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CRED v.1.4 Technical Report

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ABSTRACT

Climate and Regional Economics of Development (CRED) is an integrated assessment model with a central focus on the global distribution of climate damages and climate policy costs. It is designed to estimate the best pace of investment in emissions mitigation and the best distribution of the necessary investment costs among regions of the world, aiming to inform global climate negotiations and help break the stalemate between developed and developing countries. Version 1.4 of the CRED model was completed in August 2012. This technical report describes the CRED v.1.4 methodology in detail.

The model's input parameters and data sources are available at the CRED model Website:

http://www.sei-us.org/cred

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SUMMARY

Version 1.4 of the Climate and Regional Economics of Development (CRED) model was completed in August 2012.[1] 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 2010 base year.[2] CRED equations are programmed in GAMS (General Algebraic Modeling System)[3], a high-level modeling language used for complex economic and engineering applications that require mathematical optimization. The CRED user interface is an Excel-2007 workbook that gathers and configures scenarios from the background dataset, including model assumptions, parameters, and other selections, feeding inputs to the GAMS model. The model writes its results, including a comprehensive package of pre-formatted tables and charts, to a second Excel workbook.

1. WHAT'S NEW IN CRED V.1.4

CRED version 1.4 includes a number of improvements to its GAMS code and to the Excel user interface and scenario output reporting. The most significant changes in version 1.4 are:

- CRED now disaggregates the world into 16 regions (up from 9 in earlier versions).
- Data have been updated, reflecting CRED v.1.4's new 2010 base year. In several instances this involved a shift in the use of data sources:
    - UN Stats replaced the World Bank as the primary data source for base-year national estimates of Gross Domestic Product (GDP).
    - The PLACE III dataset, updated from PLACE II, provides more detailed information regarding the percentage of each country's population living at altitudes less than 5 meters above sea level.
    - Data for 2010 national CO_2 emissions are now primarily based on data from the Carbon Dioxide Information Analysis Center (CDIAC); in previous CRED versions these data were taken from the World Resources Institute's Climate Analysis Indicators Tool (CAIT).
- There is an improved algorithm for calculation of regional vulnerability indices.
- The use of McKinsey data to estimate marginal abatement cost (MAC) and capital expenditure curves has changed; CRED v.1.4 uses data from McKinsey's Climate Desk Version 2.1, an update that adjusts for impacts of the global financial crisis (McKinsey & Company 2010). Some additional steps were required to calculate marginal abatement cost and abatement capital expenditure curves for CRED's 16 regions.

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[1] See Ackerman et al. (2011a) and Ackerman et al (2011b) for descriptions of CRED v.1.2 and CRED v.1.3, respectively.

[2] Calculations are performed for 300 years; the last 100 years are discarded to avoid end effects.

[3] See http://www.gams.com. CRED v.1.4 was developed in GAMS distribution version 23.2.1 for 64-bit Microsoft Windows 7.

- The projections of increasing potential abatement of CO_2 emissions through 2100 were simplified and updated.
- The climate module has been recalibrated to match the results of the MAGICC[4] model, and to reflect the climate literature's current understanding of the likelihood of non-declining temperatures.
- Calculation of the social cost of carbon (SCC) based on a CO_2 emissions pulse at a specified time is now included as an optional feature.

2. CRED WORLD REGIONS

CRED v.1.4 disaggregates the world into sixteen regions, grouped for some reporting purposes into high, middle, and low-income categories:

High-income (regional average 2010 consumption per capita = $25,000 or more)

- United States (excludes Puerto Rico and other territories)
- Western Europe (EU-15, Iceland, Norway, Switzerland)
- Japan
- Other High-Income (Canada, Taiwan, Singapore, South Korea, Australia, New Zealand)

Middle-income (regional average 2010 consumption per capita = $5,000 - $10,000)

- Brazil
- Mexico
- Rest of Latin America and the Caribbean (includes Puerto Rico)
- Other Europe (Turkey and all EU members except EU-15)
- Eastern Europe (Russia, Ukraine, Belarus, Moldova, Albania, non-EU ex-Yugoslavia)
- Middle East (excludes North Africa and includes Iran)
- South Africa

Low-income (regional average 2010 consumption per capita below $3,000)

- China (includes Hong Kong and Macao but not Taiwan)
- India
- Southeast Asia/Pacific
- Other Developing Asia (Pakistan, Bangladesh, Nepal, Bhutan, Afghanistan, Mongolia, North Korea, Asian ex-USSR)
- Rest of Africa (includes North Africa)

These regional categories are defined for compatibility with McKinsey abatement, abatement cost, and capital expenditure data (discussed below) in most but not all cases. CRED v.1.4 classifications differ from the existing McKinsey regions. For example, CRED's Southeast Asia/Pacific and Other Developing Asia regions are a single region in McKinsey's data. Other mismatches occur in the divisions within Europe, and in CRED's Other High Income region. Modifications of the abatement and expenditure curves to fit the CRED regional boundaries are discussed below.

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

3. DATA SOURCES

Regional data for the model's new base year, 2010, are aggregated from individual country data obtained from major international data sources. All monetary amounts are in 2010 U.S. dollars at market exchange rates – not in purchasing power parity terms. Key data sources include the following:

- The primary source for GDP estimates is UNStats.[5]
- The World Bank Development Indicators[6] provide supplementary GDP estimates, as well as national estimates of agriculture and tourism as a percentage of GDP.
- The Penn World Tables[7] provides estimates of country-specific investment rates.
- The Carbon Dioxide Information Analysis Center (CDIAC)[8] provides estimates of national emissions in 2010, based primarily upon GDP and historic emissions intensities. Where necessary, this is supplemented by an extrapolation from the Climate Analysis Indicators Tool (CAIT) 2008 estimates based upon GDP growth. This is a change from earlier versions of CRED, which were based solely upon the CAIT database.[9]
- The PLACE III database, developed by Columbia University's Socioeconomic Data and Applications Center (SEDAC),[10] provides national estimates of the population living less than 5 meters above sea level.
- Population is based on the U.N. 2008 long-range median forecast[11] through each country's post-2100 minimum, and assumed constant thereafter.
- The Food and Agriculture Organization's (FAO) AQUASTAT database[12] provides estimates of freshwater resources in each nation.

4. CLIMATE MODULE

For climate dynamics, CRED uses the DICE 2007[13] equations, modeling three compartments (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 MAGICC5.3 model over a range of stabilization scenarios (WRE 350 through 750)[14] and zero emission pathways; this required modest but significant changes to the DICE parameters.

In effect, we are using a reduced-form approximation of MAGICC, providing very close agreement with MAGICC across that range of scenarios. We also adopt MAGICC's exogenous estimates of non-CO_2 forcings in place of DICE's piecewise linear formula (Figure 1). The inputs to the climate module are current global emissions and non-CO_2 forcings, previous temperature,

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[5] http://unstats.un.org

[6] http://data.worldbank.org/indicator

[7] http://pwt.econ.upenn.edu

[8] http://cdiac.ornl.gov

[9] http://cait.wri.org

[10] http://sedac.ciesin.columbia.edu/

[11] http://www.un.org/esa/population/unpop.htm

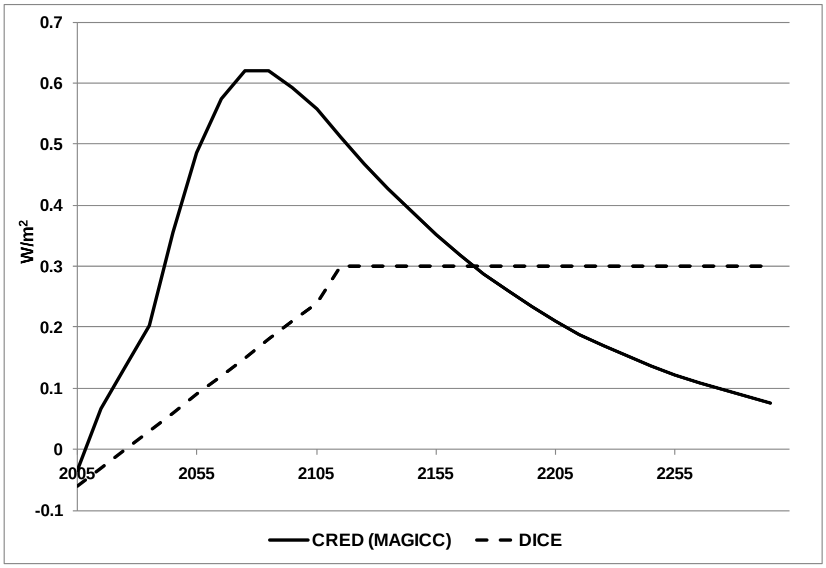
[12] http://www.fao.org/nr/water/aquastat/main/index.stm

[13] See Nordhaus (2008) and http://nordhaus.econ.yale.edu/ .

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

and previous concentrations of carbon dioxide in each of the three compartments. The outputs are current temperature and concentrations.

Figure 1: CRED versus DICE non-CO_2 forcings



For the climate sensitivity parameter – the temperature increase resulting from a doubling of atmospheric CO_2 concentrations – CRED v.1.4 uses a default of 3.0°C, although other climate sensitivity values can be explored.

5. ECONOMY MODULE

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

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

Here r is region and t is time, measured in 10-year periods. TFP is a region-specific estimate of total factor productivity, assumed to grow at a constant rate of 1 percent per year in each region. Labor is represented by population (in effect, assuming constant employment and labor force participation rates over the long run). Capital, constrained to be non-decreasing over the first 250 years of the model, combines both “standard” and “green” investments, where the latter is emission-reducing investment (discussed below):

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

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, emission-reducing investment is half as productive of income as standard investment.

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

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

In CRED v.1.4, initial country-specific levels of capital stocks are estimated for the base year, 2010; these are then aggregated to the broader CRED regions. For consistency, the base-year investment levels in CRED are constructed by applying country-level investment shares for 2010 to the same GDP data used in the initial capital stock estimation. The methodology used to estimate capital stocks in 2010 is described in Box 1.

Box 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 et al. 2011); annual capital-output ratios for 93 countries for 1970-1990 from Nehru and Dhareshwar (1993); capital-output ratios and capital stock estimates for 22 selected OECD countries through 2001, from Kamps (2004); and GDP data from UNStats and the World Bank.

An initial capital stock estimate for each country is used to initiate capital stock accumulation in the first year (1970 or later) with available data from the Penn World Table series ki (investment as a share of GDP). Initial capital stock estimates are calculated by applying the Nehru and Dhareshwar capital-output ratio, when available, to that year's GDP; a global GDP-weighted average capital-output ratio was applied when country-specific ratios are not available. Sensitivity analyses show that, as a consequence of the extensive depreciation over the 40-year period, the capital stock in 2010 is relatively insensitive to a range of estimates of initial capital in 1970.

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

Capital(t,r) = (1-Depreciation) * Capital(t-1,r) + InvestShare(t-1,r) * GDP(t-1,r)

The depreciation rate was obtained by calibrating our estimates of capital-output ratios in 2001 to the Kamps estimates of OECD capital-output ratios. A depreciation rate of 4.4 percent per year provided the best fit, and was used throughout the base-year capital stock calculation. (CRED uses a default depreciation rate of 5 percent per year for future projections.)

In a separate calculation, investment-output ratios for 2010 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 2010 for the 185 countries in the Penn tables, the CRED regions' own capital-output ratios and investment-output ratios are calculated; for each country missing capital stock and investment data, they are estimated by applying the average ratios of the respective region.

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.[15] The savings rate and the allocation of savings for each region are chosen in the optimization process, described further below.

6. CLIMATE DAMAGES

For global damages, CRED uses the equation:

$$(4)\quad \text{Output net of damages}_t = \text{Gross global output}_t * \text{Global damage share}_t$$

where gross output 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). A "damage function" is specified by four parameters (a, b, c, d) used in the definition of the damage share:

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

CRED v.1.4 allows the choice of one of four sets of global damage share parameters (a, b, c, and d) from the four damage function options shown in Table 1.

Table 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 2012) can be viewed as combining two separate estimates; parameters a and b dominate at low temperatures whereas, 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 low temperature (first initial, either Nordhaus or Hanemann) and high temperature damages (second initial, either Nordhaus or Weitzman). The N-N 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 a temperature increase of 2.5°C, rising 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, 2.4 times the Nordhaus value. The H-N damage function recalibrates damages to 4.2

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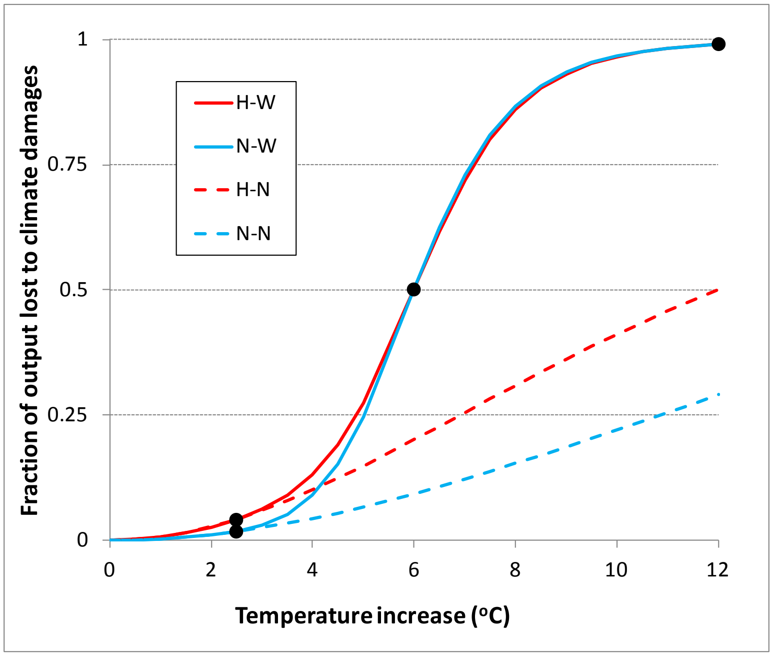
[15] An optional development constraint can be applied to enforce a lower bound on all regions' per capita consumption, starting at a selected future date. This constraint has not been employed in CRED runs to date.

percent of output at 2.5°C but maintains the quadratic relationship for extrapolation to higher temperatures; half of global output is not lost until temperature increases reach 12°C.

Weitzman (2010) discusses increasingly ominous scientific evidence regarding climate risks and much greater losses at higher temperatures, suggesting that a better representation of the current understanding of climate risks might model damages as a 50 percent loss of output at 6°C and 99 percent loss at 12°C. The CRED N-W and H-W damage functions benchmark damages against the Nordhaus and Hanemann estimates for a 2.5°C temperature rise, respectively, with damages reaching the Weitzman estimates at higher temperatures. All four damage functions are displayed in Figure 2, with large dots indicating the points used for calibration.

Figure 2: Global damage shares from the 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 ($\mathrm{X_r}$) is weighted by GDP and converted to a component index, X-index$_\mathrm{r}$, which ranges from 0.0 at the least vulnerable region to 1.0 at the most vulnerable:

$$(6)\ \ \text{X-index}_\mathrm{r} = {(\mathrm{X_r} - \mathrm{X_{min}})}\Big/{(\mathrm{X_{max}} - \mathrm{X_{min}})}$$

Note that $\mathrm{X_{max}}$ and $\mathrm{X_{min}}$ are defined for $\mathrm{X_r}$ at the regional level.[16] The average of the three component indices is the regional vulnerability index, ($\mathrm{VI_r}$):

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

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

This index is assumed to be constant over time, and ranges from a high (most vulnerable) of 0.823 in 'Other Africa' to a low (least vulnerable) of 0.098 in the United States.

We then allocate the total global damages to each region in proportion to their regional output and their vulnerability index:[17]

$$(8)\ \ \mathrm{Regional\ damage\ index_{t,r}} = \frac{\mathrm{VI_r^{\alpha}} * \mathrm{Output_{t,r}}}{\sum_r \left(\mathrm{VI_r^{\alpha}} * \mathrm{Output_{t,r}}\right)}$$

$$(9)\ \ \mathrm{Damages_{t,r}} = \mathrm{Regional\ damage\ index_{t,r}} * \mathrm{Global\ damages_t}$$

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

$$(10)\qquad \mathrm{Net\ output}\ _{\mathrm{t,r}} = \mathrm{Output_{t,r}} - \ \mathrm{Damages_{t,r}}$$

7. EMISSIONS AND MITIGATION

CO_2 emissions are calculated on a gross basis, prior to abatement; abatement is then calculated and subtracted from gross emissions. (CRED only models CO_2, using the MAGICC exogenous forcings to account for the impact on temperature of all other greenhouse gases.) Gross CO_2 emissions in industrial sectors (excluding land-use changes) are assumed to be proportional to output; the base-year (2010) emissions intensity for each region is calculated from 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:

$$(11)\qquad \mathrm{E\text{-}intensity_{t,r}} = \mathrm{E\text{-}intensity_{2010,r}} \left({}^{\mathrm{ypc_{t,r}}}\!/_{\mathrm{ypc_{2010,r}}} \right)^{-0.1}$$

$$(12)\qquad \mathrm{CO_2 emissions_{t,r}} = \mathrm{E\text{-}intensity_{t,r}} * \mathrm{Output_{t,r}} + \mathrm{LandUseCarbonFlux_r} - \mathrm{Abatement_{t,r}}$$

Emissions from land-use changes ("carbon flux") are assumed to be constant over time at the 2010 level.

Abatement is set to zero in 2010 by definition; calculations for later years represent incremental abatement beyond practices prevailing in 2010. Abatement costs and potential for each region are based on the McKinsey cost curves for 2030, modified for use in CRED.[18]

CRED v1.4 uses the revised Climate Desk v2.1 data (updated to account for the world financial downturn, expected higher energy prices and new emissions mitigation policies). McKinsey data was downloaded from the McKinsey Climate Desk for each of its 21 regions, with its 11

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[17] 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.

[18] McKinsey & Company (N.d.), https://solutions.mckinsey.com/climatedesk/.

economic sectors grouped into two classifications – agriculture and forestry ("land-use" for short), and all other sectors ("industry"). To obtain marginal abatement cost and capital expenditure curves, parallel analyses were performed on each of the 32 sets of data (land-use and industry sectors in each of the 16 regions). As in the familiar McKinsey cost curves, cumulative abatement and the marginal cost per ton of abatement are graphed on the horizontal and vertical axis, respectively, arranging the measures in order of increasing marginal cost. Each set of data includes significant negative-cost abatement opportunities; however, these potential cost savings are not modeled in CRED due to the continuing controversies over 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 32 data sets using a curve of the form:

$$(13) \qquad \mathrm{MC_q} = {}^{\mathrm{Aq}}/_{(\mathrm{B}-\mathrm{q})}$$

Here q is the cumulative quantity of abatement and B is the upper limit on feasible abatement; the cost curve approaches infinity as q approaches B (a pattern that fits well to the McKinsey data). The parameter A can be interpreted as the marginal cost at q = B/2. Each curve is fitted to the positive-cost measures and then extrapolated across the negative-cost measures in the McKinsey data, essentially assuming that McKinsey's negative-cost 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 given carbon price, p:

$$(14) \qquad \mathrm{q} = {}^{\mathrm{Bp}}/_{(\mathrm{A}+\mathrm{p})}$$

The McKinsey data provides separate 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 to reach abatement level q; this can be well approximated by a quadratic:

$$(15) \qquad \mathrm{CumCost_q} = \mathrm{Eq} + \mathrm{Fq}^2$$

With estimated values of A, B, E, and F for each of the 32 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.[19] 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, after depreciation, remaining from the previous time period (10 years earlier).

$$(16) \qquad \mathrm{AbateInvest_{t,r}} = \mathrm{CumCost_{t,r}} - (1-\mathrm{Depreciation})^{10} * \mathrm{CumCost_{t-1,r}}$$

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[19] A, B, E, and F are estimated to minimize the sum of squared differences between the curves and the positive-cost portion of each empirical curve, subject to the constraints $A > 0$, $B > 0$, $E>0$, and $(E + 2Fq_{max}) > 0$ (where q_{max} is McKinsey's maximum abatement level). The latter implies that marginal capital cost requirements are positive at maximum abatement levels q_{max} (i.e., the derivative of equation (15) is positive).

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 will raise the value of B uniformly throughout the model's first century, such that 100 percent abatement of industrial emissions becomes possible in each region by 2100. After that time, B grows in proportion to the regional GDP.[20]

8. OPTIMIZATION: SOLVING THE MODEL

CRED is an optimization model in which the GAMS solver explores values of decision variables, maximizing a global utility function across time periods and regions to determine the optimum values.[21] The CRED decision variables, subject to the constraints discussed below, are:

- the sixteen carbon prices (p) in each time period, one for each region; these determine the level of abatement and of abatement investment, also called 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 available for domestic investment, in each region and time period; and
- the funds available 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;[22]
- carbon prices are constrained to be non-decreasing over time (and cannot increase by more than \$100/tC per decade, nor exceed \$500/tC[23]); as a result, green investment also is non-decreasing;

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

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

[22] 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.

- 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, to be 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 (cpc), weighted by population:

$$(17)\qquad \mathrm{Utility} = \sum\nolimits_{\mathrm{t,r}} \frac{\mathrm{population_{t,r}} * \ln(\mathrm{cpc_{t,r}})}{(1+\rho)^{10\mathrm{t}}}$$

The summation is over all regions and years; ρ is the rate of pure time preference, used for discounting utility. (Note that t, in equation (17), is measured in decades since the base year, so the exponent of 10t represents the number of years.) The default value of ρ in CRED is 0.1 percent per year, the same as in the Stern Review (Stern 2006).

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. 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 transferred to outside of the region; the allocation of such investment flows to recipient region(s), as well as 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.

9. THE SOCIAL COST OF CARBON

The social cost of carbon (SCC) is not used within CRED, but can be calculated and reported to allow comparison with other models and analyses. The SCC calculation involves comparison of two similar CRED solutions, based on identical inputs except that one adds a "pulse" of extra emissions in a specified year. The solution with the added emissions will have higher temperatures and damages, and therefore lower consumption, in all years after the pulse.

The SCC is the value of the difference in global consumption between the two scenarios, per ton of emissions in the pulse. Differences in consumption, in years following the pulse, are expressed in utility terms – i.e., multiplied by the marginal utility of consumption in that year – and then discounted to the pulse year at the rate of pure time preference (the same discount rate used in the utility function). The logarithmic utility function, in equation (17), implies that marginal utility is proportional to the inverse of consumption per capita. Therefore, the SCC calculation is

$$(18)\qquad SCC(p) = 10 \sum\nolimits_{t \geq p} \Delta C_t \frac{cpc_p}{cpc_t} e^{-10\rho(t-p)}$$

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[23] The maximum abatement potential for all 21 McKinsey regions for the industry and land-use sectoral aggregations are achieved for marginal abatement costs (MAC) at or below \$500/tC. Without a cap on abatement costs, CRED often pursues very small increments of abatement that are apparently available at extraordinary costs per ton, an artifact of the form of equation (13). Sensitivity analyses show that CRED solutions are virtually unchanged when the cap is doubled; that is, model results are not sensitive to the exact level of the cap.

Here p is the pulse decade, t is measured in decades, ΔC_t is the (annual) difference in global consumption at time t, and the consumption per capita fraction converts ΔC_t to its utility equivalent as of time p.

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