), which are generated via global climate interactions (associated with rising average global temperature) with local characteristics.[24]

A second method involves looking at observed activities (or modeling fairly close to observed ranges) at different global temperatures and extrapolating to much bigger temperature differences. That clearly involves a risk of overlooking the point that such extrapolation will depend almost entirely on the assumed curvature/shape of fitted functions.

Third, some impact analyses focus primarily on agricultural output and bring in only narrow determinants. With agricultural output just 15 percent or so of GDP, for example, in India, even a 20 percent yield loss (these are the types of scale that some studies generate) would imply a fall in GDP of only around 3 percent.[25] However, such modeling would generally leave out dramatic changes in the monsoon, the melting of Himalayan snows and disturbance of river flows and flooding, summer temperatures beyond human tolerance, population movement as a result of such effects, and so on.

Less formal but perhaps very informative could be lines of enquiry from historical geography. Major droughts in modern times have moved people on a substantial scale, whether they be in the horn of Africa (see, e.g., Norwegian Refugee Council 2012; FAO 2011; Darcy, Bonard, and Dini 2012; Slim 2012) or the U.S. "Dust Bowl" of the 1930s.[26,27] And past environmental damage and climate change have led to failure of civilizations and places being abandoned, e.g., Mayan and Akkadian civilizations.[28] Modern society may be more resilient than past societies but the world of those societies saw only minor fluctuations in average global surface temperature and the scale of the risks in a 4°C (or more) warmer world, together with some more recent experience, suggest this resilience would be severely challenged.

We cannot predict the scale of population movement and of possible resulting conflict at 4°C and upwards. But it is surely unreasonable to assume that we can be confident that this scale will be very small. By

[24] Mendelsohn, Nordhaus, and Shaw (1994), Mendelsohn and Schlesinger (1999), and Mendelsohn and Dinar (2003) introduced methods of cross-sectional analysis to measure climate change impacts on agriculture in the United States, and many others have followed. These methods do not ignore water completely, e.g., Mendelsohn and Schlesinger (1999) control for precipitation in their regression analysis, but this provides, at best, only a partial account of possible water-related impacts. For a review of cross-sectional analysis, see the Special Issue in Climate Change "Measuring Climate Impacts with Cross-Sectional Analysis" (May 2007).

[25] Some analyses based on narrow determinants produce estimates of losses of 10-20 percent for global average temperature increases for 2°C and upwards for northern India (Lobell et al. 2012). There is a so-called fertilization effect of more CO_2, which may influence agricultural output upwards. See, for example, World Bank (2012, 2013); IPCC (2007b); Holden et al. (2013).

[26] As characterized by, for example, John Steinbeck, *The Grapes of Wrath*, 1939.

[27] See Hornbeck (2012).

[28] The Mayans damaged their environment, were hit by climate changes (extreme long-term drought), were destabilized by internal conflict, and kings and nobles focused on the short term and failed to address the long-term risks. The Mayan population collapsed, from between 3–14 million in the eighth–ninth centuries to around 30,000 by the sixteenth century when the Spanish arrived. Great Mayan cities such as Tikal and Palenque were abandoned. On the collapse of Mayan society see Jared Diamond *Collapse; How societies choose to fail or survive* (p. 157). The Akkadian Empire and civilizations in Mesopotamia also saw abrupt climate change that led to collapse and abandonment (Weiss 2000).

excluding large-scale migrations from impact and economic modeling we may be omitting what could arguably be one of the most important consequences of climate change. Conflict can arise from movement within countries,[29] but perhaps conflict would be still more severe for movement across borders: for example, from possible desertification in northern Mexico or around the Sahara or central Asia, or possible inundation of parts of Bangladesh or Indonesia. We must also note that unlike some past wars, which could be settled by peace treaties, the reasons for the movements causing such conflicts, a changing climate, could not simply be "switched off." It is interesting to note that in a number of countries, including the United States, the military and intelligence services take risks from climate change very seriously (see, e.g., Steinbruner, Stern, and Husbands 2012).

3. *Economic Models*

3.1 *Economic Models and Possible Scale and Nature of Risks*

Starting with the pioneering articles by Bill Nordhaus (Nordhaus 1991a, 1991b) and book by Bill Cline (Cline 1992), economists have, over the last two decades, tried to build models that can inform policy on climate change. They have become known as Integrated Assessment Models (IAMs). They have produced valuable insights. Indeed, in one chapter (chapter 6) of the Stern Review (2007) we made use of the PAGE model developed by Chris Hope. There has been growing concern, however, I think justified, that these models have major disconnects with the science in the way that they have been constructed, i.e., in the assumptions they embody. There are very strong grounds for arguing that they grossly underestimate the risks of climate change, not simply because of the limitations of climate and impact models already described, but because of the further assumptions built into the economic modeling on growth, damages and risks, which come close to assuming directly that the impacts and costs will be modest, and close to excluding the possibility of catastrophic outcomes.[30] This is the sense which "gross" is used in the title of the paper.[31]

Pindyck (2013—accompanying paper) argues that the models tell us very little and "create a perception of knowledge and precision, but that perception is illusory and misleading." Lenton and Ciscar (2013) review the limitations of the models and state that there is a "…huge gulf between natural scientists' understanding of climate thresholds or tipping points and economists' representations of climate catastrophes in integrated assessment models (IAMs)." Ackerman and Stanton (2012) also review the limitations of the major models and state, (p. 86), "An examination of those three models [PAGE, DICE, and FUND] shows that current economic modeling of climate damages is not

29 Some have suggested this as an important cause of conflict in Sudan where, in Darfur, pastoralists moving as pastures dried out came into conflict with those in sedentary agriculture (see Raleigh and Kniveton 2012; Sachs 2006; UNEP 2007).

30 The modeling in the Stern Review also likely understated the risks for similar reasons that we describe. For example, the worst case scenario was a temperature rise of over 8°C by 2200 that corresponds to a relatively small 35 percent loss of GDP, compared to today; and that would be under the baseline scenario where the world is assumed to be many times richer by then (see Stern 2007, figures 6.5c and 6.6).

31 Kopp, Hsiang, and Oppenheimer (2013) provide a short summary of the IAMs, including their shortcomings, and a proposal for taking IAMs forward. For other recent literature examining IAMs, see Pindyck 2013; Marten et al. 2013; Anthoff and Tol 2013; Ackerman and Munitz 2012; Ackerman and Stanton 2012; Tol 2012; Nordhaus 2011; van Vuuren et al. 2011; Warren et al. 2010; Ackerman et al. 2009; Mastrandrea 2009; Parry et al. 2009; Weitzman 2009; Hof, den Elzen, and van Vuuren 2008; Mastrandrea and Schneider 2001; Schneider 1997.

remotely consistent with the recent research on impacts" (see also Moyer et al. 2013). They point out these models were used by the U.S. Interagency Working Group in 2009 to estimate the social cost of carbon for use in cost–benefit analysis of U.S. regulations of $21/t$CO_2$ (Greenstone, Kopits, and Wolverton 2011). This was recently revised upwards to around $35/t$CO_2$.[32] Lest I am in danger of being misunderstood, that number is far better than zero. My point is that estimates based on these models are very sensitive to assumptions and are likely to lead to gross underestimation.

3.2 *Assumptions that Drive the Underestimation*

Even though there have been advances in economic modeling and models differ in their assumptions, four basic features of the economic models have remained largely unchanged since the early stages of their development:

(i) underlying exogenous drivers of growth (in aggregated one-good models)
(ii) damage functions (usually, but not always, multiplicative) that relate damage to output in a period to temperature in that period
(iii) weak (quantitatively) damage functions, and
(iv) very limited distribution of risks.

The problems of underestimation in economic modeling of costs/impacts of climate change arise directly from these basic assumptions on the modeling of growth and climate impacts. A general functional form in such models presents output at time t as follows:

$$(1) \qquad H(K, N, L, t, T).$$

K is capital, N is labor, L is land, and T is temperature, all at time t (each of K, N, L, could be vectors). This formulation involves a crucial separability across periods—i.e., output depends only on variables at time t, including temperature. Damage from earlier climate change resulting in reduced K this period could be indirectly included in these models if savings are lower in an earlier period as a result of earlier damage to output, but such savings effects are generally small.[33] And savings could be increased by anticipated future output damage. But capital, labor and land in this period could be influenced by earlier direct damage. However, such direct effects are rarely incorporated, or if they are, then they are small: damages are usually modeled as loss of output flow rather than damages to stocks. A further separability arises if damages are written:

$$(2) \qquad H = g(t, T)\, F(K, N, L).$$

Still further separability is often imposed on the function as follows:

$$(3) \qquad H = f(t)\,(1 - D(T))\, F(K, N, L),$$

[32] See IWG SCC, 2013. The reasons for the revisions were changes in the underlying models, largely to incorporate greater damages, rather than change in method of computation (see Moyer et al. 2013). Nevertheless, the basic story of Figure 1 below in terms of damages of only a few percent, even at 5°C, remains. Tol (2012) surveys estimates of the total economic impacts of climate change and calculates the expected value of the social cost of carbon (SCC) at $29/tC ($8/tCO_2) in 2015, rising at around 2 percent p.a. Anthoff and Tol (2013) undertake a decomposition analysis of the SCC using the FUND model. They identify key parameters that contribute most to variation in SCC estimates, including climate sensitivity, agriculture, energy demand and migration, and note that the latter two have received insufficient research attention. They recognize the uncertainty in modeling impacts with many results based on extrapolation and incomplete research and some potentially important factors, such as conflict and ocean acidification, omitted (Anthoff and Tol 2013). I am grateful to Richard Tol for these references.

[33] See Fankhauser and Tol (2005).

so that growth from technical progress has an element that is exogenous[34] and multiplicative as represented by $f(t)$, and $D(T)$ is a damage function with an effect on output, via $(1 - D)$, which is also multiplicative.[35] From there $f(t)$ is often specified as embodying exponential growth at rate g and takes the form Ae^{gt}, where g is often, but not necessarily, seen as constant over time.[36] $D(T)$ is often a simple power function, or a quadratic.[37] Damage functions are often calibrated by forcing them to fit current temperature and one other temperature point (delivering the estimate of at most two parameters).

3.2.1 *Damages and Growth*

For much of Nordhaus's work using the DICE model (Nordhaus 2008; Stern 2007, chapter 6), the loss via $D(T)$ at 5°C is in the region of 5–10 percent GDP (figure 1).[38,39]

Most reasonable modelers will accept that at higher temperatures the models go beyond their useful limits; Nordhaus suggests that we have insufficient evidence to extrapolate reliably beyond 3°C.[40] These models are not equipped to deal with the kinds of temperature changes and the possible impacts scientists are worried about. Yet, if the science tells us that there are major risks of temperatures well above 3°C we have to try to think about such consequences in assessing policy. And given that the world may not have seen 3°C for around 3 million years we have to wonder whether these models give an adequate account even of the risks associated with 3°C. To illustrate the difficulties encountered, whilst recognizing the wise cautionary advice of Nordhaus on making such extrapolations, if we do extrapolate, Ackerman, Stanton, and Bueno (2010) show that in a standard model such as Nordhaus (2008) temperature increases of up to 19°C might involve a loss in output of only 50 percent, against a baseline where the world is assumed to be many times richer by 2100 (table 1). This illustrates both the modest nature of damages and the perils of such extrapolation—it seems possible or likely that such temperatures could involve complete human extinction, indeed at much lower temperatures than that.

Some have responded to the apparent absurdities of such weak damage functions by invoking higher order terms (see Weitzman 2012). These are steps in a sensible direction (see also Nordhaus 2012) but the models still appear to suffer from the omission of the scale of damage that could arise from catastrophes, mass migration and serious conflict, most retain exogenous drivers of growth, and

34 Some other forms of technical progress could be accommodated by keeping t as an argument of $F(\,)$.

35 In the FUND model damages can also depend on output.

36 Some models, e.g., WITCH, have a form of endogenous technical progress.

37 Dietz and Asheim (2012) use a linear, quadratic and power function of 7, consistent with Weitzman (2012). In the Stern Review, page 660, damages are represented by $(T/2.5)^{\gamma}$. The damage exponent is treated as a Monte Carlo parameter using a triangular probability distribution with a minimum of 1 (results in a linear function) and a maximum of 3 (stronger convexity) (see also Stern 2008, Ely Lecture, Table 2, $\gamma = 2$, 2.5 and 3). Some are trying to improve specifications of damage functions, e.g., Ackerman, Stanton, and Bueno (2010) and Kopp, Hsiang, and Opeenheimer (2013). DICE models generally have a $D(T)$, which is one minus the inverse of a quadratic of T.

38 In much of Tol's work (see Stern 2007 and Dietz et al. 2007) on the FUND model damages at 5°C are still lower, around 1–2 percent of GDP (figure 1). For a recent critique of the FUND model, see Ackerman and Munitz (2012)—with responses, including from Bill Nordhaus, which highlights several additional concerns with the economic models, published at http://frankackerman.com/tol-controversy/.

39 See Tol (2012) for a discussion on impacts at higher temperatures.

40 In a private communication (reproduced with permission), Bill Nordhaus remarks, "I think we do not have sufficient evidence to extrapolate reliably above 3 degrees C . . . While damage estimates at high temperatures are necessary for modeling purposes (like many other variables such as GDP or energy technologies), they are placeholders subject to further research and should be used with sensitivity analyses to indicate their importance for the key result, such as estimates of current policy or the current social cost of carbon." I am very grateful for his sharing of these thoughts.

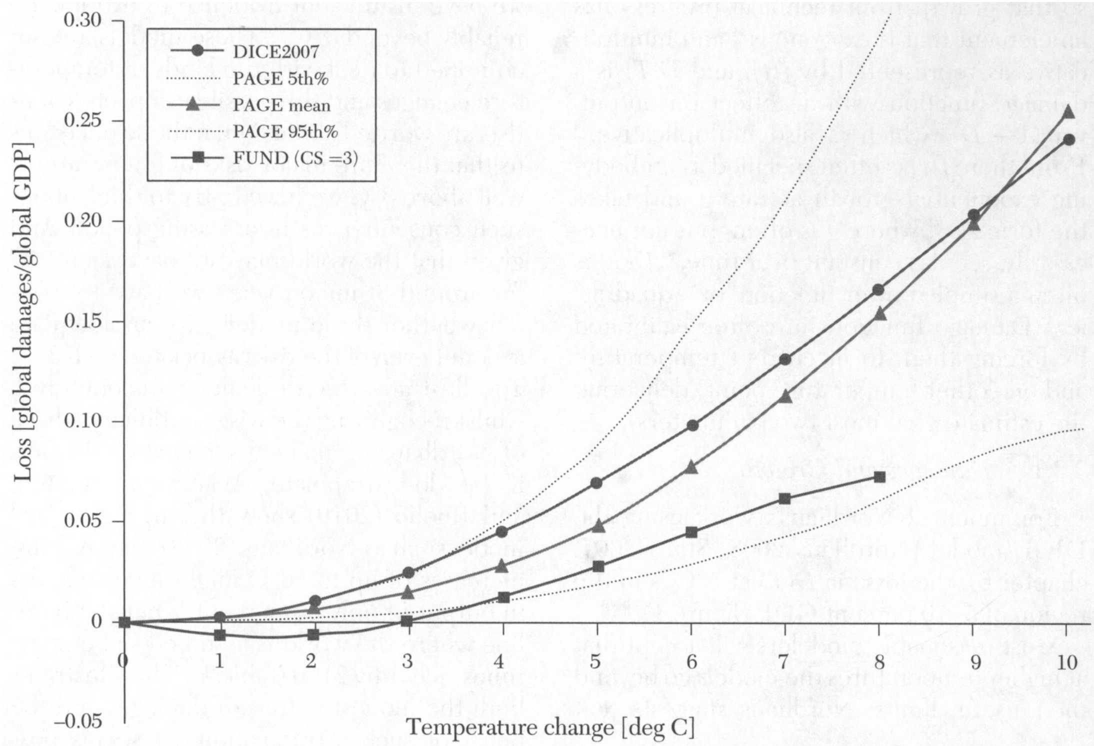

Figure 1. Annual Consumption Loss as a Fraction of Global GDP in 2100 due to an Increase in Annual Global Temperature in the DICE, FUND, and PAGE Models

Source: IWG SCC, 2010.

most have inherently narrow risk descriptions (although see below on Weitzman's work). The sensitivity of welfare/policy analysis to the damage function assumptions was noted in Stern (2008), table 2: for example, increasing the damage-function exponent from 2 to 3 raises the overall cost of climate change in the models there by a factor of 3 to 10.[41] Moyer et al. (2013) shows the great sensitivity of the social cost of carbon to the assumption that damages affect only current output rather than all future output through lasting impacts on overall factor productivity.

We should note that not all the models are the same and we use the separability assumption in the form of growth effect times damage effect times output for expositional purposes only. The key point is not so much constancy or separability but the exogeneity of a key driver of growth combined with weak damages. With exogenous growth that is fairly high (say at 1 percent or more over a century or more) and modest

[41] One side effect of increasing the exponent can be to make damages lower at lower temperatures where the curve is calibrated to "fit" through zero temperature change and one other point.

TABLE 1
OUTPUT AFTER A CENTURY RELATIVE TO NOW (BASE VALUE = 100)

Growth rate	Yr 100	With output loss 5%	10%	20%	50%
1%	270	256 (14)	243 (27)	216 (54)	135 (135)
2%	724	688 (36)	652 (72)	579 (145)	362 (362)
3%	1,922	1,826 (96)	1,730 (192)	1,538 (384)	961 (961)

Note: Table entries are output levels and losses are in parentheses (output in time zero = 100).

damages, future generations are more or less assumed to be much better off (table 1).[42]

Exogenous growth of any long-term strength is simply not credible in the face of the scale of the disruption that could arise at these higher temperatures. Potential large-scale destruction of capital and infrastructure, mass migration, conflict, and so on, can hardly be seen as a context for stable and exogenously-growing production conditions; see below for further discussion of risk, or its relative absence, in these models.

3.2.2 *Ways Forward in Modeling Aggregate Damages*[43]

Whilst I shall argue that we need a broader range of models and perspectives we should also ask how we can do better within the context of models based on aggregate output. There has been some recent progress, see Pindyck (2013) and Moyer et al. (2013), which focus on effects on the growth rate itself or on factor productivity (i.e., a permanent "kick downwards" in the production function).

[42] See also figure 1 of Moyer et al. (2013), which illustrates that the core assumptions of these models imply that future generations will be much better off than our own.

[43] I am particularly indebted to Peter Diamond for discussion of these issues.

Here are four ways in which the scale and long-lasting effects of damage might be incorporated in formal modeling based on the insights of standard production and growth theory.

1. *Damage to social, organizational or environmental capital.*
   We can think of social, organizational or environmental capital as further arguments in the production function $H(\,)$. These forms of capital could be permanently or long-term damaged by hostile climate and extreme events and by migration, disruption and conflict. The knowledge, structures, networks and relationships that organizational or social capital represent could be disrupted or destroyed.

2. *Damage to stocks of capital or land.*
   Climate events such as storms or inundation can do permanent or long-term damage to capital and land. If it is necessary to abandon certain areas, capital, infrastructure and land have zero use value and are essentially lost. This could be incorporated via permanent damage or a reduction in capital occurring in period t as a result of temperature and events in that period. An equation relating the stock of the relevant capital

in period $t + 1$, K_{t+1}, to the stock in period t could have a term $(1 - \delta(T))K_t$ where the function $\delta(T)$ denotes the loss of this type of capital in period t. An analogous modeling could apply to the types of capital indicated in the previous remark.

3. *Damage to overall factor productivity*. Whilst relevant capital stocks might survive, the ability to use them effectively might be damaged by a hostile environment. For example, water infrastructure, even if it survived unscathed from climate events, might be much less productive if the water flows for which it is designed changed radically. With constant returns to scale, damage to all capital stocks and factors in equal proportion would have the effect of a permanent reduction in an overall multiplicative factor on total output. In terms of equation (2) above we might imagine that in $g(t, T)$ the T argument is a vector containing past as well as current temperature.

4. *Damage to learning and endogenous growth*.
Endogenous growth theory usually relates productivity to experience. This could be, for example, experience of investment or of production. Essentially we try to model learning processes. If our experience is related to previously fairly stable circumstances then the learning it embodies might become much less relevant if those conditions changed radically (agriculture or fisheries could be examples). If investment is mostly repair and replacement, it may carry much less learning than that which involves innovation and new ideas. Thus climate change could undermine the key drivers of endogenous growth and thus the growth rate.

All four of these ways forward could lead directly to different production and damage specifications for economic modeling. The basic point that should be incorporated is that the impacts of climate change can cause lasting damage to capital stocks, to productivity, and to growth rates; current models where this lasting damage is omitted are likely to be deeply misleading. The extension of modeling work suggested is indeed worth pursuing. However, I should emphasise that the narrow dimensionality of models whose focus is on one form of output will inevitably narrow its perspective and leave out many important risks.

3.2.3 *Risk*

For most of the IAMs, risk plays a very limited role. The PAGE model (used in Chapter 6 of the Stern Review) has more focus on probability distributions than most others, but its probability distributions have been largely shaped by trying to straddle existing models with a tightly bounded range. The models themselves pay little attention to the potential scale of the risks likely to be embodied in the phenomena being analyzed. Only if these models were run probabilistically, with wide probability distributions over important parameters including those influencing growth, temperature and damages, could these models be capable of producing futures that are as dismal and destructive as climate science suggests may be possible.[44]

This is a point rightly emphasized by Weitzman, e.g., (2011), in his valuable contributions emphasizing fat tails. I would suggest, however, that there are immense problems arising from the middle of distributions (say 4°C or so on some extrapolations of emissions, e.g., IEA 2013; Rogelj,

[44] More recent versions of PAGE move in the direction of the inclusion of possible catastrophic events. There have been other attempts, too, but they have all been rather limited (see Kopits, Marten, and Wolverton 2013.)

Meinshausen, and Knutti 2012)—such problems are not tail effects. To focus on tails suggests a remoteness of the potentially huge risks that may be misleading. The tail is even worse.

Taken together, the assumptions in most IAMs that we have highlighted lead, not just to low estimates of the social cost of carbon, but also to recommendations that we should head for concentrations of, say, 650 ppm CO_2e (see Nordhaus 2008). The science tells us that there are immense risks at these concentrations; some economic models apparently tell us they are "optimum."

3.3 *Discounting and Dimensionality*

3.3.1 *Discounting*

It is the unwarranted assumption that future incomes will almost certainly be much higher than now that, in large measure, lies behind the suggestion that discount rates should be high. If future generations could be much poorer than us, discount factors could be above one and discount rates could be negative over long periods. Discount rates in the markets cannot be reliable guides when growth rates could be dramatically different from those currently assumed for the medium term. Further, markets based on short-term private individual decisions may have limited relevance for capturing the specifications and parameters relevant for modeling long-term social decisions. On top of that, the capital markets are deeply imperfect. Thus taking social discount rates from the markets is likely to be very misleading. We have to go back to the fundamentals; and in doing so many ethical systems would place at centre stage relative incomes, then and now (See Stern 2008, Stern 2009 chapter 5, or Stern 2012 and Stern forthcoming for further discussion).

It has been somewhat depressing that so many of the discussions of discounting have failed to take due account of the fundamental principles of discounting as set out in the work of the 1960s, 1970s, and 1980s, which explained the dependence of social discounting on the specification of good, of income group, and of future prospects (see, e.g., Arrow and Lind 1970; Arrow et al. 1982; Little and Mirrlees 1974; Drèze and Stern 1987, 1990). Basically, the discount factor between time zero and time t for good i, $\lambda_{i,t}$ is the shadow[45] value of good i at time t relative to time zero and will depend, inter alia, on the particular good and circumstances at time t and time zero. If good i were very scarce at time t then its shadow price could be high and the discount factor could be above 1. The discount rate is the proportional rate of fall of the discount factor and thus also depends on i and t. Both discount factors and discount rates also depend on the state of nature in models with uncertainty; the stochastic relationship between benefits/costs and levels of well-being will be central. With the possibility of decline in incomes and major decline in environmental services discount rates for some or all goods could be negative in such circumstances for a while.[46] It is discounting and the discount factors that are the primary concepts in the sense that they directly embody shadow prices. Their use leads us to directly examine issues relating to the good in question and scarcity. To jump to discount rates risks missing the key underlying concepts and theory.[47]

[45] For formal definitions of shadow prices, see Drèze and Stern 1987 and 1990).

[46] The difference between discount rates for good i and for good j is the (proportional) rate of change in the relative shadow price.

[47] Similar views on discounting are in large measure reflected also by Pindyck (2013) (accompanying paper) via his focus on the need to make decisions in the face of potentially catastrophic effects. He also emphasizes the lack of direct evidence for damage functions. Weitzman in his interesting accompanying paper focuses on covariances between benefits/costs and standards of living and their implications for discounting and discount rates.

3.3.2 *Dimensionality*

Given the scale and nature of the phenomena at issue, a focus on GDP or aggregate consumption is surely far too narrow to capture our concerns about consequences. The history of the collapse of the Mayan civilization is written as one of failing to understand and act on the risks; such history understandably focuses first on mass population decline, not only or primarily on a fall in output. The GDP of Europe during WWII does not by itself illuminate the real tragedy of that war, with over 50 million dead (military and civilian). China's recorded GDP during the Great Leap Forward and Great Famine (1958–62) fell (*−4 to −5% p.a.*) but this does not convey the extreme loss of life (Bolt and van Zanden 2013) and social trauma; around 20 to 30 million or more people died (Dikötter 2010; Zhu 2012).

Aggregation of lives into aggregate income or consumption via a price of a life, as some of the economic models do, gets us into great philosophical difficulties. See for example, Broome (2004) and Stern (forthcoming). It is surely more transparent and arguably more rather than less rigorous to analyze possible consequences on a number of dimensions rather than force an aggregation that would bury or conceal some very difficult issues. The environmental ecosystem would surely be another highly relevant, indeed central, such dimension. This broader approach may make simple-minded optimization more difficult, but that follows from the nature of the issues at hand.

4. *Conclusion*

Where do we go from here? Essentially we need a new generation of models in all three of climate science, impact and economics. I think the scientists are moving purposefully in that direction and that some of this will be reflected in the forthcoming IPCC Fifth Assessment Report. I am less convinced that one sees this within economics. We have to embrace many models, each with its own insights. They should be capable of speaking about the scale of risks we face. And we need greater judgment in using the models. As the late Frank Hahn used to say, "a model is just a sentence in an argument." We need more and better sentences that embody more of the risks that are at the heart of the problem. And, in exercising the judgment necessary in putting the sentences together, one should remember Amartya Sen's remark, "it is better to be roughly right than precisely wrong." In particular, it is time for our profession to think much more carefully about processes of damage and destruction. We have considered theories of growth and have produced valuable insights. We should combine these insights with an examination and modeling of ways in which disruption and decline can occur.

Some more specific suggestions follow:

- Scientists should try to describe the risks in a 4°C (or more) warmer world as best they can, including extreme events, thresholds/tipping points, and complex interactions between temperature, precipitation, ecosystems, oceans, ice sheets, etc. Speculation is unavoidable but is most appropriate coming from those best placed, the scientists.
- Impact modelers should work by starting with an examination of the issues likely to hit or displace lives and livelihoods, particularly those issues that are currently poorly represented in the models, and focus on the major risks around these issues. This will inevitably involve being more stochastic in language and analysis.
- Economic modelers should abandon the assumption of damages being focused on current output and should incorporate lasting damage in the models. They should embrace a real possibility of

> creating an environment so hostile that physical, social, and organizational capital are destroyed, production processes are radically disrupted, future generations will be much poorer and hundreds of millions will have to move.

A fundamental difficulty here is that this is a problem where delay can be dangerous. The flow-stock process of emissions to concentrations embodies a ratchet effect, since it is very hard to extract CO_2 from the atmosphere. And high-carbon capital and infrastructure can be locked in. There is a fine chapter in the splendid book *Investment under Uncertainty* by Dixit and Pindyck (1994) that makes this point rigorously and powerfully and very early in the economics debate on climate change. We have to make policy in real time whilst we are trying to build better models and learn about the many underlying uncertainties.

In these circumstances, it is vital that we treat policy analysis as that of a risk-management problem of immense proportions and discuss risks in a far more realistic way. We know that models leave out much that is important—that is what makes them models. But we must also assess how they may mislead. Many scientists are telling us that our models are, grossly, underestimating the risks. In these circumstances, it is irresponsible to act as if the economic models currently dominating policy analysis represent a sensible central case. Put simply, the "consensus" of the IAMs is in the wrong place, from the point of view of the science, the economics, and the ethics.

Presenting the problem as risk-management is likely to point strongly towards a policy for a rapid transition to a low-carbon economy. As in past waves of technical change this could involve a few decades of discovery, innovation, investment, and growth. Further, we shall probably find, if we manage the transition well, that such growth can be cleaner, quieter, safer, more energy-secure and more bio-diverse. But that is another story.

Appendix

Part 1

We look to scientists to provide some clues on the nature of risk. Based on the mainstream scientific literature, at 4°C or warmer we have to consider:

- Much of southern Europe may experience drying and desertification (Solomon et al. 2009); the Sahara might advance southwards with possibly profound effects on the populations of Northern Nigeria, with a pressure on people to move south. Increased desertification in Mexico could put pressure on populations to move north (IPCC 2012).
- Much of the snow and ice on the Himalayas would have gone with possibly radical effects on pattern and timing of flows into and of the rivers that serve one or two billion people with consequent rapid run offs, major flooding, and soil erosion on a massive scale (Kaltenborn, Nellemann, and Vistnes 2010; World Bank 2013).[48]
- Similarly, the melting of snow and ice on the Andes and Rockies could dramatically alter water supplies to the western regions of South and North America (Kaser, Großhauser, and Marzeion 2010; Kaltenborn, Nelleman, and Vistnes 2010) as well as the Amazon river. Increasing precipitation falls as rain rather than snow, reducing water storage and increasing flooding. Many models suggest profound effects on water availability for billions of people, with likely

[48]The major rivers include the Yellow (Huang He), Salween, Yangtze, Mekong, Brahmaputra, Yamuna, Ganges, and Indus.

significant impacts on agriculture (e.g., Solomon et al. 2009).

- The North Indian monsoon that shapes the agricultural lives of hundreds of millions may be radically altered. Although there are a number of models that can simulate the current Indian summer monsoon (see, e.g., Annamalai, Hamilton, and Sperber 2007), such models may underrepresent potential future changes (see Valdes 2011) that could be sudden and dramatic.
- The Amazon forest might die back at radically altered climates, with the release of huge amounts of CO_2, and, e.g., possible desertification of much of the heavily populated state of Sao Paulo (Kriegler et al. 2009; Cook and Vizy 2008; Jones et al. 2009; Malhi et al. 2009; Huntingford et al. 2013; World Bank 2012).
- Extreme weather events are likely to be more intense, e.g., storms, cyclones. Tropical cyclones take their energy from the seas and higher temperatures make the winds stronger: damages go up with approximately the third power of wind speed (Emanuel 1987; Knutson and Tuleya 2004; IPCC 2012; World Bank 2012 and 2013).
- Storm surges could result in salination of large areas and their effective loss to agriculture (Agrawala et al. 2003), and grave damage to low-lying regions.
- Global sea levels rise slowly with thermal expansion but the effects could be massive. In the Pliocene Epoch, where temperatures may have been 3°C or so warmer than preindustrial times, around 3 million years ago, it was around 20 meters higher than now (Miller et al. 2012). It has been estimated that up to 200 million people might be displaced by a 2 meter rise (Nicholls et al. 2011): current projections suggest a 2 meter sea level rise might occur some time by the end of this century. Many low-lying countries and cities (many are coastal) across the world would be profoundly affected. Effects could come through much more quickly than the slower time scales indicated by thermal expansion if land-based ice slides into the oceans; an effect looking increasingly possible but not yet included in the formal science models (van der Veen 2010).
- Heat stress. "Wet-bulb" temperatures above 35°C induce hyperthermia and death in humans as the dissipation of metabolic heat becomes impossible. "Wet-bulb" temperature is the temperature at which the air would be saturated ("wet-bulb" temperatures rarely exceed 30°C in any part of the world today), in contrast to "dry-bulb" temperature, which is normal air temperature (often above 35°C in certain regions). The difference between these two types of temperature is a measure of "relative humidity"; they converge at 100 percent humidity. "Wet-bulb" temperatures above 35°C are likely to start to occur in "small zones" at around 7°C global warming. At 11–12°C warming these zones would expand to encompass the majority of today's human population (Sherwood and Huber 2010). At those temperatures, most of the planet may become almost uninhabitable, with large areas becoming uninhabitable as we move in this direction.

Part 2[49]

Examples of Research Programs that Aim to Push the Models Forward

The EU funded EMBRACE project (work package 5). EMBRACE aims to "identify and assess processes that may result in abrupt or irreversible climatic changes." This work package uses Coupled

[49] I am grateful to Jason Lowe of the U.K. Met Office Hadley Centre for his guidance.

Model Intercomparison Project Phase 5 (CMIP5) Earth System models, including the UK Met Office HadGEM2-ES model, to simulate better some potentially abrupt/irreversible systems. They do not simulate all potential thresholds/tipping points, but sea-ice, Atlantic Meridional Overturning Circulation and tropical forest systems are being included, and a series of experiments are being run. This work includes development of an early warning toolkit to predict abrupt change by analyzing change in variability that precedes the abrupt change.

Work at the UK Met Office Hadley Centre aims to estimate permafrost emissions offline and add them back into the HadGEM2-ES model to explore the feedbacks (on permafrost emissions see, e.g., Burke, Hartley, and Jones 2012; Schneider von Deimling et al. 2012). This work is in conjunction with the COMBINE project that will explore other missing feedbacks. There has also been initial work using HadGEM2-ES to investigate potential consequences of an abrupt methane release from ocean hydrates. And wetland methane emissions are now included in HadGEM2-ES.

Thresholds for ice sheets on land, currently not included in HadGEM2-ES as it does not include a dynamic ice sheet model, will be included in the new Earth System Model UKESM1 currently under development. Ocean circulation (see, e.g., Hawkins et al. 2011; Weaver et al. 2012) tropical forests (see, e.g., Good et al. 2013; Murphy and Bowman 2012) and changes to the hydrological cycle (see, e.g., Good et al. 2012; Levine et al. 2013) are also being investigated with HadGEM2-ES.

Research on extreme events is progressing and includes tropical cyclone tracking, forest fire danger indices, new models of drought in Africa, the ISI-MIP model inter-comparison project for impact models, regional modeling (downscaling) and anthropogenic aerosol effects on Atlantic hurricane frequency (on extreme events see, e.g., Hansen, Sato, and Ruedy 2012; Rahmstorf and Coumou 2011; Dole et al. 2011).

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