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Reason, Empathy, and Fair Play: The Climate Policy Gap

Elizabeth A. Stanton, Frank Ackerman and Ramón Bueno

Abstract

To achieve the greatest possible human welfare, the Stockholm Environment Institute's Climate and Regional Economics of Development (CRED) model calls for rapid reduction of greenhouse gas emissions to keep cumulative 21st century carbon dioxide emissions below 2,000 Gt. We explain why as some other models claim very slow emission reductions are best. We make three changes to the basic assumptions of the well-known DICE model to include the most recent estimates of economic damages from climate change, express greater concern about the well-being of future generations, and expect rich countries to invest in emissions and poverty reduction in poorer countries.

JEL Classification: Q54, Q56, O13, O11, F59, E17

Keywords: Climate change; climate policy; equity; discounting; economic development; CRED model

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Notes on authors:

Elizabeth A. Stanton is a Senior Economist at Stockholm Environment Institute' U.S. Center, an affiliate of Tufts University. liz.stanton@sei-us.org.

Frank Ackerman is a Senior Economist at Stockholm Environment Institute' U.S. Center, an affiliate of Tufts University. frank.ackerman@sei-us.org.

Ramón Bueno is a Scientist at Stockholm Environment Institute' U.S. Center, an affiliate of Tufts University. ramon.buen@sei-us.org.

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Typesetter: *Nancy Settecasi*

United Nations
Department of Economic and Social Affairs
2 United Nations Plaza, Room DC2-1428
New York, N.Y. 10017, USA
Tel: (1-212) 963-4761 • Fax: (1-212) 963-4444
e-mail: esa@un.org
http://www.un.org/en/development/desa/papers/

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Executive Summary

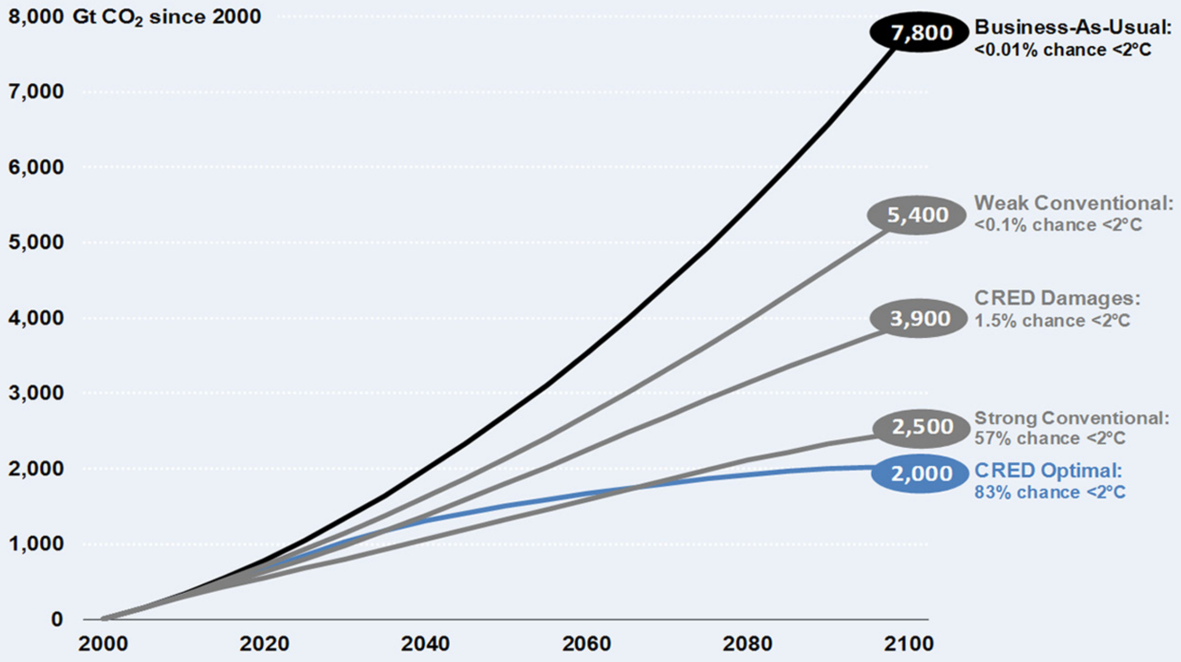
To achieve the greatest possible human welfare, the Stockholm Environment Institute's Climate and Regional Economics of Development (CRED) model calls for a rapid reduction of greenhouse gas emissions, beginning in the next decade and keeping cumulative 21st century carbon dioxide emissions below 2,000 Gt. This report reveals why CRED recommends such stringent reductions when some other climate-economics models say that very slow emission reductions are the best policy.

Beginning with a **Weak Conventional** policy – mimicking the basic assumptions used in the well-known DICE model – we make three successive changes to arrive at a recommendation for immediate, steep emission reductions:

- **Reason:** The **CRED Damages** policy brings estimates of the economic damages from climate change in line with the most up-to-date science.
- **Empathy:** The **Strong Conventional** policy adds greater concern about the well-being of future generations.
- **Fair Play:** The **CRED Optimal** policy adds a third change – rich countries are able and should be willing to invest in emissions and poverty reduction in poorer countries.

Figure ES1: Modeling Reason, Empathy, and Fair Play in CRED

Including assumptions of reason, empathy, and fair play in the CRED model transforms a Weak Conventional emissions reduction policy with a less than 1-in-1,000 chance of keeping temperature increases below 2°C into the CRED Optimal scenario with a better than 4-out-of-5 chance.



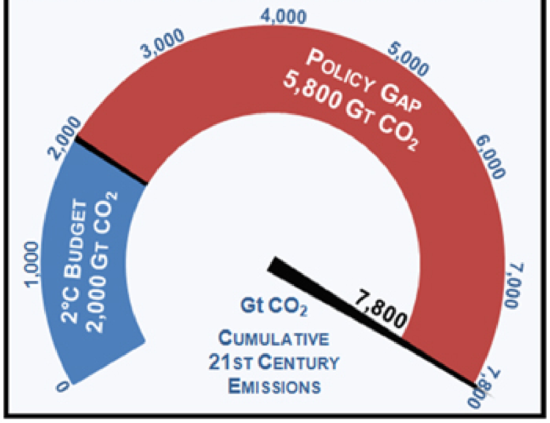
The Policy Gap

Without a deliberate policy of greenhouse gas reduction, annual CO_2 emissions are expected to more than quadruple over the course of this century. This would imply virtually no chance of keeping temperature increases below 2°C, and a 50/50 chance – a coin toss – that temperatures will have grown by more than 3.7°C by the end of this century. For a good chance of staying below 2°C of warming, a goal that is widely accepted as a threshold for avoiding dangerous climate impacts, cumulative 21st century emissions will need to be limited to no more than 2,000 Gt CO_2 – of which more than 300 Gt, 15 percent of the allowable 100-year total, were emitted by 2010.

Business-As-Usual emissions, in the absence of new climate policies, would total 7,800 Gt for the century, with a less than 1-in-10,000 chance of keeping temperatures below 2.0°C of warming. Thus there is a need for policies that can eliminate a staggering 5,800 Gt, three-fourths of Business-As-Usual emissions (see Figure ES2). A **Weak Conventional** policy scenario, of the sort modeled in many existing economic analyses, finds that the "optimal" policy leads to 5,400 Gt of cumulative emissions, and has a less than 1-in-1,000 chance of staying below 2.0°C (see Figure ES3). Something stronger is needed to hold the 100-year emissions total far below the Weak Conventional policy scenario.

Figure ES2: Business-As-Usual Emissions

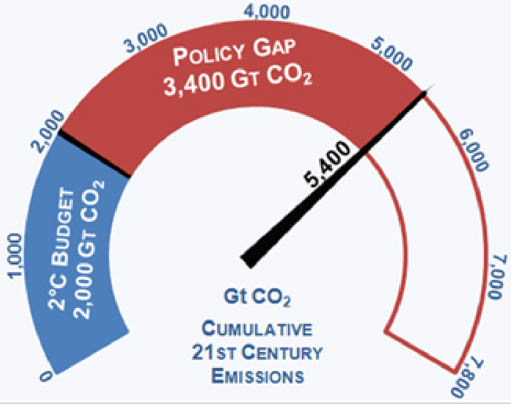
Less than 0.01% chance of staying below 2°C



The daunting challenge of reducing emissions rapidly enough to avoid dangerous climate change is all the more complex because it is inescapably entwined with two other policy dilemmas: How much should we care about, and invest in, the well-being of future generations? And what should we be doing to promote equity and economic development in today's very unequal world economy? Established models of climate economics often seem to ignore both the needs of future generations and the needs of low-income nations today.

Figure ES3: Weak Conventional Policy

High Discount Rate, DICE damages, No Transfers, Less than 0.1% chance of staying below 2°C



This report re-examines the economics of climate policy using the CRED model. CRED is designed to find an optimal climate policy – one that maximizes human welfare – in a context that recognizes and incorporates the needs of future generations and today's developing nations. We identify the effects on cumulative emissions of a number of policy options and modeling assumptions, leading to construction of a policy scenario that stays below the 2,000 Gt ceiling.

The optimal policy recommended by CRED calls for significant investment by high-income regions in developing countries, both to reduce emissions and to promote economic growth; this allows rapid reduction of global emissions and rising per capita incomes in all regions. Per capita incomes and consumption in rich countries continue to rise throughout, although at a slower rate than in the early stages of the no-policy Business-As-Usual scenario.

While the Weak Conventional policy scenario is an improvement over Business-As-Usual, it falls far short of what is needed. The reduction from the Weak Conventional to the CRED Optimal emissions trajectory involves three major steps, drawing on three very different, but equally crucial, arguments (see Box 1).

Box 1: Ground Rules for Achieving the CRED Optimal Scenario

Reason: Scientists' broad consensus on future climate conditions is accurate;

Empathy: Our impact on future generations should be an important consideration in current policy-making; and

Fair Play: Rich countries have a responsibility to support both economic development and emission reductions in poor countries.

With these assumptions in place, CRED drives down global emissions rapidly and allows incomes to rise in developing countries, while preventing rich countries' incomes from falling or stagnating. This report explores the factors that might cause us to choose one climate policy over another.

Reason: Understanding the Science

The first step involves climate science. Greenhouse gas emissions are released into the Earth's atmosphere, where, through complex interactions among many non-linear processes, global average temperatures grow warmer, sea levels rise, ocean waters become more acidic, and long-standing weather patterns are altered. These climatic changes are expected to have grave, and in some cases irreversible, effects on both natural ecosystems and human communities.

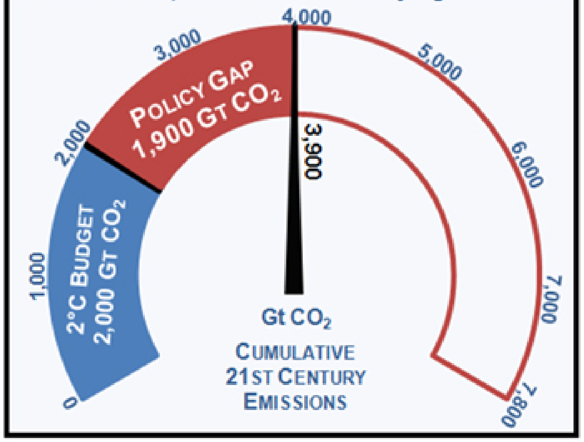
Exactly how much damage would follow from a given level of emissions is a complicated and under-researched question; representations of climate dynamics in economic models often lag behind the latest scientific knowledge. In this regard, three areas of climate science research deserve special mention: uncertainty about climate sensitivity values; the prospect of non-declining temperatures; and the wealth of recent scientific findings regarding climate impacts.

The effect of greenhouse gas emissions on global average temperatures is described in terms of "climate sensitivity," or the long-term temperature increase resulting from a doubling of the atmospheric concentration of CO_2. The precise value of climate sensitivity is unknown, but there is an emerging scientific consensus about the probability of various climate sensitivity values. The median estimate of climate sensitivity is often said to be 3°C, with a 1-in-20 chance that it is greater than about 7°C. In CRED, an emissions scenario with an assumed climate sensitivity of 3°C is said to have a 50/50 chance of staying under the maximum temperature that it reaches; an assumed climate sensitivity of about 7°C has a 95-percent chance of staying under the scenario's maximum temperature, and so on.

In the past, many emission-reduction scenarios have involved "overshoot," where concentrations and temperatures temporarily exceed long-term goals before declining to the target levels. Recent research regrettably suggests that temperature overshoot scenarios are not possible; regardless of future CO_2 reduction, temperatures will not decline from a past peak for centuries, if not millennia. In our analysis this is addressed by reporting expected temperatures only up to their peak levels.

Many climate-economic models are badly out of date in their estimates of expected climate damages. It is unfortunately common to find models still relying on research from the early 1990s, a time when the extent of likely climate damages and the risk of catastrophe were not yet understood, and unrealistically optimistic estimates of agricultural impacts, in particular, were common. CRED allows a choice of alternative estimates of the relationship between temperature and climate damages; alongside traditional, lower damage estimates, we analyze damage functions that assume a complete collapse of the world economy at around 12°C of warming. Introducing this change alone into the Weak Conventional policy scenario inspires much more active policy in order to avoid extreme, high-temperature damages. With more realistic **CRED Damages**, cumulative 21st century emissions are reduced to 3,900 Gt, with a little better than 1-in-100 chance of remaining under 2.0°C (see Figure ES4).

Figure ES4: CRED Damages
High Discount Rate, Severe Damages,
No Transfers, 1.5% chance of staying below 2°C



Empathy: Caring about Future Generations

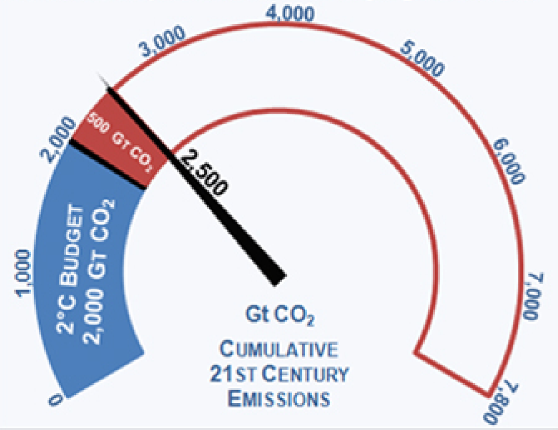
A second step in emission-reduction results from attitudes toward the future. An important ethical judgment embodied in climate-economics models determines how much weight is given to the interests of future generations. Because the effects of today's emissions will be felt for hundreds, if not thousands, of years, every model must make some assumption about the importance of expected future damages for current-day decision-making.

In CRED, as in many other models, this key judgment is represented by the "pure rate of time preference," an important component of the discount rate. The pure rate of time preference is the discount rate that would apply if all generations were equally wealthy. (Under the common assumption that future generations will be richer, the discount rate is increased to reflect the expected differences in wealth.)

The pure rate of time preference is not a scientific constant; rather, it is an answer to a crucial ethical question: How much *should* we, as a society, care about the impact of our actions on future generations? Yet the answer to this question has a profound effect on model results. The higher the discount rate, the less important future climate damages are assumed to be for today's decision-makers. At the extremes, a very high discount rate causes a model to ignore any climate damages that occur more than a few decades into the future, whereas at a very low discount rate, climate damages are almost equally important regardless of when they occur.

The Weak Conventional and CRED Damages policy scenarios assume a 1.5 percent rate of pure time preference, a common value in economic models. Lowering that rate to 0.1 percent, the value adopted by the Stern Review, in combination with the higher damage estimate (economic collapse at 12°C of warming) reduces cumulative 21st century emissions to 2,500 Gt, within sight of the 2,000 Gt target. This high damage/low time preference, or **Strong Conventional** policy scenario has a somewhat better than 50/50 chance of keeping warming under 2.0°C (see Figure ES5).

Figure ES5: Strong Conventional Policy
Low Discount Rate, Severe Damages, No Transfers, 57% chance of staying below 2°C



This might look like a happy ending to this story, except for a lack of realism in the Strong Conventional policy scenario, which assumes that no cross-regional investments or transfers of resources implies that each region is on its own. Poor countries as well as rich ones are expected to look at ominous climate risks through the lens of a low discount rate, and to prioritize investment in emission reduction. Yet countries with limited resources and pressing needs for economic development are unlikely to finance the needed investments in abatement on their own.

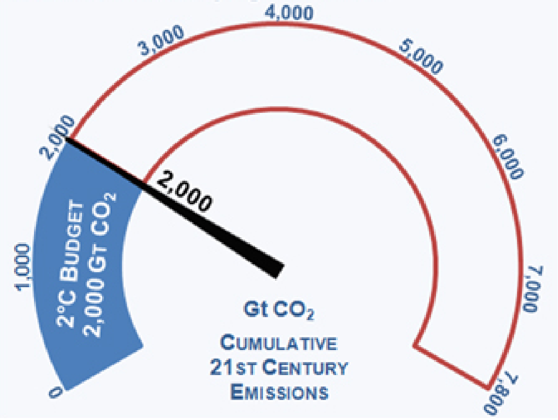
Fair Play: Prioritizing Equity in Today's World

A final step toward emission reduction, and toward political feasibility, reflects a commitment to global equity. Climate policies can be judged in terms of their fairness, not only to future generations but also among different world regions and income groups today. How will we spend our 2,000 Gt CO_2 – or more precisely, the 1,700-odd Gt that remain available for the rest of the century? Which countries will use up this remaining budget? And who will pay for the measures necessary to put an end to additional emissions? These questions are at the heart of current climate policy negotiations, but they are too often absent from climate-economics analysis.

Economic models that maximize global welfare, including many climate-economics models, contain a built-in bias toward equalization of incomes. The well-established principle of diminishing marginal utility implies that an additional dollar of income is worth more to a lower-income person or region. So redistribution from rich to poor should increase global welfare – assuming, of course, that the welfare of people everywhere is of comparable worth (a common assumption in applied modeling, although it has long been out of fashion in abstract economic theory).

This bias toward equality is hidden in conventional models by a technical device that effectively blocks redistribution, and by the political or institutional assumption that there will be no substantial transfers of resources between regions. CRED, in contrast, allows the extent of cross-regional transfers to vary; the model chooses not only the magnitude and location of the needed investments, but also the source of those investments.

Figure ES6: CRED Optimal Policy
Low Discount Rate, Severe Damages, Transfers, 83% chance of staying below 2°C



CRED's fully unconstrained solution involves massive transfers of resources from rich countries to the rest of the world, funding both emission reduction and economic development. These transfers are so larget high-income per capita consumption drops to the level of middle-income countries, remaining there for decades until an egalitarian rising tide lifts everyone's level of consumption. This scenario has both the greatest global human welfare *and* the best climate outcomes of all the scenarios we have examined; nonetheless, it seems well outside the realm of political feasibility. Therefore, the scenarios discussed here include a constraint that per capita consumption rises, at least gradually, in all regions at all times.

The **CRED Optimal** policy scenario, modifying the Strong Conventional scenario to allow substantial cross-regional transfers while guaranteeing rising per capita consumption to all, achieves the 2,000 Gt target for 21st century emissions, offering about a 4-out-of-5 chance of remaining below 2°C of warming (see Figure ES6). Moreover, it greatly reduces global income inequality at the same time. In 2005, per capita consumption was 39 times higher in the United States, the richest region, than in Africa or Developing Asia/Pacific, the poorest regions. That ratio remains roughly unchanged in conventional policy scenarios, but drops to less than 6 by 2100 in the CRED Optimal scenario.

Assumptions like these – that the whole world shares one set of aspirations and policy priorities, or that climate policy is best examined against a backdrop that freezes the current income distribution, or that high-income regions cannot or will not invest in emissions and poverty reduction in low-income regions – do not represent universally held beliefs. When climate-economics models use these assumptions, it is imperative that their results be accompanied by an explanation of modeling choices, expressed in non-technical terms. CRED results (summarized in Table ES1) demonstrate that modeling choices regarding cross-regional investment affect not only who pays for how much abatement, but also how quickly emission reductions occur, how quickly developing countries are able to raise living standards, and what chance global emission-reduction efforts have at keeping temperature increases below 2°C. For climate-economics models to have policy relevance, a transparent analysis of international equity is essential.

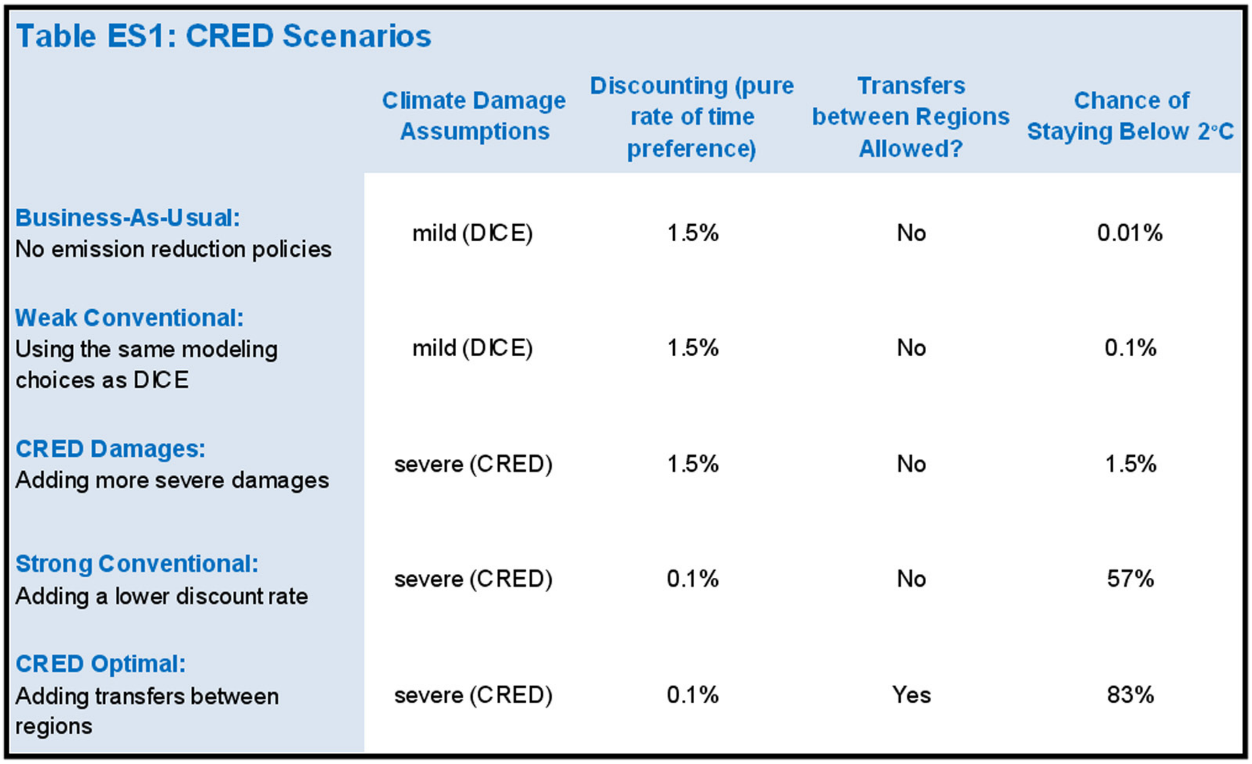


Table ES1: CRED Scenarios

	Climate Damage Assumptions	Discounting (pure rate of time preference)	Transfers between Regions Allowed?	Chance of Staying Below 2°C
Business-As-Usual: No emission reduction policies	mild (DICE)	1.5%	No	0.01%
Weak Conventional: Using the same modeling choices as DICE	mild (DICE)	1.5%	No	0.1%
CRED Damages: Adding more severe damages	severe (CRED)	1.5%	No	1.5%
Strong Conventional: Adding a lower discount rate	severe (CRED)	0.1%	No	57%
CRED Optimal: Adding transfers between regions	severe (CRED)	0.1%	Yes	83%

Closing the Gap: A Precautionary Response

There is no easy solution to the climate crisis. Many economic analyses fail to come to grips with the severity of the problem. For example, CRED's Weak Conventional scenario – based on the modeling choices made in the well-known DICE model – would allow 21st century emissions of 5,400 Gt, with only a 1-in-1,000 chance of staying below 2.0°C of warming. Such scenarios are incompatible with the scientific warnings of widespread, serious damages if warming exceeds 2°C. There are multiple factors that account for this disparity between climate science and climate economics, including:

- **Failure of reason (not understanding or not believing the science)**
  Focusing on the most likely climate sensitivity (that is, the impact of emissions on temperatures) can only tell us so much. The smart gambler never places a bet without first knowing the odds: To make good decisions about an uncertain future, we need to know not only the best guess (50/50), but also the long shots, such as the 1-in-5 and the 1-in-50 outcomes. Similarly, prudent households and investors often seek to insure themselves against low-probability risks of disastrous losses.
  Also uncertain is the relationship between temperatures and economic losses. While we will never be able to predict these impacts too exactly, there is no reason to cling to outdated, unduly rosy estimates, rather than following the best, most recent findings of climate scientists.
- **Failure of empathy (not caring about the fate of future generations)**
  A society that cares deeply about the well-being of future generations will embrace a very different climate policy than a society that can't see past the current economic crisis. Which one are we? The longer we take in reducing emissions, the more likely we are to exceed 2°C and bequeath serious economic damages from climate change to future generations.
- **Failure of fair play (not supporting a solution that is equitable to low-income countries and groups today)**

  Rich countries tend to support plans for emission reductions that are based on the principle of "grandfathering": Reductions are tied to historical emissions, so the more you've emitted in the past, the more you get to emit in the future. With a fixed 2°C budget of 2,000 Gt CO_2 for the 21st century, emission reductions are a zero sum game – if one country emits more, other countries must emit less.

  Developing countries should, and do, object to the "logic" of grandfathering. Unless rich countries are willing to pay for emission-reduction efforts outside of their borders, the high cost of maintaining or lowering per capita emissions will make it all but impossible for poorer countries to raise living standards. Developing countries are unlikely to direct all of their resources to emission reduction at the expense of poverty reduction; cross-regional transfers are essential to achieving a good chance of staying below 2°C.

In the CRED model, these scientific uncertainties and ethical dilemmas are addressed explicitly, making it possible to test out new values, alone and in combination. The CRED Optimal scenario, incorporating all of these concerns, produces a successful climate outcome (a less than 1-in-5 chance of exceeding 2°C) along with a dramatic reduction in global inequality; low-income regions experience rapid growth while high-income regions grow at a slower, gradual pace.

Currently, the only existing global policy measure that addresses the climate crisis is voluntary and very small in scale; under the Cancun Agreement, a non-binding agreement adopted in 2010, countries accounting for more than 80 percent of present-day emissions have submitted voluntary pledges amounting to a cumulative reduction relative to the Business-As-Usual scenario of 100 Gt by 2020. Because many of these pledges promise reductions with respect to potentially growing business-as-usual emissions, and not with respect to today's emissions, even if all countries carry through with their Cancun pledges global emissions are expected to be higher in 2020 than they are today. The Cancun Agreement, as an agenda for the next decade, does not preclude a 50/50 chance of staying below 2°C, but achieving this goal would require deep and sustained post-2020 emission reductions.

The question then for policy makers and for the public is: What is an acceptable level of risk? What percentage chance of exceeding 2°C are we willing to take on? There is no single right answer, but rather a continuum of choices; a lower probability of dangerous climate change requires greater and faster reduction in emissions.

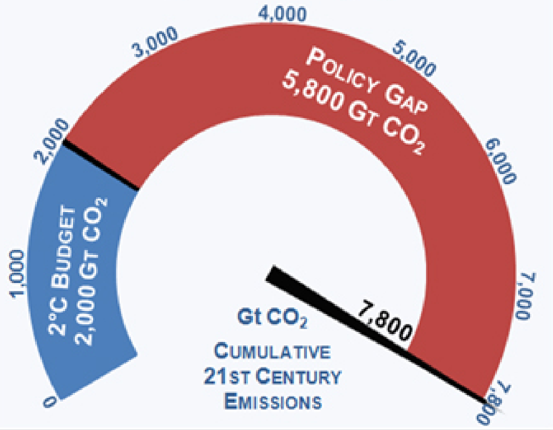
A precautionary response – limiting our risk of exceeding 2°C to 1 in 5 or even lower – requires that global emissions begin to fall rapidly within the next 10 years. The climate policy gap is not insurmountable, but closing it will require reason, empathy, fair play, and a great deal of political will. The CRED model offers a framework designed to analyze the full range of relevant, interacting issues.

The Policy Gap

Without a deliberate policy of greenhouse gas reduction, carbon dioxide (CO_2) emissions are expected to more than quadruple during this century. That's the Business-As-Usual scenario – annual CO_2 emissions grow from 30 gigatons (a gigaton is a thousand million tons, abbreviated Gt) in 2000 up to 130 Gt in 2100.[1] (Recent estimates suggest that annual CO_2 emissions had already climbed to 38 Gt in 2010.)[2] If emissions continue to grow at this pace, there is less than a 1-percent chance of keeping temperature increases below 2°C, a key threshold for dangerous climate change, and a 50/50 chance – a coin toss – that temperatures will have grown by more than 3.7°C by the end of this century.[3] At the same time, fundamental differences over who should pay for the costs of climate protection threaten to block any serious international agreement.

In this report, results from the Climate and Regional Economics of Development (CRED) integrated assessment model are used to illustrate the impacts of high-emission business-as-usual scenarios and low-emission rapid emission-reduction scenarios, as well as other policy options that take a slower path to emission reduction. CRED was created by the Stockholm Environment Institute in 2010 to bring the analysis of climate economics together with international equity. CRED allows examination of emission-reduction scenarios and, separately, of who pays for them. (For detailed descriptions of the CRED model see Ackerman, Stanton and Bueno (2011a; 2011b).)

Figure 1: Business-As-Usual Emissions
Less than 0.01% chance of staying below 2°C



The importance of limiting global average temperature increases to 2°C to avoid the worst damages from climate change is widely accepted. The *Synthesis Report of the 2009 Copenhagen Climate Congress,* for example, states that, "While there is not yet a global consensus on what levels of climate change might be defined to be 'dangerous,' considerable support has developed for containing the rise in global temperature to a maximum of 2°C above pre-industrial levels. …Beyond 2°C, the possibilities for adaptation of society and ecosystems rapidly decline with an increasing risk of social disruption through health impacts, water shortages and food insecurity."[4]

In the climate science literature, projections of unacceptable damages and irreversible changes at 2°C, and even at 1.5°C, abound. The 2007 Intergovernmental Panel on Climate Change's (IPCC) *Fourth Assessment Report* summarized these findings. Among the expected impacts of continued climate change: The number of people exposed to water stress will triple by 2050; 20 to 30 percent of species will be at risk of extinction by 2100; human health will suffer; and communities living in coastal lowlands, river deltas, and low-lying islands will be exposed to storm-surge flooding in the short run and permanent inundation in the long run. The most up-to-date compilations of the climate science literature support these findings, highlighting more recent projections of a precipitous decline in agricultural productivity and much more rapid increases in sea level than reported in the IPCC's last assessment.[5]

This report approaches emission-reduction goals in terms of a cumulative emissions budget for the 21st century (with some discussion of the importance of the pace of emissions within that budget). CO_2 persists in the atmosphere for centuries, so the warming that we will experience is roughly proportional to the total emissions over the century. As this report explains, for there to be a very good chance of limiting temperature increases to 2°C and averting the worst climate damages, no more than a cumulative 2,000 Gt CO_2 can be released into the atmosphere between 2000 and 2100.[6] (To give this budget some context: More than 300 Gt had already been released from 2000 to 2010, so the remaining budget is less than 1,700 Gt for the next 90 years.)

While the relatively safe level of emissions is 2,000 Gt for the century, **Business-As-Usual** emissions – in the absence of new climate policies – would add up to 7,800 Gt, leaving a very large policy gap: A reduction of 5,800 Gt below expected Business-As-Usual emissions will be needed to assure the best chance of keeping temperature increases under 2°C (see Figure 1).[7]

Pictured together with Business-As-Usual emissions in graphs throughout this report is the low-emission, **CRED Optimal** scenario, with about a 4-out-of-5 (83-percent) chance of keeping temperature increases below 2°C and a 50/50 chance of staying below 1.8°C. In this scenario, atmospheric concentrations peak in 2045 at 445 ppm CO_2, and cumulative 21st century emissions are kept within the 2,000 Gt budget (see Figure 2). It is important to note that cross-regional investment – rich countries sharing their resources with poorer countries – is a critical component of the CRED Optimal scenario; without these investment flows, it is difficult to envision a successful rapid abatement scenario.

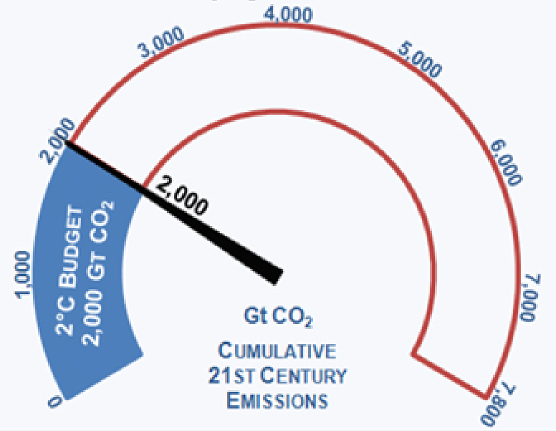


Figure 2: CRED Optimal Policy
Low Discount Rate, Severe Damages, Transfers, 83% chance of staying below 2°C

With a 4-out-of-5 chance of keeping temperatures below 2°C, the CRED Optimal scenario is the model's recommendation of the best course of action given the following basic ground rules regarding reason, empathy, and fair play (see Box 1).

Box 1: Ground Rules for Achieving the CRED Optimal Scenario

Reason: Scientists' broad consensus on future climate conditions is accurate;

Empathy: Our impact on future generations should be an important consideration in current policy-making; and

Fair Play: Rich countries have a responsibility to support both economic development and emission reductions in poor countries.

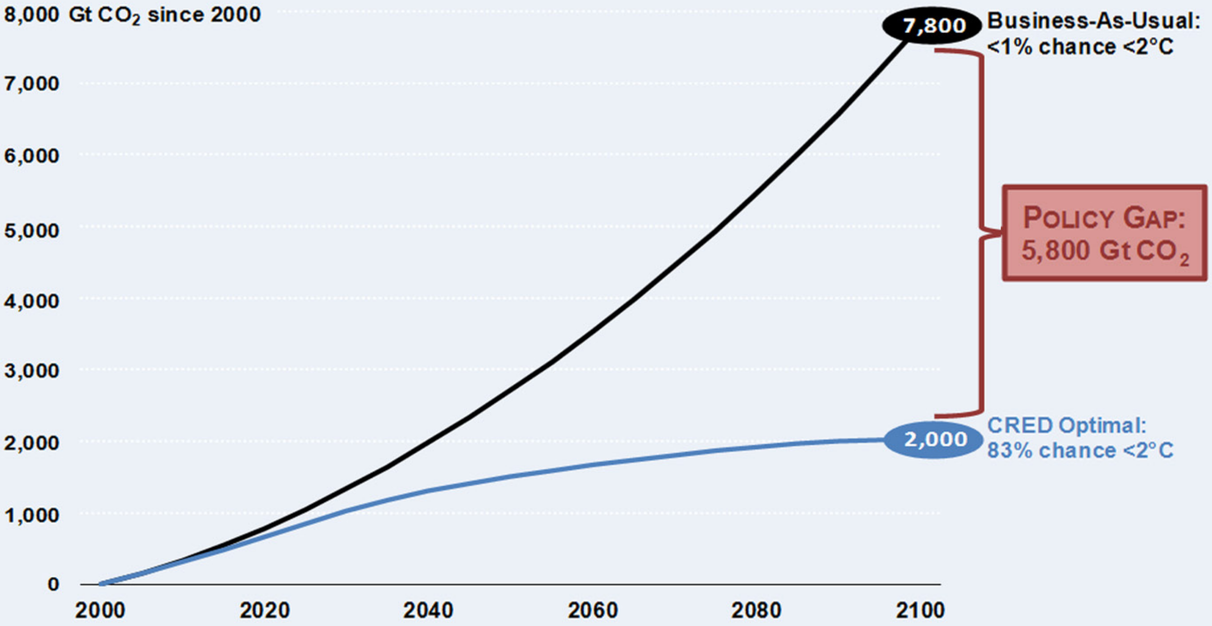
With these assumptions in place, CRED drives down global emissions rapidly and allows incomes to rise in developing countries, while preventing rich countries' incomes from falling or stagnating.

These two emission scenarios – Business-As-Usual with a less than 1-percent chance of avoiding the worst damage from climate change, and CRED Optimal with an 83-percent chance – frame the discussion of potential climate policy responses in this report (see Figure 3). Between them lies a gaping chasm.

As a global society we jointly face the challenge of narrowing this 5,800 Gt CO_2 gap. This report looks at existing and proposed climate policies in the context of this emission-reduction gap, and explores the factors that might cause us to choose one policy over another.

Figure 3: Global Emissions in the Business-As-Usual and CRED Optimal Scenarios

In the Business-As-Usual scenario, global emissions continue to grow at today's pace, approaching a cumulative 7,800 Gt CO_2 by 2100. CRED's Optimal scenario calls for emissions to slow immediately, eliminating all annual emissions by the end of the century, and offering an 83-percent chance of staying below 2°C.



Climate Economics and Climate Policy

Decision-makers have a difficult mission ahead of them: Not just finding a way to release 5,800 fewer gigatons of CO_2 over the next century, but constructing a policy for those emission cuts that every country in the world can agree on. A successful climate action policy will have to be effective, efficient, and equitable – and these essential qualities have requirements that often pull in different directions. To help sort out competing demands, policy makers turn to economists to translate scientists' projection of future climatic conditions into estimates of economic losses.

Many climate economists use a "welfare maximization" framework – in effect, a global cost-benefit analysis – to identify a recommended course of action. CRED uses this approach, as do many other integrated assessment models, including the well-known DICE model.[8]

CRED, DICE and similar models offer policy advice by calculating what pace of both conventional and emission-reducing investments would result in the greatest global social welfare (measured in terms of consumption per capita) given a set of starting assumptions about:

- how greenhouse gas emissions relate to global annual average temperature;
- how temperatures relate to economic damages;
- the importance given to expected future damages in current-day decision-making; and
- the degree to which richer countries will share their resources to foster emission reductions in poorer countries.

Based on specific values for each of these four assumptions, welfare-maximizing models try out investment and emission-reduction pathways to find the one that results in the greatest social welfare. Any change to these assumptions – all of which involve either deep uncertainty or ethical judgment – means a different optimal result and, therefore, a different policy recommendation. The bottom line: Advice given by climate economists to policy makers is extremely sensitive to some very *ad hoc* modeling decisions.

According to the DICE model, the best climate policy would allow increases in emissions throughout this century, with a 50/50 chance that temperatures will exceed 2.6°C by 2100.[9] The **DICE Optimal** scenario recommends an emission pathway that would result in a cumulative 3,800 Gt CO_2 emitted during the 21^{st} century, leaving a policy gap of 1,800 Gt above the allowable 2°C budget (see Figure 4).

Figure 4: DICE Optimal Policy

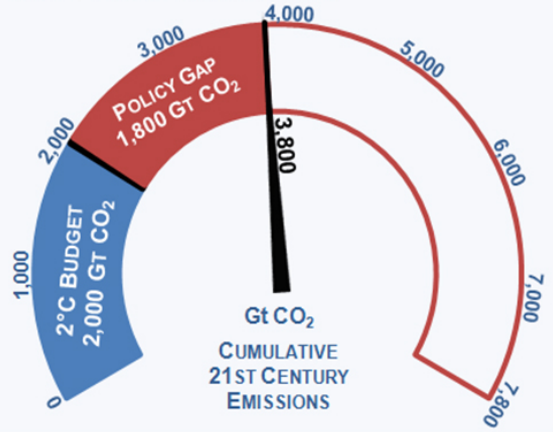
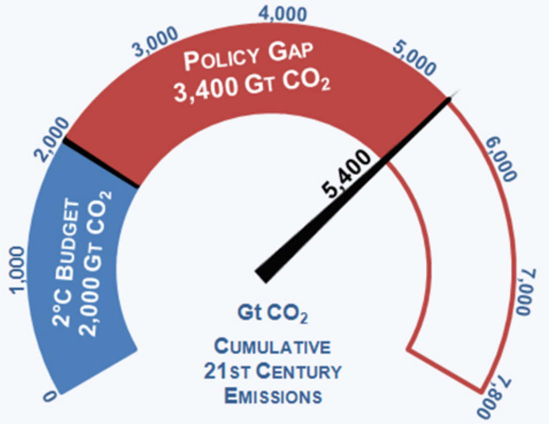


Figure 5: Weak Conventional Policy

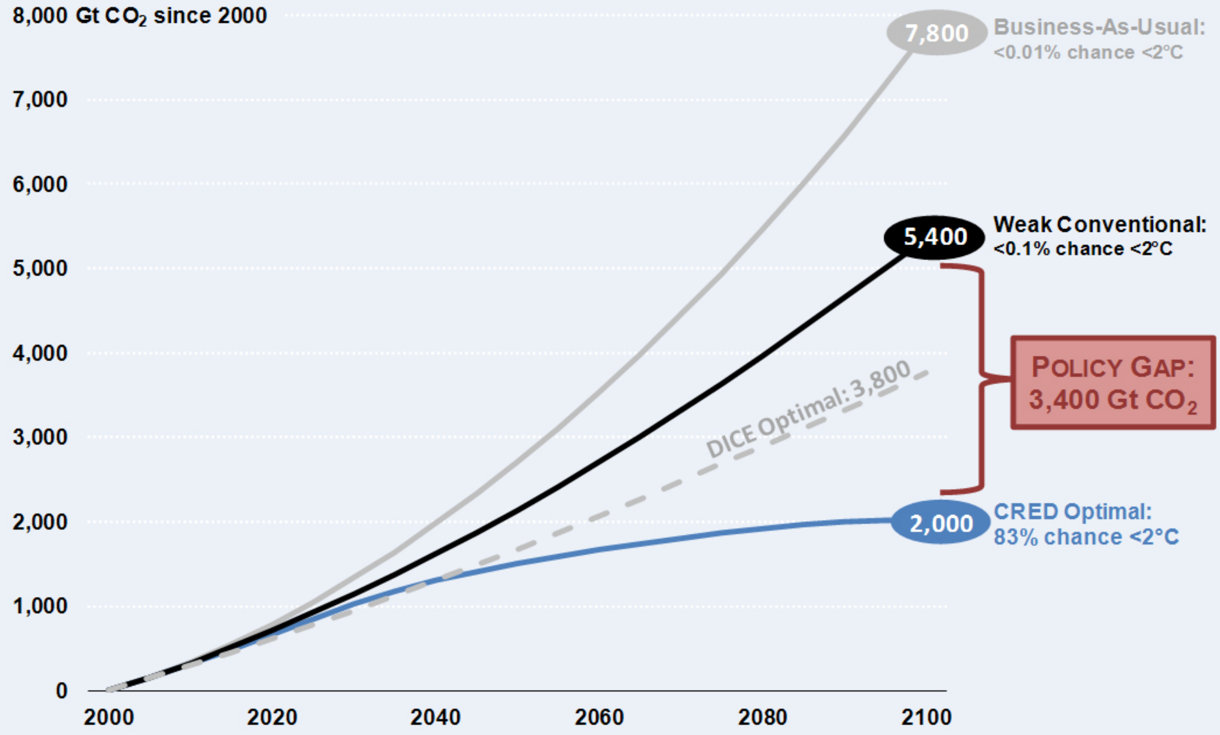
High Discount Rate, DICE damages, No Transfers, Less than 0.1% chance of staying below 2°C



DICE, however, may be unduly optimistic. When the same assumptions used by DICE are modeled in CRED – which includes a more up-to-date representation of the climate's physical processes, as well as a more detailed understanding of the costs of emission-reduction technologies – the optimal policy (recommended by CRED given these starting assumptions) allows even more greenhouse gas emissions.

Figure 6: Global Emissions in the Weak Conventional and DICE Optimal Scenarios

The DICE Optimal scenario allows global emissions to grow by nearly 40 percent over the next century. When the DICE modeling assumptions are used in CRED's Weak Conventional scenario, emissions grow even more quickly. The Weak Conventional scenario provides less than a 1-percent chance of staying below 2°C.



CRED's **Weak Conventional** scenario – with DICE's high discount rate and relatively mild climate damages, along with no transfers of resources between regions – recommends 5,400 Gt in cumulative 21st century CO_2 emissions, leaving a policy gap of 3,400 Gt. The result is a less than 1-percent chance of keeping temperature increases below 2°C, and a 50/50 chance that temperatures will exceed 3.0°C by 2100 (see Figures 5 and 6).

The Weak Conventional policy prevents 2,400 Gt CO_2 from entering the atmosphere, as compared to Business-As-Usual emissions. That's an important contribution to global emission reductions, but not enough for even a 1-percent chance of preventing dangerous climate change. (The Business-As-Usual scenario has a less than 1-in-10,000 chance of keeping temperature increases below 2°C; the Weak Conventional scenario brings this probability up to a little less than 1-in-1000 chance.)

Why would climate-economics models recommend that emissions continue to increase throughout the century? The advice given by these models depends both on choices modelers make about how to represent uncertain future outcomes, and on some sticky ethical dilemmas. Throughout this report we examine how changing these modeling choices affects the policy recommendations taken from climate-economics analysis.

Reason, Empathy, Fair Play

Three key modeling choices regarding emissions' effect on temperature and temperature's effect on damages are discussed in the next section, **Reason: Understanding the Science.** Traditionally, most climate models have treated emissions' effect on temperature as certain; that is, the most likely effect – that doubling the amount of CO_2 in the atmosphere will increase long-term temperatures by 3°C – is assumed to be the only case worth considering. The relationship between emissions and temperature, however, is not at all certain, but there is a pattern to its uncertainty that – at least in broad strokes – is well understood by climate scientists. In this report, we incorporate the best current understanding of the pattern of emissions-to-temperature uncertainty by presenting, for each scenario, the likelihood of varying degrees of warming.

Another key finding from climate science is also commonly misrepresented in the models that guide policy makers. Some policy analyses rely on "overshoot" scenarios that show greenhouse gas concentrations and temperatures first becoming too high and then being brought back down to target levels. Overshoot scenarios cannot work because global average temperatures grow much more easily than they decline. Once a peak temperature is reached, new research suggests that it will not fall for several centuries, even if CO_2 concentrations are lowered substantially.

The final disconnect between climate science and climate economics has to do with the relationship between global average temperatures and economic damages, often represented by a "damage function". When the DICE damage function is replaced with an estimate that is more in line with recent research, CRED's recommended emission pathway declines sharply. With a more accurate picture of the economic consequences of rising temperatures, climate-economics models recommend faster, deeper cuts in emissions.

The next key modeling choice, the importance of future impacts to current decisions, is addressed in the following section, **Empathy: Caring about Future Generations**. The policy recommendations given by climate-economics models depend strongly on the discount rate, a number that contains a hidden ethical judgment. A component of the discount rate, called the "pure rate of time preference," represents modelers' best guess about how much our current generation cares about their emissions' impacts on future generations. The more we are assumed to care, the more quickly emissions are reduced in the optimal scenario. If we care little about future damages, then – from the perspective of today's decision makers – there is little urgency to reduce greenhouse gas emissions.

The final modeling choice, how the burden of paying for emission reductions will be shared, is the topic of the fourth section, **Fair Play: Prioritizing Equity in Today's World**. While many climate-economics models contain a hidden assumption, implying that today's huge gap between high-income and low-income countries is here to stay, CRED makes cross-regional transfers an explicit modeling choice. When rich countries invest in emission reduction and economic development abroad, the optimal abatement policy starts out a little slower because more resources are being devoted to raise incomes in the poorest countries. Within a few decades, however, emissions fall sharply enough to meet the cumulative 21st century budget, and the likelihood of keeping temperatures below 2°C is greater than in scenarios without cross-regional investment. The competing priorities of poor and rich nations are the centerpiece of current international climate negotiations; a good representation of these dynamics is essential to the policy relevance of climate-economics models.

The report concludes with the final section, **Closing the Gap: A Precautionary Response**. The CRED optimal scenario offers a precautionary – or standards-based – approach to preventing dangerous climate change that would limit our risk of exceeding 2°C to less than 1 in 5, keeping cumulative emissions below 2,000 Gt CO_2. To date, voluntary pledges will result in cumulative global emissions just 100 Gt lower than in the Business-As-Usual scenario. The remaining policy gap is enormous: 5,700 Gt above the 2°C budget. To close this gap we'll need to take climate science seriously and take a good look at how our actions affect both future generations and near-term poverty reduction efforts.

Reason: Understanding the Science

Greenhouse gas emissions are released into the Earth's atmosphere, where, through a complex interaction of many non-linear processes, global average temperatures grow warmer, sea levels rise, ocean waters become more acidic, and long-standing weather patterns are altered. These climatic changes are expected to have grave, and in some cases irreversible, effects on both natural ecosystems and human communities. Even if significant investment were to take place in adapting to new temperatures, sea levels and weather patterns, serious economic damage is the very likely consequence of continued growth in emissions.

Exactly how much economic damage would follow from a given level of emissions is a complicated and under-researched question. Both the effect of emissions on temperatures and the effect of temperatures on economic damages are uncertain, and the best scientific knowledge about these uncertainties is often left out of climate-economics models.

In this regard, three areas of climate science research deserve special mention for their key importance in estimating economic damages from climate change, and their poor representation in current climate-economics modeling: The probability distribution of climate sensitivity values; the prospect of non-declining temperatures; and the wealth of recent scientific findings regarding climate impacts.

Climate policy debate, in the United States and elsewhere, involves a noisy confrontation with the so-called skeptics, whose position is more accurately described as science denial. Conventional economic analysis, in contrast, could be called risk denial – accepting a (very optimistic) picture of the most likely climate outcomes, but paying little or no attention to worst-case risks. When climate economists – and the policy makers they advise – fail to understand the well-established findings of climate science, the result is likely to be too little emission reduction, too late.

Climate Sensitivity

The effect that greenhouse gas emissions have on the global average temperatures is estimated in terms of "climate sensitivity," or the impact that a doubling of the atmospheric concentration of CO_2 has on long-term temperatures. Climate sensitivity is uncertain (its exact value is unknown and perhaps unknowable) but there is an emerging consensus among scientists about the probability of various climate sensitivity values. Put another way, the true value of climate sensitivity is not known, but scientists' estimates are converging about the likelihood of any potential value. In broad strokes: The median estimate of climate sensitivity is often said to be 3°C (that is, there is an equal likelihood of the true value being above or below that point), with a 1-in-20 chance that it is less than 2°C, and a 1-in-20 chance that it is greater than about 7°C. Recent literature on climate sensitivity has produced a variety of probability distributions that share this same basic shape, but differ in smaller details.[10]

Many climate-economics models ignore this uncertainty, and only produce results based on the median, best guess, 3°C climate sensitivity value. The relevance of these climate policy recommendations to real-world decision making is dubious. There is a 50-percent chance that future emissions will have a stronger effect on temperatures – that is, cause a greater than 3°C increase in temperatures – and a 50-percent chance that emissions will have a weaker effect. Modeling based on the median climate sensitivity provides a central estimate that may be the best single guess – but, in the absence of information about less likely but far more catastrophic outcomes, how useful is the best guess in making weighty policy decisions? If all decisions were made on the best-guess method, no one would ever buy insurance against any potential loss.

In reporting results from the CRED model, and in scenarios produced by the British government's AVOID program discussed later in this report, climate sensitivity is approached in terms of its probability distribution. Using this method, emission scenarios are referred to as having a 50/50 chance of keeping temperatures below the level they reach when using the median 3°C climate sensitivity (and a 50/50 chance of exceeding that level). The same emissions scenarios can also be run with other values for climate sensitivity. By varying this key parameter in CRED, climate sensitivity values are identified that keep temperatures below given thresholds (such as 2°C) in 2100. These threshold climate sensitivities are then matched to their probabilities in a well-known climate sensitivity distribution.[11] For example, at the 3°C climate sensitivity, CRED's Business-As-Usual scenario reaches a temperature increase of 3.7°C in 2100 – so, based on the uncertainty about climate sensitivity, there is a 50/50 chance of the Business-As-Usual scenario either exceeding or remaining below this level. In this same scenario, a 1.3°C climate sensitivity keeps 2100 temperatures just below 2°C. The probability that the climate sensitivity is 1.3°C or lower is 0.009 percent (9/1,000th of 1 percent, or about a 1-in-10,000 chance), which is the basis for the statement that the Business-As-Usual scenario has less than 1-percent chance of staying below 2°C.

This manner of presenting results puts them in the context of the likelihood of their occurrence: The Business-As-Usual scenario has a less than 1-percent chance of staying below 2°C and a 50/50 chance of staying below 3.7°C through 2100. Similarly, if a particular level of risk is deemed acceptable – a 50/50 chance of exceeding 2°C, or a 1-in-5 chance, or a 1-in-50 chance – then a CRED model scenario can be tailored to show the pattern of investments that will result in the greatest social welfare while keeping below that threshold of risk. The more difficult question of what level of risk is acceptable is returned to in the final section of this report, which addresses a precautionary approach to forming climate policy.

Non-Declining Temperatures

Of the many new and important findings of climate science, one in particular stands out as a game changer. Most current physical and economic models of emission scenarios allow for a process known as "overshoot": Atmospheric concentrations of CO_2 rise in this century but then begin to decline again, and global average temperatures fall with them with a lag of, at most, a few decades. In overshoot scenarios, immediate abatement is less urgent because it is assumed to be possible to reverse high concentration levels and bring down temperatures.

Regrettably, new research indicates that, while it may be possible to overshoot a concentration target and then bring atmospheric levels back down, temperatures will decline only very slightly as CO_2 concentrations fall. Studies based on several climate models show that temperatures will climb towards a peak determined by the highest CO_2 concentration levels reached and then decline by less than 0.5°C – regardless of declining concentrations – for centuries or millennia. In short, global average temperatures will become stuck at roughly the highest level that they reach.[12] A leading cause of this phenomenon is the process of heat exchange with the oceans: as atmospheric concentrations rise and the world warms, the oceans absorb a significant fraction of the increased heat; as concentrations decline, decreases in radiative forcing from greenhouse gases in the atmosphere are offset almost exactly by decreases in the oceans' absorption of heat.

The importance of this new understanding of the climate system cannot be overstated. There is no wiggle room in climate policy. If greenhouse gas concentrations become too high, extreme emission reductions in later years cannot reverse the process of climate change – at least not for several centuries. The 2,000 Gt budget for 21st century cumulative CO_2 emissions is all that we have to "spend," and in the first decade of the century more than 300 Gt have already left our wallets. To keep temperature increases below 2°C, global emissions must begin to fall precipitously in the next decade. And climate-economics models must redefine rosy overshoot scenarios as policy failures.[13]

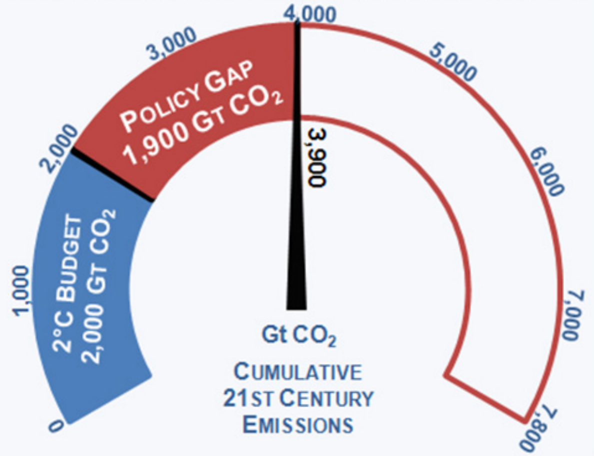
Climate Damages

There is a third important way in which climate-economics models have fallen behind the best understanding of climate scientists. In DICE, and in other prominent models like PAGE and FUND, assumptions made about the relationship between temperature and economic damages are significantly out of date.[14] In DICE the share of global economic output lost at various levels of temperature increase is as follows: If global average temperatures increase by 2.5°C, climate damages are modeled as equaling just under 2 percent of world output; this is extrapolated to higher temperatures using a simple, arbitrarily chosen algebraic function, which implies that damages do not reach half of world output until a 19°C increase.[15]

DICE damages do a poor job of representing the current projections made by climate scientists. An example may help illustrate just how big this disconnect is. If temperatures were to increase by 7°C some regions of the world would become uninhabitable without air conditioning. At 12°C increase, all of the most populous regions of the world would be uninhabitable without air conditioning.[16] Today, 2.5 billion people, nearly two-fifth of the world's population, subsist on less than $800 a year. For this enormous swath of the population, most of whom live in hot, tropical countries, purchasing an air conditioner is simply out of the question; indeed, one-fifth of the world population still does not have access to electricity.[17] A 12°C increase in temperatures would mean that human beings could no longer live in most developing countries; the economic consequences of such a future would be nothing short of devastating. In the more severe damage estimates used in CRED, we have taken this to mean that 12°C would cause the near-complete destruction of the world economy.

Figure 7: CRED Damages

High Discount Rate, Severe Damages, No Transfers, 1.5% chance of staying below 2°C

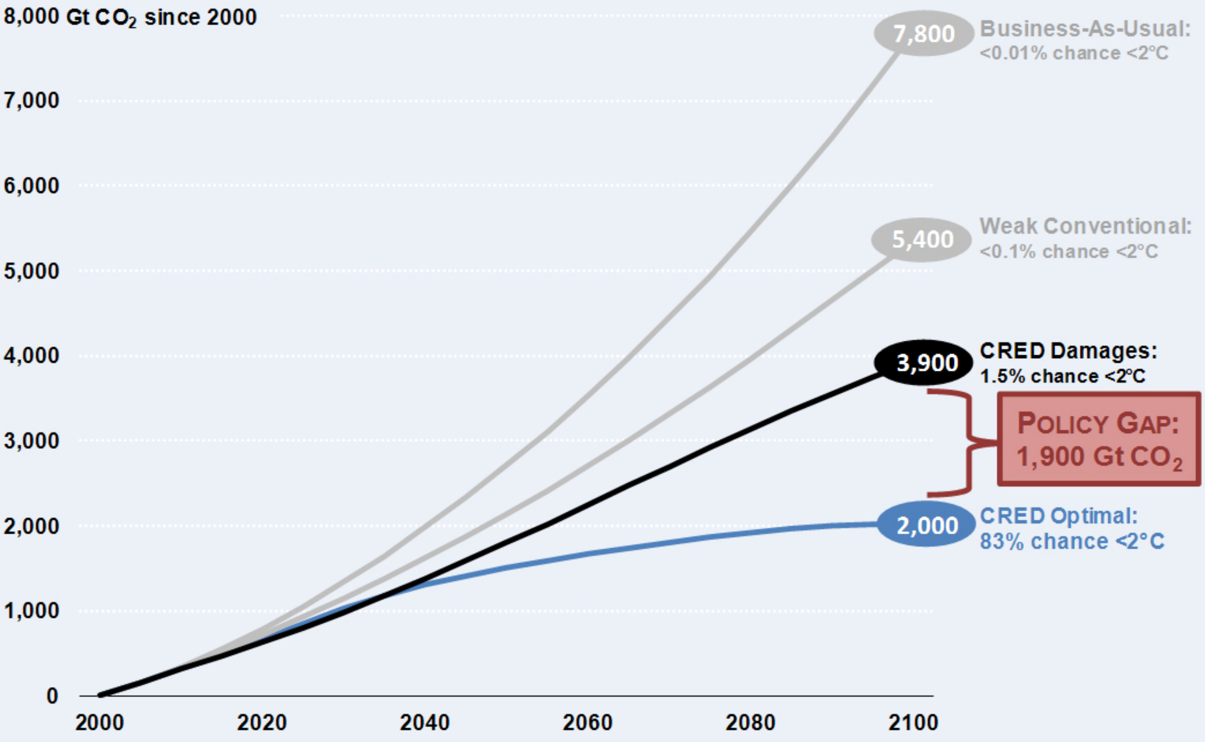


The CRED model allows a range of temperature-to-damage relationships to be represented. CRED can be run using the DICE formulation of climate damages. The Weak Conventional policy, using DICE modeling choices including its damage parameters, results in 5,400 Gt CO_2 in cumulative 21st century emissions and a 3,400 Gt policy gap (see Figure 5 in the first section). The Weak Conventional policy is based on the assumption of a high discount rate, the modest DICE estimate of damages, and no transfer of resources between regions.

CRED can also use parameter combinations that result in damages that are much more consistent with current scientific findings. Less severe DICE damages[18] can be replaced by more severe CRED damages[19] while maintaining all other DICE modeling choices. CRED damages reach 4.2 percent of global output at 2.5°C, 50 percent at 6°C, and 99 percent at 12°C.

Figure 8: Global Emissions with Severe Damages

The DICE models assumes that damages from climate change will be as small as 2 percent of GDP after a 2.5°C increase in global temperatures. Maintaining all other DICE assumptions while introducing more severe CRED damages results in a climate policy with a better than 1-in-100 chance of staying below 2°C.



Where the Weak Conventional scenario allows a cumulative 5,400 Gt CO_2, this one change in modeling assumptions brings that recommendation down to 3,900 Gt in the **CRED Damages** scenario. Instead of a little less than 1-in-1,000 chance of staying below 2°C with the DICE damage function, the CRED damage function returns a better than 1-in-100 chance (1.5 percent) of staying below 2°C and a 50/50 chance of keeping temperature increases below 2.6°C in 2100 (see Figures 7 and 8).

As a result, CRED's annual emission pathway increases much more slowly and begins to decline around 2070. While, following this policy advice, the pace of emission reductions would still be far too slow for the best chance of staying below 2°C, the scenarios compared here demonstrate the importance of modeling choices that are fully at the discretion of the economists who design these models. The difference between the recommendations based on the most commonly used damage function in the literature and a damage function reflecting catastrophic risks, implied by the latest climate science, is 1,500 Gt CO_2 during the 21st century.

Empathy: Caring about Future Generations

Representing the best scientific knowledge is not the only way in which climate-economics models are falling short: An important ethical judgment call embodied in these models is frequently made in a way that effectively dismisses the interests of future generations. Because the effects of today's emissions will be felt for hundreds, if not thousands, of years, every model must make some assumption about the importance that expected future damages are given in current-day decision-making.

In CRED, as in many other models, this key judgment is represented by the "pure rate of time preference," an important component of the discount rate. The pure rate of time preference is the discount rate that would apply if all generations were equally wealthy. Under the common assumption that future generations will be richer, the discount rate is increased to reflect the expected differences in wealth. (For reference, under both CRED and DICE default assumptions the discount rate is equal to the pure rate of time preference plus double the long-term rate of economic growth; in both models, that long-term growth rate is about 1.5 percent.)

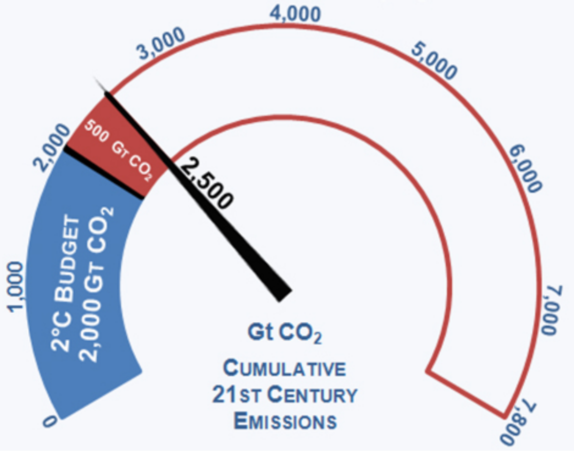
The higher the discount rate, the less importance far-future climate damages are assumed to have to today's decision-makers. At the extremes, a very high discount rate causes the model to ignore any climate damages that occur more than a few decades into the future, whereas at a very low discount rate, climate damages are almost equally important to decision-making regardless of when they occur. The CRED policy scenarios in this report explore pure rates of time preference from 0.1 percent – the value used in the influential, and controversial, Stern Report – to 1.5 percent – the value used in the ubiquitous DICE model.[20] As a quick rule of thumb: The higher the pure rate of time preference, the slower the emission reductions in the optimal policy scenario recommended by the model as leading to the greatest social welfare.

There is no scientific standard for the pure rate of time preference. Its uncertain value is better thought of as the answer to a crucial ethical question:

How much *should* we, as a society, care about the impact of our actions on future generations?

High discount rate: When the pure rate of time preference is set to the DICE default of 1.5 percent (with the more severe CRED damage function described in the previous section), there is a somewhat better than 1-in-100 chance (1.5 percent) that temperature increases will stay below 2°C. Cumulative emissions for the 21st century reach 3,900 Gt CO_2, greatly exceeding the 2,000 Gt budget (see the CRED Damages scenario in Figures 7 and 8 in the second section).

Figure 9: Strong Conventional Policy
Low Discount Rate, Severe Damages,
No Transfers, 57% chance of staying below 2°C



Low discount rate: When the pure rate of time preference is lowered to 0.1 percent, CRED's **Strong Conventional** policy calls for still more rapid emissions cuts. With this scenario, there is a better than 50/50 chance (57-percent) of success in keeping temperature increases below 2°C (see Figures 9 and 10).

With a low discount rate, more severe damages, and no transfer of resources between countries, this Strong Conventional scenario is the most that the CRED model can do to reduce the risk of exceeding 2°C without addressing issues of emissions abatement equity: 2,500 Gt CO_2 in cumulative 21^{st} century emissions – a 500 Gt policy gap.

In making decisions about how to respond to climate change, we have no choice but to look ahead towards future impacts. But how far ahead do we care to look? Hundreds of years? A few generations? The next election cycle, or the next news cycle? Our climate policy actions will be very different depending on our answer to this question. Using a low 0.1 percent pure rate of time preference in modeling does not mean that we treat the concerns of future generations as equally important to our own (recall that the discount rate includes an additional term for economic growth, implying that the richer that future generations become, the less we need to worry about them today), but it does extend our horizon, allowing us to see and react to future damages that are greatly obscured by a relatively high 1.5-percent rate.

The final Strong Conventional scenario presented in this section might appear to be the solution: With high estimates of future damages and low time preference, the optimal global policy closely approaches the 2,000 Gt budget for the century and has a strong probability of staying below 2°C. But a closer look reveals the lack of realism in that scenario. If future damages are high and the importance of the future is also high (due to a low rate of time preference), then the optimal policy is for every country to prioritize emission reduction over immediate economic growth. This is economically feasible (which is not to say that it is politically easy, or guaranteed to succeed) in high-income countries. For low-income countries, the greater urgency of immediate consumption and economic growth makes it essentially impossible for domestic savings alone to fund the level of investment needed to protect future generations. This brings into question the feasibility of rapid abatement scenarios in which cross-regional investment is banned or otherwise assumed impossible.

The underlying problem is that climate solutions must be created in the context of an extremely unequal world, requiring coordination across countries with widely differing resources and national interests. This crucial issue is the subject of the next section.

Fair Play: Prioritizing Equity in Today's World

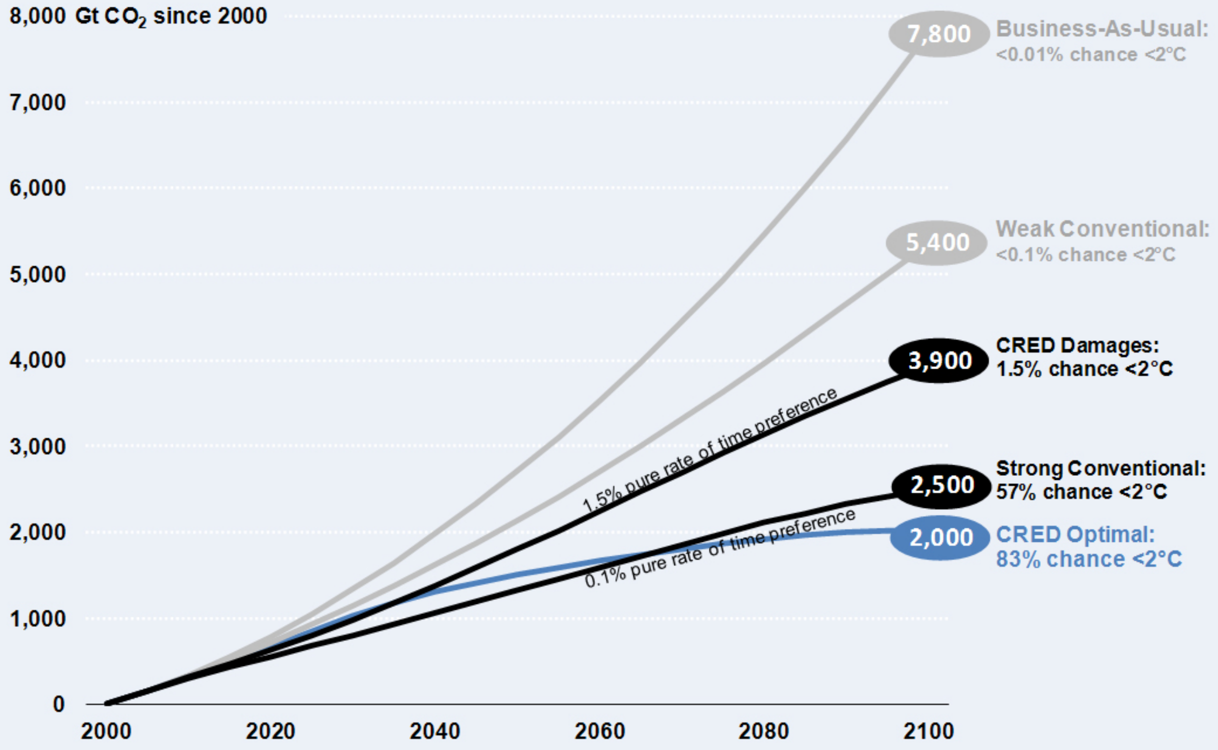
A final important modeling choice affects the recommendations given by climate-economics models. Keeping 21^{st} century CO_2 emissions down to 2,000 Gt means both that rich countries must lower their high emissions intensity – or CO_2 emissions per dollar of economic output – and poorer countries must find a way to maintain, or ratchet down, their already low emissions per dollar.

Two problems emerge. First, developing and installing low-carbon technologies requires upfront investments. In low-income countries, purchases of these technologies – especially where the present-day physical and knowledge-based infrastructure is not consistent with local production of products like solar panels, wind turbines, or electric cars – may come at the expense of slowing down economic development and derailing poverty reduction measures.

Second, there is no roadmap for transforming a resource-dependent low-income economy into a low-carbon technology and services-dependent high-income economy. It's simply never been done. All countries that have achieved high living standards (measured in terms of GDP per capita, life expectancy,

Figure 10: Global Emissions with High and Low Discount Rates

The pure rate of time preference, a key component of the discount rate, represents the degree to which current decision makers take future generations' interests into account. The lower the discount rate, the greater the weight assigned to future climate damages, and better the chance of staying below 2°C.



and literacy rates) owe their success to fossil fuels, and have far higher emissions per dollar than today's developing countries could possibly obtain under the 21st century emissions budget of 2,000 Gt CO_2.[21]

Climate policies can be judged in terms of their fairness, not only to future generations (discussed in the previous section) but also among today's different world regions and income groups. How will we spend our 2,000 Gt CO_2 – or more precisely, the 1,700-odd Gt that remain available for the rest of the century? Which countries will use up this remaining budget? And who will pay for the measures necessary to put an end to additional emissions? These questions are at the heart of current climate policy negotiations, but they are too often absent from climate-economics analysis.

Some models look at the world as a single actor; there is no push and pull regarding the interests of different countries or income groups because there is only one "country": the world as a whole. These single-world-region models can provide little assistance in addressing issues of global compromise among groups with disparate priorities.

Other climate-economics models divide the world into multiple regions, usually by geography and development status; in these models, the optimal policy is the investment and emissions pathway that brings about the greatest global social welfare, totaled across all regions. Working with this multi-region structure leads to a surprising discovery that echoes the findings of early 20th century economists: Unless constrained to do otherwise, these models will reduce investment in rich regions in order to give as much standard and low-carbon investment as possible to poorer countries. The result: The optimal policy includes a rapid redistribution of income, taken from the rich and invested in the poor.[22]

The reason behind this massive redistribution of resources is simple and well understood. With remarkably few exceptions, economic models include the assumption that a new dollar of income will do more to increase the well-being of a poor person than of a rich person. In welfare-maximizing climate-economics models, the one and only goal is to raise social welfare. And since transferring income from rich to poor regions increases welfare, that – together with emission reductions – is what an unconstrained model would offer as a policy recommendation. Yet almost all multi-regional welfare-maximizing climate-economics models contain a hidden constraint that keeps the ratio of rich-to-poor country per capita income roughly constant over time, preventing any redistribution of resources.[23] To put this in the context of climate policy negotiations, these models assume that high-income countries cannot (or will not) contribute a portion of their resources to invest in greenhouse gas abatement in poorer countries.

CRED is unusual in that it does not prevent income redistribution, and, if run without any constraints at all, its optimal policy is always for rich countries to invest a large share of their savings in poorer countries, both for economic development and for emission reductions. In fact, CRED's imperative to increase social welfare by equalizing income levels around the world is so strong that it calls for policy measures that seem politically unfeasible.[24] For that reason, all of the CRED scenarios discussed in this report include the constraint that no region's consumption per capita may decrease over time – an assumption that still allows for income redistribution and poverty reduction, but at a much slower pace.[25]

With all regions' per capita consumption prevented from decreasing, CRED also allows for a choice of the maximum fraction of output (net of damages) that rich regions will provide for investment in poorer countries. In all of the CRED scenarios reviewed so far, this value has been set to zero – in essence, every region is on its own when it comes to paying for emission reductions. With no cross-regional investment and using the more severe CRED damage function and low 0.1-percent pure rate of time preference discussed in the previous sections, CRED's Strong Conventional policy recommends an emissions pathway with 2,500 Gt CO_2 in 21st century cumulative emissions and a more than 50/50 chance (57 percent) of staying below 2°C (see Figures 9 and 10 in the previous section).

When this restriction is lifted, allowing regions to invest up to 40 percent of their net output in their poorer neighbors, the CRED Optimal policy amounts to just 2,000 Gt in 21st century cumulative emissions, keeping within the budget for avoiding dangerous climate change (Figures 2 and 3 in the first section). This small, but important, decrease in cumulative emissions – as compared to the Strong Conventional policy – masks some of the larger differences between these two scenarios: global damages from climate change are smaller under the CRED Optimal policy,[26] and there is a far better chance (83 percent compared to 57 percent) of staying below 2°C. Moreover, as noted above, the CRED Optimal policy models a process that could actually fund the needed emission reductions; in contrast, the Strong Conventional policy requires an unrealistic level of investment in abatement by low-income countries.

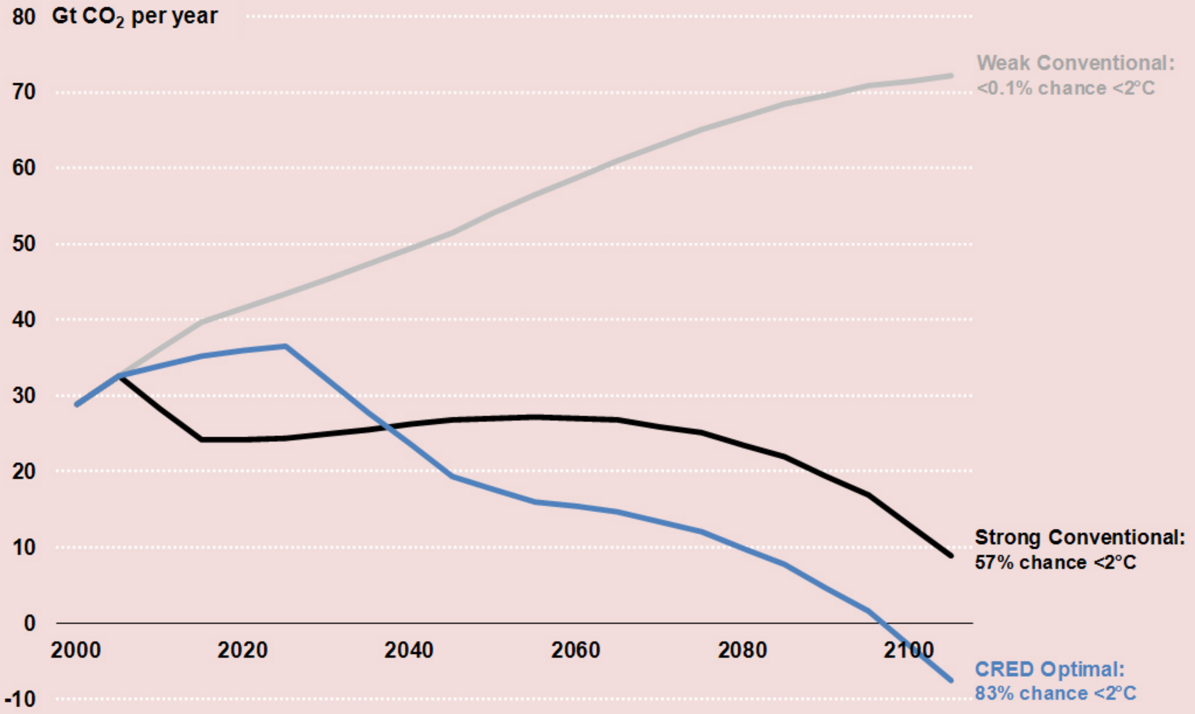
There are two key differences between the Strong Conventional (57-percent-chance) scenario with no cross-regional investment and the CRED Optimal (83-percent-chance) scenario with up to 40 percent of rich regions' net output invested in poorer regions: the pace of emission reductions, and the pace of poverty reduction.

The Pace of Emission Reduction

The first important difference that sets the CRED Optimal policy apart from the Strong Conventional policy is the pace of global emission reduction. When cross-regional investment is permitted, emissions fall more slowly in the next twenty years. In selecting the investment and emission-reductions pathway that maximizes social welfare, the CRED model prioritizes early standard (not related to abatement) investment in developing countries, increasing these regions' income per capita, and then after a few decades shifts more of the investment funds received from richer countries towards emission abatement (see annual emissions in Figure 11).

Figure 11: Global Emissions with Cross-Regional Transfers

If low-income countries have to pay for all of their own emissions reduction efforts, achieving a 50/50 chance of staying below 2°C would make their economic development impossible. When rich countries invest in their poorer neighbors, emissions abatement and poverty reduction can occur simultaneously.



The Pace of Poverty Reduction

In addition to the pace of global emission reductions, there is a second critical difference between the scenarios that allow cross-regional investments and those that do not. Today's high-income countries' per capita consumption (on average, $24,100) is about 17 times higher than that of low-income countries (on average, $1,500).[27] In the Strong Conventional scenario, with a 57-percent chance of staying below 2°C, this ratio creeps up to 18 over the next century (see Figure 12; regions are defined in Table 1). At the end of the century, average consumption (in today's dollars) is $101,000 per person in rich regions and $5,500 in poorer regions. When the cap on cross-regional investment is increased from zero in the Strong Conventional policy to 40-percent of rich countries' output in the CRED Optimal policy, the ratio of incomes falls steadily, approaching 3 by 2100 ($40,000 versus $11,800).

Figure 12: Ratio of High-Income to Low-Income Regions' Consumption per Capita

Today, the average income in rich countries is 17 times higher than the average income in poor countries. Without cross-region transfers, this ratio gets a little worse over the next century. With transfers, the ratio drops substantially: in 2105, consumption per capita would be 3 times higher in rich countries.

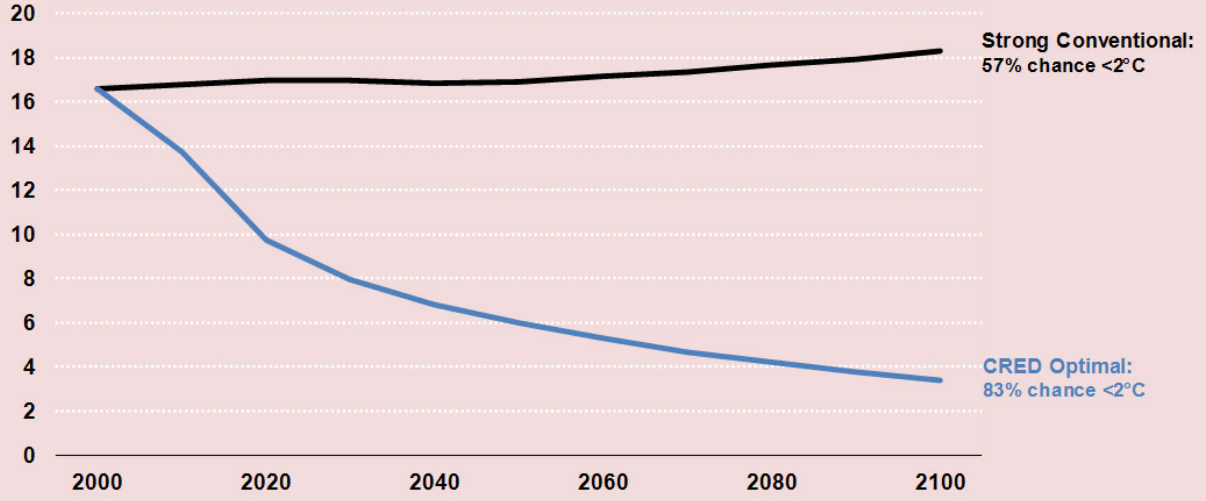


Table 1 compares consumption per capita in the nine CRED regions.[28] In 2005, average consumption per capita in the richest region, the United States, was 39 times higher than in the poorest regions – Africa and Developing Asia/Pacific.

In the Strong Conventional scenario, with no cross-regional investment, consumption per capita grows in all regions but the ratio of the U.S. to the poorest regions' stays about constant. In contrast, in the CRED Optimal scenario, where cross-regional transfers are assumed possible, U.S. consumption per capita in 2100 drops to only about 6 times higher than that of Africa or Developing Asia/Pacific.

Table 1: Consumption per Capita by Region, Scenario, and Year

		2100	
	2005	Strong Conventional, No Transfers	CRED Optimal, With Transfers
High-Income Regions:			
Europe	$20,500	$84,000	$33,000
United States	$32,000	$130,200	$51,400
Other High Income	$22,900	$91,400	$36,800
Low-Income Regions:			
Africa	$800	$3,600	$8,800
China	$1,100	$4,800	$12,000
Developing Asia/Pacific	$800	$3,600	$9,000
Eastern Europe	$3,600	$10,900	$21,300
Latin America/Caribbean	$4,000	$17,200	$25,900
Middle East	$3,900	$14,500	$25,900
U.S. to Africa/Developing Asia ratio	39	37	6

Deciding how investment resources will be shared among world regions is critical to the progress of global climate negotiations, and just as critical to climate economists' policy recommendations. While there is no "correct" answer to how much each country should pay towards global emission reductions, both at home and abroad, the assumption that no cross-regional transfers will take place (endemic in climate-economics models) is neither transparent nor particularly helpful.

Assumptions like these – that the whole world shares one set of aspirations and policy priorities, or that climate policy is best examined against a backdrop that freezes the current income distribution, or that high-income regions cannot or will not invest in emissions and poverty reduction in low-income regions – do not represent universally held beliefs. When climate-economics models use these assumptions, it is imperative that their results be accompanied by an explanation of modeling choices, expressed in non-technical terms. CRED results demonstrate that modeling choices regarding cross-regional investment affect not only who pays for how much abatement, but also how quickly emission reductions occur, how quickly developing countries are able to raise living standards, and what chance global emission-reduction efforts have at keeping temperature increases below 2°C. For climate-economics models to have policy relevance, a transparent analysis of international equity is essential.

Closing the Gap: A Precautionary Response

There is no easy solution to the climate problem. Cut emissions, yes, but who will cut them how much by when? And who will pay for those reductions? Where multiple interest groups have competing demands, policy makers often turn to economists to provide guidance on these complicated decisions. Many prominent climate-economics models use a form of cost-benefit analysis called welfare maximization to map out the future investments and emission reductions that are expected to result in the greatest social welfare. According to the well-known DICE model, the best climate policy would allow for emissions to continue to increase throughout the 21st century, adding an additional 3,800 Gt CO_2 to the atmosphere in that period and resulting in a 50/50 chance that temperatures will grow more than 2.6°C by 2100. (And our re-analysis of the DICE default assumptions in CRED resulted in an even less ambitious emission-reduction policy.)

While their model structures are not strictly comparable, the well-known PAGE and FUND models make similar modeling choices and come to similar conclusions.[29] A recent U.S. government study assigns a common discount rate to all three models and then compares them in terms of their estimated social cost of carbon (that is, the long-term damage consequences associated with a one-ton increase in CO_2 emissions; for the 2015 social costs of carbon implied by the CRED scenarios presented in this report, see Appendix B). The higher the social cost of carbon, the deeper and faster the recommended emission reductions. The DICE model reports a 2010 social cost of carbon of $28; PAGE, $30; and FUND, $6. The three-model average of $21 has been adopted for use as a price for carbon in U.S. federal environmental regulation.[30] With a carbon price this low, emission reductions will be slow, small and insufficient to stay below the 2°C threshold.

In a reanalysis of the U.S. government's social cost of carbon using the DICE model we found that introducing some of the factors discussed here, such as the more severe damage function, resulted in social cost of carbon values up to $900 for 2010. At carbon prices this high, any feasible emission-reduction strategy becomes cost effective.[31]

The policy recommendations taken from these commonly used models are difficult to reconcile with the projections of climate scientists, who call for immediate emission reductions to prevent global average temperatures from growing any more than 2°C above preindustrial levels. The difference is stark: Climate economists who recommend a policy with a 50-percent chance that temperature increases will exceed 2.6°C by 2100 and then keep on rising, versus climate scientists who predict widespread, serious damages – including many irreversible losses – if temperature increases exceed 2°C. Recent climate science also reveals that if emission reductions do not move quickly enough and the 2°C threshold is crossed, it will not be possible to bring temperatures back down for at least several centuries, even if atmospheric concentrations are later reduced.

Box 2: Important Dynamics in Current Climate Policy

Failure of reason (not understanding or not believing the science):

Focusing on the most likely climate sensitivity (that is, the impact of emissions on temperatures) can only tell us so much. The smart gambler never places a bet without first knowing the odds: To make good decisions about an uncertain future, we need to know not only the best guess (50/50), but also the long shots, such as the 1-in-5 and the 1-in-50 outcomes. Similarly, prudent households and investors often seek to insure themselves against low-probability risks of disastrous losses.

Also uncertain is the relationship between temperatures and economic losses. While we will never be able to predict these impacts too exactly, there is no reason to cling to outdated, unduly rosy estimates, rather than following the best, most recent findings of climate scientists.

Failure of empathy (not caring about the fate of future generations):

A society that cares deeply about the well-being of future generations will embrace a very different climate policy than a society that can't see past the current economic crisis. Which one are we? The longer we take in reducing emissions, the more likely we are to exceed 2°C and bequeath serious economic damages from climate change to future generations.

Failure of fair play (not supporting a solution that is equitable to low-income countries and groups today):

Rich countries tend to support plans for emission reductions that are based on the principle of "grandfathering": Reductions are tied to historical emissions, so the more you've emitted in the past, the more you get to emit in the future. With a fixed 2°C budget of 2,000 Gt CO_2 for the 21st century, emission reductions are a zero sum game – if one country emits more, other countries must emit less.

Developing countries should, and do, object to the "logic" of grandfathering. Unless rich countries are willing to pay for emission-reduction efforts outside of their borders, the high cost of maintaining or lowering per capita emissions will make it all but impossible for poorer countries to raise living standards. Developing countries are unlikely to direct all of their resources to emission reduction at the expense of poverty reduction; cross-regional transfers are essential to achieving a good chance of staying below 2°C.

This report examines the factors that cause climate-economics models to recommend policies that do not reflect climate scientists' urgent call for action. These are important elements in the dynamics of current climate policy negotiations, and at the same time key modeling parameters used in climate-economics analysis: a failure of reason, a failure of empathy, and a failure of fair play (see Box 2).

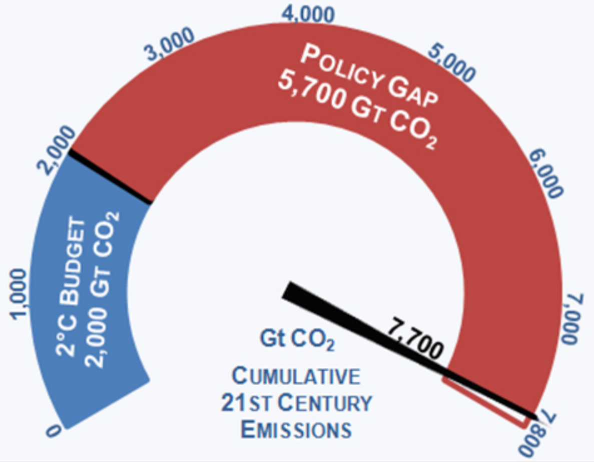
In the CRED model, these scientific uncertainties and ethical dilemmas are expressed explicitly, making it possible to test out new values, alone and in combination. Taken together, these adjustments result in climate policy recommendations that have a 50/50 chance of staying below 2°C. When, in addition, rich countries are assumed to share resources with their poorer neighbors, the result is poverty alleviation, emission reduction, and an even better chance – 4 out of 5 – of keeping temperature increases below the critical 2°C level.

Cancun Agreement

There is a 5,800 Gt CO_2 policy gap between Business-As-Usual 21st century cumulative emissions and the maximum emissions consistent with keeping the chance of exceeding 2°C down to 1 in 5. The only existing global policy measure that addresses that gap is voluntary and very small in scale. The second commitment period of the Kyoto Protocol will come to a close in 2017 or 2020.[32] Beyond that date there is only the 2010 Cancun Agreement, a non-binding agreement of the delegates to the 16th session of the United Nations Framework Convention on Climate Change's Conference of Parties. (The 2011 Durban Agreement does not include any additional emission reductions.[33]) Under this Agreement, countries accounting for more than 80 percent of present-day emissions have submitted voluntary pledges to reduce emissions through 2020.

Many of these pledges, however, promise reductions not with respect to today's emissions, but instead with respect to potential business-as-usual emissions. As a result, even if all countries carry through with their Cancun pledges, global emissions are expected to be higher in 2020 than they are today. A 50/50 chance of staying below 2°C would require deep and sustained post-2020 emission reductions.[34] The cumulative reduction relative to Business-As-Usual is 100 Gt by 2020 (see Figure 13).

Figure 13: Cancun Agreement



In the post-Cancun Agreement scenario depicted here, emissions are permitted to rise through 2020 to levels consistent with pledges. After 2020, global emissions are modeled as falling by 3 percent every year. Cumulative 21st century CO_2 emissions stay under the 2,000 Gt limit, and research from the British government's AVOID program projects that this scenario has a 50-percent chance of keeping temperature increases below 2°C. This is a much lower chance than for our 2,000 Gt CRED Optimal scenario described in the first section (see Figures 2 and 3), with an 83-percent chance of keeping temperature increases below 2°C; a likely explanation is that the Cancun-AVOID scenario emissions are front-loaded. With more of the 2,000 Gt of emissions released into the atmosphere earlier, the Cancun-AVOID scenario allows somewhat more warming to occur over the course of the century.

Unfortunately, the AVOID research – and that of other research groups that have come to similar conclusions, including the United Nations' Environment Program and the European Climate Foundation – can tell us little about the chances for success of the Cancun Agreement itself.[35] The best that can be said about the Agreement is that the global emissions increase that it permits through 2020 does not render the goal of staying below 2°C impossible.

No global accord exists, voluntary or otherwise, to restrict emissions after 2020, much less to organize the ambitious annual 3-percent decrease required in AVOID's post-2020 Cancun scenario. Indeed, that study's authors state: "The 2020 pledges alone and no further cuts after 2020 are very unlikely to limit the global temperature rises to 2°C in 2100 let alone beyond 2100. …The current 2020 target is a significant first step. It is still feasible to limit warming to 2°C, with a 50-percent probability, but it would be extremely challenging and depend on substantial cuts in global emissions after 2020."[36]

In the short period covered by the Agreement, the Cancun pledges result in cumulative emissions 100 Gt CO_2 lower than the Business-As-usual Scenario. The remaining policy action required to avoid the worst climate damages – 5,700 Gt in emission cuts – is not addressed by any global policy measure (see Figure 14 where the solid red line shows the emissions expected to result from the **Cancun Agreement** and the dotted red line shows the subsequent emissions necessary for a 50/50 chance of keeping temperatures under 2°C).

Closing the Policy Gap

Cost-benefit, or welfare maximization, models are not the only way that climate economists can contribute their expertise to the climate policy debate. Other modelers follow a standards-based or precautionary approach using cost-effectiveness analysis. Using a standards-based approach a threshold is set, such as a 2°C maximum temperature increase, and then the model identifies the least-expensive investment and emissions pathway consistent with that threshold. (The CRED model can be used either as a cost-benefit or a standards-based model.) The pace of emission reduction depends on the level of risk considered acceptable: A 1-in-50 chance of exceeding 2°C would require quicker and deeper emissions cuts than would a 1-in-2 (or 50/50) chance.

The question then for policy makers and for the public is: What is an acceptable level of risk? What percentage chance of exceeding 2°C are we willing to take on?

According to the CRED model, limiting the chance of exceeding 2°C to 1 in 5 would require that emissions be kept under a cumulative 2,000 Gt CO_2 during the 21st century. Policies that are still more risk-averse, accepting only a 1-in-50 chance of exceeding 2°C, for example, would require still lower emissions. An equitable climate policy – one that allows both for adequate emission reduction and for economic development in poor countries – would require rich countries to accept a slower pace of economic growth at home in order to invest in development and emission-reduction measures in the developing world. Without these cross-regional transfers poor countries are unlikely to both keep their emissions low and increase standards of living.

The Cancun Agreement, which addresses climate policy only through 2020, will reduce cumulative emissions by about 100 Gt CO_2 compared to a business-as-usual scenario; even if those emission reductions continued for the rest of century (which is not guaranteed by the Agreement), most of the policy gap would remain to be addressed by other measures. If we take climate science seriously, care about the well-being of future generations, and want to make sure that developing countries have the opportunity to reduce poverty, then we'll close that gap. Too often, climate-economics models implicitly assume that we don't believe the science, care only about the most immediate impacts, and think that every country must pay for its own emission-reduction measures. As a result, these models recommend an "optimal" policy that allows emissions to keep growing throughout this century.

A precautionary response – limiting our risk of exceeding 2°C to 1 in 5 or even lower – requires that global emissions begin to fall rapidly within the next 10 years. The climate policy gap is not insurmountable, but closing it will require reason, empathy, fair play, and a great deal of political will.

Appendix A: CRED v.1.3 Technical Description

Version 1.3 of the Climate and the Regional Economics of Development (CRED) model was completed in June 2011.[37] CRED is an integrated assessment model, projecting global climate and development scenarios at 10-year intervals over a 300-year time span, starting from a 2005 base year.[38] CRED equations are programmed in GAMS (General Algebraic Modeling System),[39] a high-level language used for complex economic and engineering applications that require mathematical optimization. The CRED user interface consists of two Excel 2007 workbooks: the input workbook gathers and configures scenarios from the background dataset, including model assumptions, parameters and other selections, and then runs the model; the model writes its results, including a comprehensive package of pre-formatted tables and charts, to another Excel workbook.

1. What's new in CRED v.1.3

Data have been updated and are now taken from more consistent sources across countries, including improvements to the population projections. In CRED v.1.3, national populations follow U.N. long-term projections until their post-2100 minimum and are then kept constant through the end of the modeling period.

- For the climate sensitivity parameter CRED v.1.3 uses 3.0°C, but explores the effect of changes to this value in sensitivity analyses.
- In the economy module, the method for estimating base-year capital stocks has been improved, and a constraint has been added that prevents capital stocks from decreasing in the first 250 years of any scenario.
- CRED v.1.3 allows a choice between four damages functions.
- There have been substantial updates to the vulnerability index, as discussed below.
- CRED v.1.3 allows a unique carbon price for each region.

2. Regions

There are nine regions of the world in CRED, three high-income and six developing:

- United States (excludes Puerto Rico and other territories)
- Europe (EU-27, Norway, Switzerland, Iceland, and Turkey)
- Other high-income (Canada, Japan, South Korea, Australia, New Zealand)
- Latin America and the Caribbean
- Middle East (excludes North Africa)
- Russia and non-EU Eastern Europe (European ex-USSR, ex-Yugoslavia, and Albania)
- Africa (includes North Africa)
- China (includes Hong Kong but not Taiwan)
- Other developing Asia (includes Asian ex-USSR and Pacific)

Regional boundaries were defined in part to ensure compatibility with McKinsey abatement cost data (discussed below). For example, Turkey is in Europe, while North Africa and the Middle East – treated as one region in many models – are in separate regions.

Regional data for the model's base year, 2005, are aggregated from individual country data taken from major international sources.[40] All monetary amounts are in 2005 U.S. dollars, calculated at market exchange rates, *not* in purchasing power parity terms. Population is based on the U.N. long-range median forecast through each country's post-2100 minimum, assumed constant in each country thereafter. GDP in the base year is taken from World Bank data, supplemented by UNStats GDP data for countries without World Bank data.

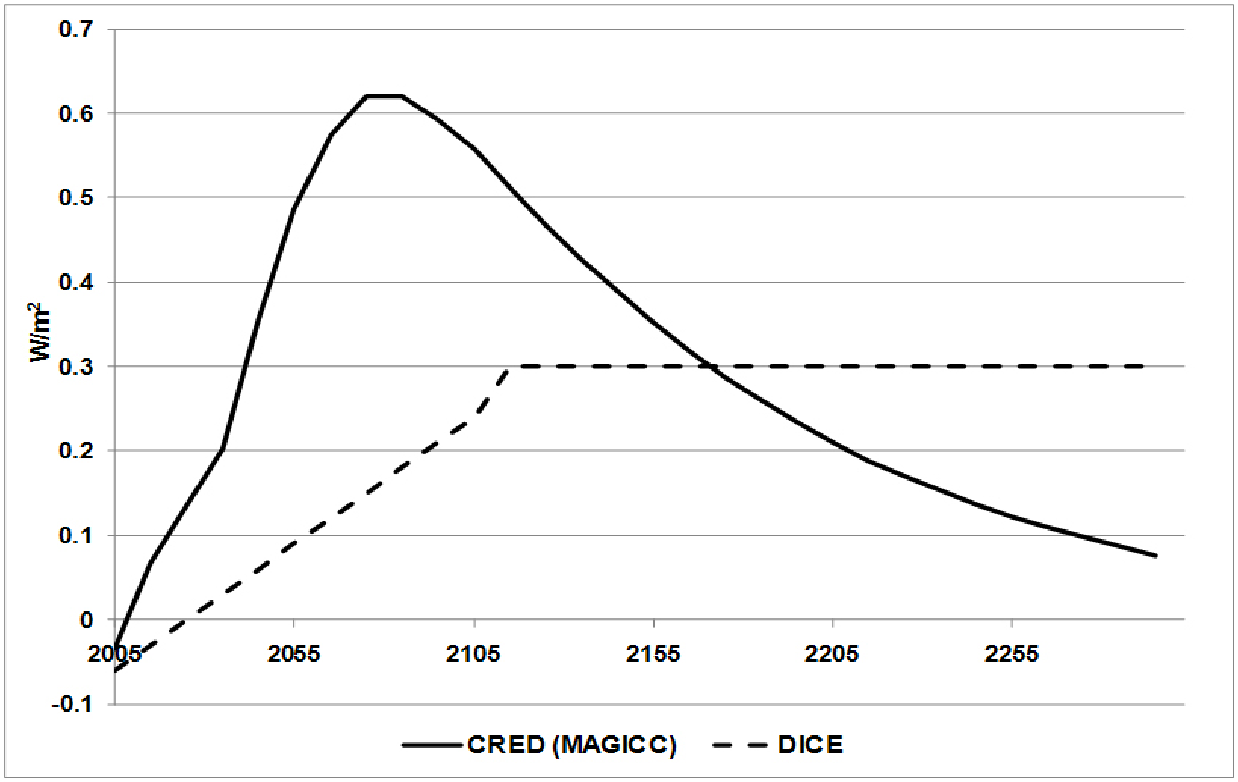
3. Climate module

CRED uses the DICE 2007[41] model's equations for climate dynamics, based on a three-compartment model (atmosphere, shallow oceans, and deep oceans) with separate carbon concentrations and transition probabilities for movement of carbon between them. The climate module was re-calibrated to reproduce the results of the MAGICC[42] model for the five WRE scenarios (WRE 350 through 750);[43] this required modest but significant changes to the DICE parameters.

In effect, we are using a reduced-form approximation of MAGICC, which yields very close agreement with MAGICC across the range of WRE scenarios. We also adopted MAGICC's exogenous estimates of non-CO_2 forcings, rather than DICE's piecewise linear formula (Figure A-1). The inputs to the climate module are current global emissions, non-CO_2 forcings, previous temperature, and previous concentrations of carbon dioxide in each of the three compartments. The outputs are current temperature and CO_2 concentrations.

For the climate sensitivity parameter – the temperature increase, in °C, resulting from a doubling of atmospheric CO_2 concentrations – CRED v.1.3 uses a default of 3.0°C. Other climate sensitivity values are explored in sensitivity analyses.

Figure A-1: CRED versus DICE non-CO2 forcings



4. Economy module

CRED uses a Cobb-Douglas production function for each region, with a capital exponent of 0.3 (the most common value in the literature):

$$(1)\quad \mathbf{Output}_{t,r} = \mathbf{TFP}_{t,r} * \mathbf{Capital}_{t,r}^{0.3} * \mathbf{Labor}_{t,r}^{0.7}$$

Here and later, r is region and t is time, measured in 10-year periods. TFP is a region-specific estimate of total factor productivity; it grows at a constant rate of 1 percent per year in each region. Labor is represented by population (in effect, assuming constant labor force participation rates over the long run). Capital, in (1), combines standard and "green" investments, where the latter is investment in mitigation (discussed below):

$$(2)\quad \mathbf{Capital}_{t,r} = \mathbf{Standard\ capital}_{t,r} + s * \mathbf{Green\ Capital}_{t,r}$$

Total capital is constrained to be non-decreasing over the first 250 years of the model.

The fixed parameter s measures the relative economic productivity of green versus standard capital. DICE and many other models assume that investment in mitigation does not enter into the production function, in effect assuming s = 0 in (2). This is unrealistic, as the "green jobs" discourse makes clear. It would also be unrealistic, however, to assume that green capital was just as productive of income as standard capital; if that were the case, there would be a trivial "win-win" solution to the climate problem, and markets would simply carry out the needed investments in mitigation on their own. Thus, s = 1 is also unrealistic. Lacking an empirical basis for an estimate, CRED assumes s = 0.5. In other words, mitigation investment is half as productive of income as standard investment.

Both standard and green capital depreciate at the same rate – 5 percent per year, compounded over the ten-year time periods of the model:

$$(3)\quad \mathbf{Capital}_{t,r} = (1 - \mathbf{Depreciation})^{10} * \mathbf{Capital}_{t-1,r} + \mathbf{Investment}_{t,r}$$

In CRED v.1.3 the initial capital stock for the base year, 2005, is estimated with a new methodology. Country-level capital-to-output ratios are calculated for 2005 and applied to GDP for that base year to estimate the capital stocks; these are aggregated to the CRED regions. For consistency, the base-year investment levels in CRED are constructed by applying country-level investment shares for 2005 to the same GDP data. The methodology used to estimate capital stocks for 2005 is described in Box A-1.

Box A-1: Estimating Base Year Capital Stock and Investment

Estimation of base year capital stocks relies on the perpetual inventory method, using as many years of investment data (since 1970) as are available for each country. The sources for this calculation are data on investment as a share of GDP for 185 countries, from the Penn World Table (Heston, Summers, and Aten 2011); capital-output ratios for 93 countries for 1970-1990 from Nehru and Dhareshwar (1993); capital-output ratios and capital stocks for selected OECD countries through 2001, from Kamps (2004)**; and GDP data from the World Bank and UNStats.**

An initial capital stock estimate for each country is assumed for the first year (1970 or later) of available data in the Penn World Table series ki (investment as a share of GDP). The Nehru and Dhareshwar capital-output ratio, when available, is applied to that year's GDP; a GDP-weighted average ratio from the Nehru and Dhareshwar data is applied when country-specific ratios are not available. Sensitivity analyses show that the capital stock in 2005 is relatively insensitive to a range of estimates of initial capital in 1970, due to extensive depreciation over the 35-year period.

The perpetual inventory method, adapted to these data sources, implies the following equation, where y is time in years, c is country, and InvestShare is the investment share of GDP (i.e. the Penn series ki):

$$\mathbf{Capital_{y,c} = Capital_{y-1,c} * (1 - Depreciation) + InvestShare_{y,c} * GDP_{y,c}}$$

The best fit to the Kamps estimates of OECD capital-output ratios in 2001 was obtained with a depreciation rate of 4.7 percent per year, so that fixed rate was used throughout this calculation. (CRED uses a default depreciation rate of 5 percent per year for future projections.)

In a separate calculation, investment-output ratios for 2005 are applied to that year's GDP to estimate base-year investment flows.

The CRED dataset includes 230 countries and territories, a number of which lack data to estimate capital stock and investment using this methodology. From the capital stocks and investments constructed for 2005 for the 185 countries in the Penn tables, the CRED regions' own capital-output ratios and investment-output ratios can be calculated; the missing capital stock and investment data are estimated by applying the regional average ratios to the excluded countries' GDP.

A minimum rate of growth of per capita consumption applies across all regions and all time periods; the default value is 0.5 percent per year.[44] The savings rate and the allocation of savings for each region are chosen in the optimization process, described below.

5. Climate damages

For global damages, CRED uses the equation:

$$\mathbf{Output\ net\ of\ damages_t = Gross\ global\ output_t * Global\ damage\ share_t} \tag{4}$$

Gross output in (4) is the global total of output calculated in (1).

The global damage share determines the gross output lost to climate damages in each time period due to increases in temperature (measured in degrees Celsius above the 1900 level). Thus a "damage function" is specified by the four parameters (a, b, c, d) used in the definition of the damage share:

$$\text{(5)}\quad \textbf{Global damage share}_t = 1 - \frac{1}{1 + a * \text{Temperature}_t^b + c * \text{Temperature}_t^d}$$

CRED v.1.3 allows the choice of one of four sets of the global damage share parameters (a, b, c, and d) and, therefore, four damage function options, as shown in Table A-1.

Table A-1: Damage function parameter options

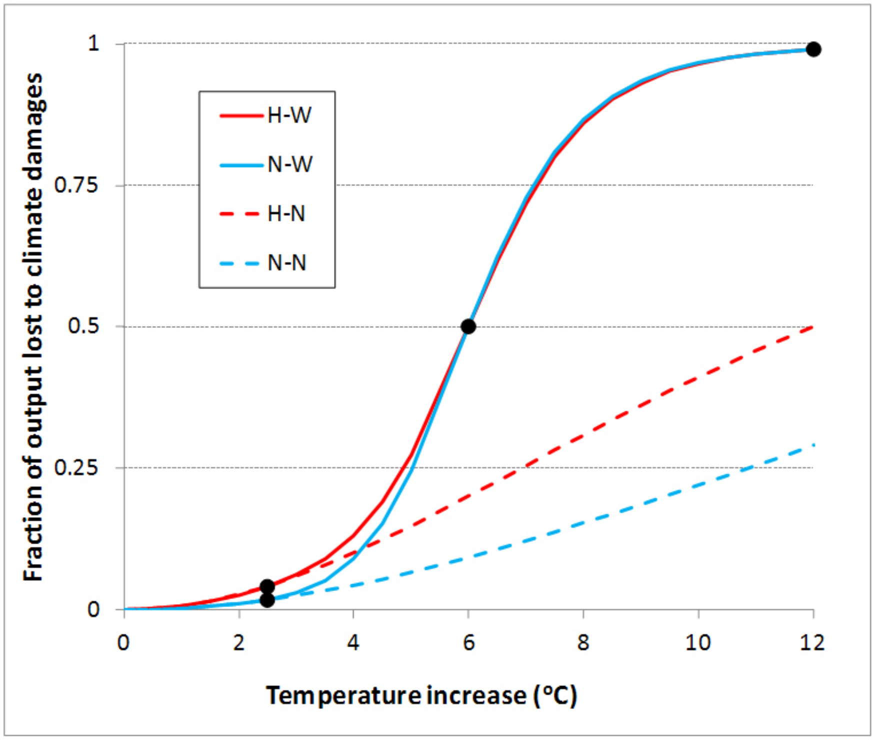
	N-N	H-N	N-W	H-W
a	0.002838	0.006985	0.002451	0.006724
b	2	2	2	2
c	0	0	$5.007*10^{-6}$	$2.635*10^{-6}$
d	0	0	6.76	7.02

These damage functions (originally described in Ackerman and Stanton 2011a) can be viewed as combining two separate estimates: parameters a and b dominate at low temperatures; at higher temperatures, parameters c and d have an increasingly important role in determining global damages. The labels given to these damage functions reflect the original authors of the estimates for damages at low temperatures (first initial, either Nordhaus or Hanemann) and higher temperatures (second initial, either Nordhaus or Weitzman), respectively. The NN damage function – based on an evaluation of several categories of climate damages at 2.5°C (Nordhaus 2008; Nordhaus and Boyer 2000) – is equivalent to that used in DICE 2007. Using these parameters, damages are 1.8 percent of output at 2.5°C and rise only gradually with temperature thereafter; half of global output is not lost until temperature increases reach 18.8°C.

Separate research addresses the low-temperature and high-temperature estimates, suggesting alternatives to each. In a review and critique of the Nordhaus damage estimates as applied to the United States, Hanemann (2008) develops alternative estimates for damages at 2.5°C, which are, in total, almost exactly 2.4 times the Nordhaus value.[45] The HN damage function recalibrates damages to 4.2 percent of output at 2.5°C but maintains the quadratic relationship to higher temperatures; half of global output is not lost until temperature increases reach 12°C.

Weitzman (2010) discusses increasingly ominous scientific evidence about climate risks that imply much greater losses at higher temperatures, suggesting that modeling damages as a loss of 50 percent of output at 6°C and 99 percent at 12°C would better represent the current understanding of climate risks. The CRED NW and HW damage functions benchmark damages at 2.5°C against the Nordhaus and Hanemann estimates, respectively, with damages reaching the Weitzman estimates at higher temperatures. All four damage functions are displayed in Figure A-2, with large dots indicating the points used for calibration.[46]

Figure A-2: Four damage function options



Global damages are apportioned among regions using the CRED vulnerability index. The regional vulnerability index is based on the proportion of GDP in agriculture and tourism, the share of the population living at elevations lower than 5 meters (as a proxy for vulnerable coastal population), and (the inverse of) freshwater resources per person. Each of these vulnerability measures is converted to a component index $\mathbf{X_r X_r}$ which ranges from 0.0 at the least vulnerable region to 1.0 at the most vulnerable:[47]

$$(6)\quad \text{X-index}_r = \left(X_r - X_{min}\,\square\right) \Big/ \left(X_{max} - X_{min}\,\square\right)$$

The average of the three component indices is the regional vulnerability index (VI_r):

$$(7)\quad \mathbf{VI_r} = \frac{\mathbf{Vulnerable\ sectors_r + Coastal\ population_r + Water\ availability_r}}{\mathbf{3}}$$

This index is assumed to be constant over time, and ranges from a high (most vulnerable) of 0.427 in Africa to a low (least vulnerable) of 0.056 in the United States.

We then allocate the total global damages to regions, in proportion both to regional output and to the vulnerability index:[48]

$$(8)\quad \text{Regional damage index}_{t,r} = \frac{\mathbf{VI}_r^{\alpha} * \mathbf{Output}_{t,r}}{\sum_r \left(\mathbf{VI}_r^{\alpha} * \mathbf{Output}_{t,r}\right)}$$

$$(9)\quad \mathbf{Damages}_{t,r} = \text{Regional damage index}_{t,r} * \mathbf{Global\ damages}_t$$

In Equations (8) and (9), regional output is gross output before damage losses are considered. Since the regional damage index is defined to sum to one, regional damages sum to global damages. Regional output net of damages is regional gross output minus regional damages. Output net of damages is the total available for savings and consumption:

$$(10)\qquad \mathbf{Net\ output}_{t,r} = \mathbf{Output}_{t,r} - \mathbf{Damages}_{t,r}$$

6. Emissions and mitigation

Emissions are calculated on a gross basis, prior to abatement; then abatement is calculated and subtracted from gross emissions. (CRED has the capacity to model emissions of several greenhouse gases, but to date it only models CO_2, and uses the MAGICC exogenous forcings to account for the impact on temperature of all other greenhouse gases.) Gross emissions in all sectors except land-use changes are assumed to be proportional to output; each region's base-year (2005) emissions intensity is calculated using historical data. Thereafter, emissions intensity (E-intensity, the ratio of gross emissions to output) is assumed to decline slowly as per capita output (ypc) rises:[49]

$$(11)\quad \text{E-intensity}_{t,r} = \text{E-intensity}_{2005,r} \left({}^{\text{ypc}_{t,r}}/_{\text{ypc}_{2005,r}}\right)^{-0.}$$

$$(12)\quad \mathbf{CO_2emissions}_{t,r} = \text{E-intensity}_{t,r} * \mathbf{Output}_{t,r} + \mathbf{LandUseCarbonFlux}_r - \mathbf{Abatement}_{t,r}$$

Emissions from land-use changes ("carbon flux") are assumed to be constant over time at the 2005 level.

By definition, abatement is set to zero in 2005; calculations for later years represent incremental abatement beyond practices prevailing in 2005. Abatement costs and potential for each region are based on the McKinsey cost curves for 2030, modified for use in CRED.[50]

McKinsey data for eleven economic sectors in each region, downloaded from the McKinsey Climate Desk, were grouped into agriculture and forestry ("land-use" for short); all other sectors were grouped together as "industry". Parallel analyses were performed on each of the 18 sets of data (land-use and industry sectors, for each of 9 regions). As in the familiar McKinsey cost curves, cumulative abatement is graphed on the horizontal axis, versus marginal cost per ton of abatement on the vertical axis, arranging the measures in order of increasing marginal cost. Although each set of data includes significant negative-cost abatement opportunities, these potential cost savings are not modeled in CRED due to continuing controversies about the meaning of negative-cost opportunities. Instead, a curve that goes through the origin (i.e., a marginal cost of zero at zero abatement) is fitted as closely as possible to the positive-cost portion of each empirical curve. (For a more detailed description of CRED's abatement cost curve methodology, see Ackerman and Bueno 2011.)

We obtained good approximations to marginal costs in each of the 18 data sets with a curve of the form:

(12) $$\mathbf{MC} = {}^{\mathbf{Aq}}/$$ [illegible]

Here q is the cumulative quantity of abatement. B is the upper limit on feasible abatement; the cost curve turns increasingly vertical as q approaches B (a pattern that fits well to the McKinsey data). A is the marginal cost at q = B/2. We extrapolated this fitted curve across the negative-cost measures in the McKinsey data, which amounts to assuming that those measures have near-zero but positive marginal costs.

Equation (13) can be inverted, to solve for the quantity of abatement available at a marginal cost less than or equal to a carbon price p:

(13) $$\mathbf{q} = {}^{\mathbf{Bp}}/_{(\mathbf{A}+\mathbf{p})}$$

The McKinsey data separately provide estimates of the capital costs associated with each abatement measure; the marginal cost in (13) is typically the annualized capital cost minus the fuel savings from abatement. To smooth the somewhat noisy capital cost data, we modeled the cumulative capital cost required (in each of the 18 cases) to reach abatement level q; this can be well approximated by a quadratic:

(14) $$\mathbf{CumCost_q} = \mathbf{Eq} + \mathbf{Fq}^2$$

With estimated values of A, B, E, and F for each of the 18 data sets, (14) yields the amount of abatement occurring at a given carbon price, and (15) yields the total green capital needed to achieve that level of abatement. The required new investment in each period is the difference between the cumulative capital stock required for abatement, from (15), and the existing green capital remaining from the previous time period (10 years earlier) after depreciation.

(15) $$\mathbf{AbateInvest_{t,r}} = \mathbf{CumCost_{t,r}} - (\mathbf{1} - \mathbf{Depreciation})^{\mathbf{10}} * \mathbf{CumCost_{t-1,r}}$$

In the land-use sectors we assume that emissions and mitigation potential are proportional to land area, and hence constant over time. Therefore, A, B, E, and F are also constant over time for land-use sectors. The McKinsey estimates for land-use mitigation potential exceed the base year land-use emissions; this gives rise to a small ongoing potential for negative emissions, or net sequestration, the only such potential in CRED.

The values of B are well below total industrial emissions in most cases. We assume that technological progress, raising the value of B, will occur uniformly throughout the model's first century such that 100 percent abatement of industrial emissions becomes possible in each region by 2105. After that time, B grows in proportion to the regional economy.[51]

7. Optimization: Solving the model

CRED is an optimization model in which the GAMS non-linear solver explores values of decision variables across time periods and regions to determine the optimum values that maximize a global utility function.[52] The CRED decision variables, subject to the constraints discussed below, are:

- the nine carbon prices (p) in each time period, one for each region; these determine the level of abatement and of abatement investment, also known as green investment in CRED, in each region and time period (equations 14-16);
- the level of standard investment occurring in each region and time period;
- the funds used for domestic investment, in each region and time period; and
- the funds used for investment outside the region, from each region and time period.

Consumption is calculated as output net of damages minus funds used for domestic and foreign investment.

Constraints on these variables include:

- global savings must equal global investments (standard plus green) in each time period;
- regional savings equal the sum of funds available for domestic investment in each region plus funds for investment outside the region (exported);
- all investment exported from a region is imported in other regions (the net global sum of inter-regional investments is zero);
- a cap on outside investment: funds for investment outside the region cannot exceed a specified percentage of the region's net output;
- total capital is constrained to be non-decreasing in the first 250 years of modeling;[53]
- carbon prices are constrained to be non-decreasing over time (and cannot increase by more than \$1,000/tC per decade, nor exceed \$5,000/tC); as a result, green investment also is non-decreasing;
- in policy scenarios, per capita consumption is constrained to grow by at least 0.5 percent per year, in every region, throughout the time span of the model;
- optionally, targets can be set to keep the maximum global temperature increase (or CO_2 concentration) under a specified limit by a specified date; alternatively, a minimum per capita consumption level can be specified such that it is reached or exceeded in all regions by a specified future date.

The CRED utility function seeks to maximize the cumulative present value, or discounted sum, of the logarithms of regional per capita consumption, weighted by population:

$$\text{(16)} \qquad \mathbf{Utility} = \sum_{\mathbf{t,r}} \frac{\mathbf{population_{t,r}} \ * \ \ln\left(\mathrm{cpc}_{\mathbf{t,r}}\right)}{(\mathbf{1} + \boldsymbol{\rho})^{\mathbf{10t}}}$$

The summation is over all regions and years; r is the rate of pure time preference, used for discounting utility. The default value of r in CRED is 0.1 percent per year, the same as in the Stern Review (Stern 2006); other values, when explored, are noted explicitly.

Inter-regional investment is a key option in CRED. When that option is switched off, each region must provide all the savings necessary for its own abatement and economic growth (its green and standard investments, respectively). In this case, savings must equal total investment for each region in each time period. When cross-regional investments are allowed, a specified fraction of each region's net output can be invested outside the region; the allocation of such investment flows to recipient region(s) and the mix of green and standard investment are decisions made by the solver during the optimization. In this case, global savings must equal global total investment for each time period.

A table of input parameters and a list of data sources are available on request from the authors.

Appendix B: CRED Scenarios

Each CRED scenario shown in this report employs the model structure and data described in Appendix A; scenarios differ in only a few key parameters: the damage parameters; the pure rate of time preference (PRTP), and the maximum share of each region's output that can be transferred to investment in other regions.

Table B-1: CRED scenarios used in this report

Scenario	Damages	PRTP (%)	Transfers	Chance <2°C	°C at Median CS	SCC in 2015
Business-As-Usual	NN	1.5	No Pooling	0.01%	3.7	$32
Weak Conventional	NN	1.5	No Pooling	0.06%	3.0	$28
CRED Damages	HW	1.5	No Pooling	1.5%	2.6	$74
Strong Conventional	HW	0.1	No Pooling	57%	2.0	$217
CRED Optimal	HW	0.1	up to 40% Pooling	83%	1.7	$127

Business-As-Usual Scenario: Business-as-usual scenarios have an additional difference from standard CRED runs: green investment (emissions abatement) is set to zero. Damages occur, reducing output, but the only tool that CRED can employ in maximizing utility is to increase or decrease standard investment in each region. In this report, the "Business-As-Usual" scenario is modeled with an NN damage function (the most optimistic CRED damage function, which is identical to the DICE 2007 damage function; see Appendix A) and a PRTP of 1.5 percent. In this scenario, there is a less than 1-percent chance of keeping year 2100 temperature increases below 2°C, and only a 50/50 chance of keeping temperatures below 3.7°C.[54] At the median climate sensitivity value – 3.0°C – the atmospheric concentration of carbon dioxide reaches 861 ppm by the end of the century; temperatures and concentrations continue to increase throughout the modeling period. In CRED's Business-as-Usual scenario, the social cost of carbon (SCC) – or the additional damages that occur as the result of adding one more ton of CO_2 emissions in 2015 – is $32.

Weak Conventional Scenario: CRED can be used to approximate DICE 2007 global modeling choices by using the optimistic NN damage function, a PRTP of 1.5 percent, and no transfer of funds for cross-region investments. Unlike the Business-As-Usual scenario, this "Weak Conventional" run – and all other CRED policy runs – allows for investment in abatement measures. Nonetheless, with these parameter choices there is still less than a 1-percent chance of keeping temperature increase below 2°C; temperatures and concentrations continue to increase throughout the modeling period, with a 50/50 change of staying below 3.0°C. The 2015 SCC for the Weak Conventional scenario is $28, quite close to the Business-as-Usual value. Because the Business-as-Usual and Weak Conventional scenarios share the same damage function and PRTP, their SCCs are directly comparable. One might expect the Weak Conventional scenario to have a much lower SCC due to its lower future emissions (and therefore lower damages); reasons why the SCC might be relatively insensitive to changes in emissions and damages are discussed in (Hope 2006).

CRED Damages Scenario: By our reading, the HW damage function is – among the four sets of damage function parameters discussed in Appendix A – the most consistent with climate impacts projected in the current climate science literature (Ackerman and Stanton 2011b). In the "CRED Damages" scenario – using HW damages, disallowing cross-regional investment, and employing a 1.5-percent PRTP – there is a 1.5 percent chance of staying below 2°C and a 50/50 chance of staying below 2.6°C. The 2015 SCC for the CRED Damages scenario is $74. Due to the substantial change in damage functions, the SCC for this and the following scenarios are not directly comparable to the values for the Business-As-Usual and Weak Conventional scenarios.

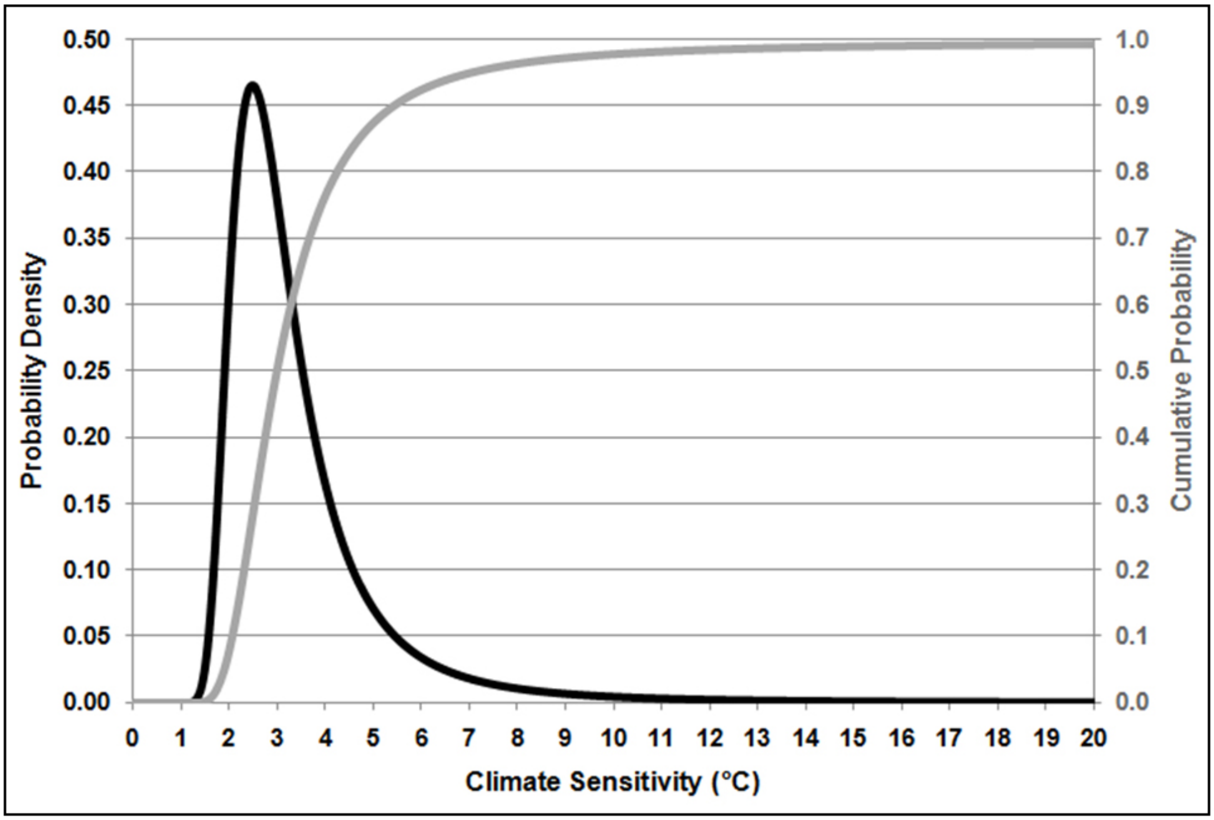
Strong Conventional Scenario: At a PRTP of 0.1 percent – the value used in the Stern Report (2006) – full abatement in the "Strong Conventional" scenario occurs in 2155 and the chance of staying below 2°C increases to 57-percent. This is the first of the scenarios presented in which full abatement of emissions occurs; global emissions fall to zero by 2145. The 2015 SCC for the Strong Conventional scenario is $217. Note that the CRED Damages and Strong Conventional Scenarios differ only in their discount rates: the smaller the PRTP, the larger the SCC.

CRED Optimal Scenario: Introducing the option of cross-region investment allows richer regions to invest in abatement at a lower cost than they would face if restricted to domestic measures. In the "CRED Optimal" scenario high as 40 percent – full abatement takes place in 2095. There is an 83-percent chance of keeping temperature increases below 2°C and a 50/50 chance of staying below 1.7°C. The 2015 SCC for the CRED Optimal scenario is $127. The Strong Conventional and CRED Optimal scenarios differ only in the level of cross-regional investment; the greater transfer of resources between regions permitted in the CRED Optimal scenario has the effect of significantly reducing the SCC (as a result of lower future emissions and damages). In both of these scenarios, temperatures peak and then fall – a result that is not relevant to cumulative emissions and the percentage change of keeping temperatures below 2°C, but has an important impact on SCC values. If the climate module were redesigned to prevent temperatures from declining as a result of falling CO_2 concentrations, SCC values for both the Strong Conventional and CRED Optimal scenarios would be higher.

Appendix C: Climate Sensitivity in CRED scenarios

Throughout this analysis, 3.0°C is taken to be the best guess, or 50th percentile value, for the climate sensitivity parameter; that estimate means that a doubling of pre-industrial CO_2 is expected to cause a long-term equilibrium increase of 3.0°C in global average temperature. CRED v.1.3 employs the Murphy, *et al.* (2004) climate sensitivity distribution shown below.[55]

Figure C-1: Murphy, *et al.* climate sensitivity distribution



For each scenario, we calculate the temperature it reaches by 2100 using the median (3°C) climate sensitivity, and report that the scenario has a 50/50 chance of staying below that temperature.

Scenarios are then run repeatedly, varying the climate sensitivity parameter. Climate sensitivity is changed in 0.1°C increments to find the lowest climate sensitivity for which year 2100 temperature increases exceed 2.0°C. The percentile position of that climate sensitivity, in the probability distribution shown above, is recorded as the probability of staying below 2.0°C. Analogous calculations can be done for the probability of staying below other temperature limits. For example, in the Business-As-Usual scenario 2100 temperatures exceed 4.0°C at climate sensitivity 3.3°C. This climate sensitivity corresponds to the 60th percentile on the Murphy, *et al.* probability distribution.

Appendix D: Other Key Scenarios

This report includes discussion of two non-CRED scenarios, described here.

Table 1: Non-CRED scenarios

Scenario	Damages	PRTP	Chance <2°C	°C at Median CS
Cancun-AVOID			50%	2.0
DICE Optimal	NN	1.5		2.6

1. Copenhagen

UNEP (2010) estimated that global emissions in 2020 – given the Cancun pledges – will fall between 46.7 and 54.8 Gt CO_2-e. The UK government's AVOID program narrowed this range to between 48.1 and 49.5 Gt CO_2-e (Lowe, *et al*. 2011), and introduced two emission trajectories that are consistent with a 50/50 chance of keeping 2100 temperature increases under 2°C; these scenarios have cumulative emissions of 3,013 and 3,031 Gt CO_2-e from 2000 to 2100.

In this report we approximate the Lowe, *et al*. emissions trajectories as follows: Excluding non-CO_2 emissions, Cancun pledge-compliant global emissions are given a central estimate of 38 Gt CO_2 in 2020, with 3 percent reductions in each subsequent year[56]. The result is a twenty-first century cumulative emissions total of 1,800 Gt CO_2.

2. DICE Optimal

Emissions for the DICE 2007 Optimal scenario are taken from Table 5-6 in Nordhaus (2008). In this scenario, temperature increases reach 2.6°C by 2100 at a climate sensitivity of 3.0°C and continue to rise thereafter (Nordhaus 2008, Table 5-8). In CRED, the DICE parameters (NN damage function, 1.5-percent PRTP) result in still worse increases in temperature, as seen in CRED's Weak Conventional scenario (in Appendix B, Table 2, above): 3.0°C by 2100, at a climate sensitivity of 3.0°C, and much less than one percent chance of keeping temperature increases below 2.0°C.

Notes

1 Throughout this report, the average of CRED v.1.3 results for 2095 and 2105 is reported as the 2100 value. For a detailed description of the CRED model, see Appendix A. For more information on the CRED scenarios used in this report, see Appendix B. In the CRED model, business-as-usual emissions reach 128 Gt CO_2 in 2100, driving up atmospheric concentrations to 861 ppm CO_2. For comparison, a recent Energy Modeling Forum (2009) meta-analysis of climate-economics models included business-as-usual scenarios resulting in 2100 atmospheric concentrations of CO_2 ranging from 612 to 1,030 ppm; the mean value was 782 ppm. In the Intergovernmental Panel on Climate Change's (IPCC) widely used SRES A2 and A1FI scenarios, 2100 atmospheric concentrations climb to 846 and 964 ppm CO_2, respectively (IPCC 2011). In its forthcoming *Fifth Assessment Report*, IPCC will replace the SRES scenarios with a set of "representative concentration pathways", including the RCP 8.5 scenario, which reaches 936 ppm CO_2 by 2100 (International Institute for Applied Systems Analysis 2009).

2 According to the World Resources Institute's Climate Analysis Indicators Tool (WRI 2010), total global CO_2 emissions were 29.7 Gt in 2000 and 33.9 Gt in 2005; energy-related CO_2 emissions, excluding land use changes, forestry, and international bunkers, were 23.7 Gt in 2000 and 27.6 Gt in 2005. The International Energy Agency (IEA 2011) has estimated that energy-related global CO_2 emissions were 30.6 Gt in 2010, a 2.1 percent annual increase from 2005. Applying this annual rate of change to 2005 total CO_2 emissions, total global CO_2 emissions for 2010 can be estimated at 37.6 Gt.

3 Temperature increases cited in this report refer to the change in the global average temperature as compared to the preindustrial average. See Section 2 and Appendix C for more discussion of scenario probabilities.

4 Richardson, *et al.* (2009).

5 Climate damages cited from the IPCC's *Fourth Assessment Report* (IPCC 2007) are taken from the Working Group II Technical Summary, TS4.1. Reviews of the climate science literature since the IPCC's 2007 report include Ackerman and Stanton (2011a), Allison, *et al.* (2009), and Warren, *et al.* (2009).

6 The maximum cumulative 21st century emissions consistent with keeping 2100 temperatures increases below 2°C varies by model. Estimates in Bowen and Ranger (2009) range from 1,908 to 2,684 Gt CO_2-e. See also Allan, et al. (2009), Anderson and Bows (2011), Gohar and Lowe (2009), Lowe, *et al.* (2011), and Meinshausen, *et al.* (2009). For a meta-analysis of allocation approaches used in stabilization scenarios see Den Elzen and Höhne (2010).

7 Unless otherwise cited, cumulative 21st century emissions are the authors' calculations using the CRED model.

8 Throughout this report, DICE refers to the DICE 2007 integrated assessment model (Nordhaus 2008). For background on integrated assessment models, see Stanton, *et al.* (2009).

9 Nordhaus (2008).

10 See Roe and Baker (2007).

11 Murphy, *et al.* (2004). See Appendix C for a more detailed discussion of climate sensitivity analysis in CRED.

12 See Matthews and Caldeira (2008), Plattner, *et al.* (2008), Lowe, *et al.* (2009), Solomon, *et al.* (2009), Eby, *et al.* (2009), and Gillett, *et al.* (2011).

13 At the writing of this report, we are currently in the process of adapting CRED's climate module to reflect this new understanding of temperature dynamics; until it does, we avoid reporting temperature overshoot results by restricting the period reported to 100 years, and focusing on the probabilities of peak temperatures.

14 The PAGE model uses separate damage functions for economic, non-economic, and catastrophic damages, differentiated by region, which are all based on other economists' estimates of damages, including those used in the DICE model (Hope, *et al.* 1993; Hope 2006). For a detailed critique of the FUND model's damage function, see Ackerman and Munitz (2011).

15 See Nordhaus (2008) and Nordhaus and Boyer (2000).

16 See Sherwood and Huber (2010).

17 According to the World Bank's World Development Indicators 2011 (The World Bank 2011), 2.6 billion people, or about 37 percent of the global population, subsists on less than $2 a day (the higher of two "international poverty lines"), or $730 a year. According to the International Energy Agency, about 1.4 billion people, or one-fifth of the world population, lack access to electricity (IEA 2010).

18 Called "NN", or "Nordhaus-Nordhaus," in Appendix A since both low-temperature and high-temperature damages are based on the work of William Nordhaus, the principal author of DICE.

19 Called "HW", or "Hanemann-Weitzman", damages in the technical description of the CRED model. See Appendix A for a description of the four damage functions available for use in CRED.

20 See Stern (2006) and, on the DICE 2007 model, Nordhaus (2008).

21 See Stanton (2011).

22 See Stanton (2010).

23 *Ibid.*

24 See Ackerman, *et al.* (2011a) for more discussion.

25 In CRED, all regions' real consumption per capita must increase by a minimum of 0.5 percent per year in every year.

26 Each scenario's social cost of carbon (the economic damages caused by an additional ton of CO_2 emissions) for 2015 is reported in Appendix B.

27 In Market Exchange Rate (and not Purchasing Power Parity) terms. High-income countries include the United States, Europe, and Other High Income Regions. Low-income countries include the Africa, China, Developing Asia/Pacific, Eastern Europe, Latin America/Caribbean, and Middle East regions. See Appendix A for a description of the CRED regions.

28 See Appendix A for a description of the CRED regions.

29 This discussion refers to the PAGE2002 model. Preliminary results from the PAGE2009 revision, not yet released, suggest that it may have significantly different recommendations.

30 See Interagency Working Group (2010), Ackerman and Stanton (2011b), and Ackerman and Stanton (2010).

31 Ackerman and Stanton (2011b).

32 United Nations Framework Convention on Climate Change (2011).

33 Climate Action Tracker (2011).

34 Lowe, *et al.* (2011). See Appendix D for details regarding this scenario of Cancun Agreement emissions.

35 UNEP (2010) and Climate Action Tracker (Ecofys, *et al.* n.d.). Also see Kartha and Erickson (2011).

36 Lowe, *et al.* (2011).

37 See Ackerman, *et al.* (2011) for a technical description of CRED v.1.2.

38 Calculations are performed for 300 years; the last 100 years are then discarded, to avoid end effects.

39 See http://www.gams.com. CRED v.1.3 was developed in GAMS distribution version 23.2.1 for 64-bit Microsoft Windows, under Vista and now Windows 7.

40 Primary data sources are: population, long-range medium variant, 2008 Revision, United Nations, Department of Economic and Social Affairs, Population Division: World Population Prospects DEMOBASE extract, 2010; GDP, percent of GDP from agriculture, percent of GDP from international tourism, *World Development Indicators 2008* (The World Bank 2008); total renewable water (actual), FAO Aquastat database (FAO); share of population living below 5-meter elevation, PLACE II (Socioeconomic Data and Applications Center, Columbia University 2010); CO_2 and all greenhouse gas emissions (including from land use change and forestry), land-use-land-use-change-forestry emissions, CAIT 8.0 (World Resources Institute 2010). Occasional supplementary data are taken from the National Accounts Main Aggregates Database (United Nations Statistics Division 2010), and national sources. All data are for 2005 where available; when this data year was not available, but other data years after 2000 were, either the earliest year after 2005 or the average of years between 2000 and 2004 was used.

41 See Nordhaus (2008) and http://nordhaus.econ.yale.edu/.

42 The Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), http://www.cgd.ucar.edu/cas/wigley/magicc.

43 The WRE scenarios are carbon dioxide stabilization pathways defined by Wigley, *et al.* (1996) that assume changes to global emissions needed to stabilize CO_2 concentrations at 350, 450, 550, 650, or 750 parts per million (ppm).

44 An optional development constraint can be applied to enforce a lower bound on all regions' per capita consumption, starting at a selected future date. This constraint has not been employed in CRED v.1.3 runs to date.

45 In an earlier version of this report this was incorrectly stated as "4 times the Nordhaus value"; the Hanemann value is 2.4 times the DICE-07 damages at 2.5 degrees (and 4 times the corresponding value in DICE-99).

46 A small anomaly is that between 6°C and 12°C the N-W damage function, despite its lower low-temperature damages, is slightly higher than H-W; the gap is greatest at 6.9°C, where N-W damages are 3.8 percent above H-W. This anomaly is an artifact of our curve-fitting procedure.

47 In the water vulnerability index, 1 person/1000 m^3/year – the Falkenmark indicator of water scarcity (Rijsberman 2006; Falkenmark, Lundqvist, and Widstrand 1989) – is substituted for $X_{maximum}$ in equation (6), and all regions with water availability less than 1000 m^3/person/year are assigned an index of 1.0, the maximum level of vulnerability.

48 A simpler and more intuitive version of this calculation, without the exponent (α) on the vulnerability index, can, in some scenarios, project damages exceeding regional output in the most vulnerable regions. The use of the ad hoc scaling factor $\alpha < 1$ in equation (8) avoids this problem.

49 Note that Equation 11 corrects a mistaken formulation that had appeared in the three previously published versions of CRED.

50 McKinsey, https://solutions.mckinsey.com/climatedesk/.

51 To keep capital costs tied to the expanding marginal cost curve in a natural manner, we let F decline such that the product BF remains constant. A and E are held constant in all cases.

52 CRED uses the CONOPT3 non-linear optimization solver, one of several offered by GAMS.

53 This ad hoc measure prevents minor oscillations in later-year capital stocks in some model solutions; it does not change the overall trajectories of the scenarios we have modeled.

54 All percentile chances referred to in this report (both the chance of keeping average global temperature increases below 2°C, and the temperature increase expected at the 50th percentile in the climate sensitivity probability distribution) refer to year 2100 temperatures. See Appendix C.

55 Estimated using the method and parameters reported in Roe and Baker (2007).

56 We convert 2020 CO_2-e emissions to CO_2 by subtracting 11 Gt CO_2-e, the level of non-CO_2 emissions used in CRED, and assume that non-CO_2 emissions remain constant through 2100. In 2005, global non-CO_2 emissions totaled 10.3 Gt CO_2-e (World Resources Institute 2010).

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