



CRED V.1.3 TECHNICAL REPORT

Revised January 25, 2012

FRANK ACKERMAN, ELIZABETH A. STANTON AND RAMÓN BUENO

Stockholm Environment Institute-U.S. Center

Corresponding author: Frank Ackerman, frank.ackerman@sei-us.org

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 both the best pace of investment in mitigation, and the best distribution of the cost of that investment to regions of the world, with the goal of informing global climate negotiations and help break the stalemate between developed and developing countries. Version 1.3 of the CRED model was completed in June 2011. This technical report describes the CRED v.1.3 methodology in detail.

Copyright © 2011 by the Stockholm Environment Institute

This publication may be reproduced in whole or in part and in any form for educational or non-profit purposes, without special permission from the copyright holder(s) provided acknowledgement of the source is made. No use of this publication may be made for resale or other commercial purpose, without the written permission of the copyright holder(s).

For more information about this document,
contact Frank Ackerman at frank.ackerman@sei-us.org.

Stockholm Environment Institute – U.S. Center
11 Curtis Avenue
Somerville, MA 02144-1224, USA
www.sei-us.org and www.sei-international.org

SUMMARY

Version 1.3 of the Climate and the Regional Economics of Development (CRED) model was completed in June 2011.¹ 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 2005 base year.² CRED equations are programmed in GAMS (General Algebraic Modeling System)³, 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)

¹ See Ackerman et al. (2011) for a technical description of CRED v.1.2.

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

³ 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.

- 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 data sources.⁴ All monetary amounts are in 2005 U.S. dollars, 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, and assumed constant in each country thereafter. GDP in the base year is based on World Bank data, supplemented by GDP data from UNStats for countries for which there were no World Bank data.

3. CLIMATE MODULE

CRED uses the DICE 2007⁵ 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 MAGICC⁶ model for the five WRE scenarios (WRE 350 through 750);⁷ 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 that range of scenarios. We also adopted the MAGICC exogenous estimates of non-CO₂ forcings, rather than DICE's piecewise linear formula (Figure 1). The inputs to the climate module are current global emissions and non-CO₂ forcings, previous temperature, and previous concentrations of carbon dioxide in the three compartments. The outputs are current temperature and concentrations.

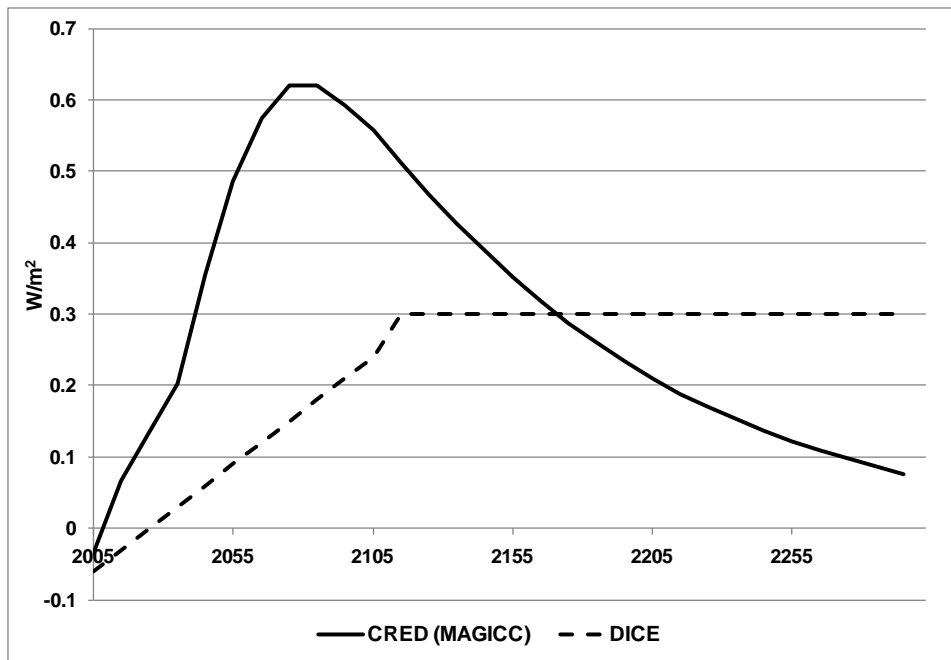
⁴ Primary data sources are: population, long-range medium variant, 2008 Revision, United Nations, Department of Economic and Social Affairs, Population Division: World Population Prospects DEMOBASE extract, 2010; GDP, percent of GDP from agriculture, percent of GDP from international tourism, *World Development Indicators 2008* (The World Bank 2008); total renewable water (actual), FAO Aquastat database (FAO n.d.); share of population living below 5-meter elevation, PLACE II (Socioeconomic Data and Applications Center, Columbia University 2010); CO₂ 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.

⁵ See Nordhaus (2008) and <http://nordhaus.econ.yale.edu/>.

⁶ The Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC), <http://www.cgd.ucar.edu/cas/wigley/magicc>.

⁷ The WRE scenarios are carbon dioxide stabilization pathways defined by Wigley et al. (1996) that assume changes to global emissions needed to stabilize CO₂ concentrations at 350, 450, 550, 650, or 750 parts per million (ppm).

Figure 1: CRED versus DICE non-CO2 forcings



For the climate sensitivity parameter – the temperature increase, in °C, resulting from a doubling of atmospheric CO₂ concentrations – CRED v.1.3 uses a default of 3.0°C. Other climate sensitivity values are explored in sensitivity analyses.

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):

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

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):

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

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:

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

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 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); 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 k_i (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, as a consequence of the 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 k_i):

$$\text{Capital}_{y,c} = \text{Capital}_{y-1,c} * (1 - \text{Depreciation}) + \text{InvestShare}_{y,c} * \text{GDP}_{y,c}$$

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.⁸ The savings rate and the allocation of savings for each region are chosen in the optimization process, described below.

⁸ 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.

5. CLIMATE DAMAGES

For global damages, CRED uses the equation:

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

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:

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

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 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 2011) 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 at 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.

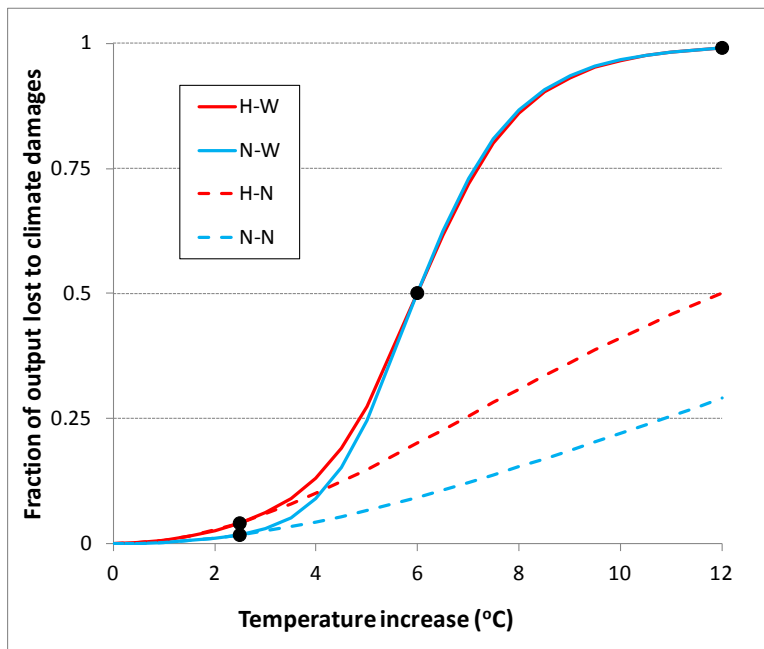
Separate research addresses the low-temperature and high-temperature estimates, suggesting alternatives to each. In a review and critique of the Nordhaus damage estimates as applied to the United States, Hanemann (2008) develops alternative estimates for damages at 2.5°C, which are, in total, almost exactly 2.4 times the Nordhaus value.⁹ 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.

⁹ 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).

Weitzman (2010) discusses increasingly ominous scientific evidence about climate risks implying much greater losses at higher temperatures, and suggests that damages should be modeled as a loss of 50 percent of output at 6°C and 99 percent at 12°C to 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 2, with large dots indicating the points used for calibration.¹⁰

Figure 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 X_r which ranges from 0.0 at the least vulnerable region to 1.0 at the most vulnerable:¹¹

$$(6) X\text{-index}_r = \frac{(X_r - X_{\min})}{(X_{\max} - X_{\min})}$$

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

$$(7) VI_r = \frac{\text{Vulnerable sectors}_r + \text{Coastal population}_r + \text{Water availability}_r}{3}$$

¹⁰ 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.

¹¹ In the water vulnerability index, 1 person/1000 m³/year – the Falkenmark indicator of water scarcity (Rijsberman 2006; Falkenmark et al. 1989) – is substituted for X_{\max} in equation (6), and all regions with water availability less than 1000 m³/person/year are assigned an index of 1.0, the maximum level of vulnerability.

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:¹²

$$(8) \text{ Regional damage index}_{t,r} = \frac{VI_r^\alpha * \text{Output}_{t,r}}{\sum_r (VI_r^\alpha * \text{Output}_{t,r})}$$

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

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:

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

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 CO₂, 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; the base-year (2005) 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:¹³

$$(11) \text{ E-intensity}_{t,r} = \text{E-intensity}_{2005,r} \left(\text{ypc}_{t,r} / \text{ypc}_{2005,r} \right)^{-0.1}$$

$$(12) \text{ CO}_2 \text{ emissions}_{t,r} = \text{E-intensity}_{t,r} * \text{Output}_{t,r} + \text{LandUseCarbonFlux}_r - \text{Abatement}_{t,r}$$

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

Abatement is set to zero by definition 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.¹⁴

McKinsey data for each region and 11 economic sectors, downloaded from the McKinsey Climate Desk, were grouped into agriculture and forestry (“land-use” for short), versus all other

¹² A simpler and more intuitive version of this calculation, without the exponent (α) on the vulnerability index, can, in some scenarios, projected 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.

¹³ Note that Equation 11 corrects a mistaken formulation that had appeared in the three previously published versions of CRED.

¹⁴ McKinsey (n.d.), <https://solutions.mckinsey.com/climatedesk/>.

sectors (“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 the 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:

$$(13) \quad MC_q = Aq / (B - q)$$

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 :

$$(14) \quad q = Bp / (A + p)$$

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:

$$(15) \quad \text{CumCost}_q = Eq + Fq^2$$

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, after depreciation, remaining from the previous time period (10 years earlier).

$$(16) \quad \text{AbateInvest}_{t,r} = \text{CumCost}_{t,r} - (1 - \text{Depreciation})^{10} * \text{CumCost}_{t-1,r}$$

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.¹⁵

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.¹⁶ 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;¹⁷
- 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 CO₂ concentration) under a specified limit by an also specified date; alternatively, a minimum per capita consumption level can be specified, to be reached or exceeded in all regions by also specified future date.

¹⁵ 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.

¹⁶ CRED uses the CONOPT3 non-linear optimization solver, one of several offered by GAMS.

¹⁷ 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.

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:

$$(17) \quad \text{Utility} = \sum_{t,r} \frac{\text{population}_{t,r} * \ln(\text{cpc}_{t,r})}{(1+\rho)^{10t}}$$

The summation is over all regions and years; ρ is the rate of pure time preference, used for discounting utility. The default value of ρ 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) 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.

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

REFERENCES

- Ackerman, F. and Bueno, R. (2011) *Use of McKinsey Abatement Cost Curves for Climate Economics Modeling*. SEI Working Paper WP-US-1102. Stockholm Environment Institute-U.S. Center, Somerville, MA. <http://sei-us.org/publications/id/362>.
- Ackerman, F. and Stanton, E. A. (2011) 'Climate Risks and Carbon Prices: Revising the Social Cost of Carbon.' *Economics: The Open-Access, Open Assessment E-Journal*, 5(2011-40).
- Ackerman, F., Stanton, E. A. and Bueno, R. (2011) 'CRED: A new model of climate and development.' *Ecological Economics*, in press. doi:16/j.ecolecon.2011.04.006.
- Falkenmark, M., Lundqvist, J. and Widstrand, C. (1989) 'Macro-scale water scarcity requires micro-scale approaches.' *Natural Resources Forum*, 13(4). 258–67. doi:10.1111/j.1477-8947.1989.tb00348.x.
- Food and Agriculture Organization of the United Nations (n.d.) 'Aquastat.' <http://www.fao.org/nr/water/aquastat/main/index.stm>.
- Hanemann, W. M. (2008) *What Is the Economic Cost of Climate Change?* eScholarship. UC Berkeley, Berkeley, CA. http://repositories.cdlib.org/are_ucb/1071/.
- Heston, A., Summers, R. and Aten, B. (2011) *Penn World Table 7.0*. Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, Philadelphia, PA. http://pwt.econ.upenn.edu/php_site/pwt_index.php.
- Kamps, C. (2004) *New Estimates of Government Net Capital Stocks for 22 OECD Countries 1960-2001*. IMF Working Paper WP/04/67. International Monetary Fund, Kiel, Germany. <http://www.imf.org/external/pubs/ft/wp/2004/wp0467.pdf>.
- McKinsey & Company (n.d.) 'Climate Desk.' <http://solutions.mckinsey.com/climatedesk/>. [Accessed 19 October, 2011].
- Nehru, V. and Dhareshwar, A. (1993) 'A new database on physical capital stock: Sources, methodology and results.' *Revista de Analisis Economico*, 8(1). 37–59.
- Nordhaus, W. D. (2008) *A Question of Balance: Economic Modeling of Global Warming*. Yale University Press, New Haven, CT.
- Nordhaus, W. D. and Boyer, J. (2000) *Warming the World: Economic Models of Global Warming*. MIT Press, Cambridge, MA.
- Rijsberman, F. (2006) 'Water scarcity: Fact or fiction?' *Agricultural Water Management*, 80(1-3). 5–22. doi:10.1016/j.agwat.2005.07.001.
- Socioeconomic Data and Applications Center, Columbia University (2010) 'PLACE II: Population, Landscape, and Climate Estimates.' *National Aggregates of Geospatial Data Collection*. <http://sedac.ciesin.columbia.edu/place/>.
- Stern, N. (2006) *The Economics of Climate Change: The Stern Review*. Cambridge University Press, Cambridge, UK.

The World Bank (2008) *World Development Indicators 2008*. World Bank Publications, New York. <http://data.worldbank.org/indicator>.

United Nations Statistics Division (2010) 'National Accounts Main Aggregates Database.' December. <http://unstats.un.org/unsd/snaama/dnlList.asp>.

Weitzman, M. L. (2010) *GHG Targets as Insurance Against Catastrophic Climate Damages*. NBER Working Paper No. 16136. National Bureau of Economic Research, Cambridge, MA. <http://www.nber.org/papers/w16136>.

Wigley, T. M. L., Richels, R. and Edmonds, J. A. (1996) 'Economic and environmental choices in the stabilization of atmospheric CO₂ concentrations.' *Nature*, 379(6562). 240–43. doi:10.1038/379240a0.

World Resources Institute (2010) 'Climate Analysis Indicators Tool.' *CAIT 8.0*, 1 December. <http://cait.wri.org/>.