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Management Flight Simulators to Support Climate Negotiations: The C-ROADS Climate Policy Model

John D. Sterman[a, d], Thomas Fiddaman[b, d], Travis Franck[c, d], Andrew Jones[d],
Stephanie McCauley[d], Philip Rice[d], Elizabeth Sawin[d], Lori Siegel[d]

Abstract

Under the United Nations Framework Convention on Climate Change (UNFCCC) the nations of the world have pledged to limit warming to no more than 2°C above preindustrial levels. However, negotiators and policymakers lack the capability to assess the impact of greenhouse gas (GHG) emissions reduction proposals offered by the parties on warming and the climate. The climate is a complex dynamical system driven by multiple feedback processes, accumulations, time delays and nonlinearities, but research shows poor understanding of these processes is widespread, even among highly educated people with strong technical backgrounds. Existing climate models are opaque to policymakers and too slow to be effective either in the fast-paced context of policymaking or as learning environments to help improve people's understanding of climate dynamics. Here we describe C-ROADS (Climate-Rapid Overview And Decision Support), a transparent, intuitive policy simulation model that provides policymakers, negotiators, educators, businesses, the media, and the public with the ability to explore, for themselves, the likely consequences of GHG emissions policies. The model runs on an ordinary laptop in seconds, offers an intuitive interface and has been carefully grounded in the best available science. We describe the need for such tools, the structure of the model, and calibration to climate data and state of the art general circulation models. We also describe how C-ROADS is being used by officials and policymakers in key UNFCCC parties, including the United States, China and the United Nations.

Keywords: Climate change, climate policy, system dynamics, decision support, interactive simulation

[a] To whom correspondence should be addressed: MIT Sloan School of Management, 100 Main Street, Room E62-436, Cambridge MA 02139 USA. jsterman@mit.edu

[b] Ventana Systems, Bozeman, MT, USA

[c] MIT Sloan School of Management, Cambridge, MA, USA

[d] Climate Interactive, Washington DC, USA

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1. Introduction

In 1992 the nations of the world created the United Nations Framework Convention on Climate Change (UNFCCC), committing themselves to limiting greenhouse gas (GHG) emissions to prevent "dangerous anthropogenic interference in the climate system,"[1] which is generally accepted to mean limiting the increase in mean global surface temperature to no more than 1.5 - 2°C above preindustrial levels.[2] In 2007 the Intergovernmental Panel on Climate Change (IPCC) concluded, in its Fourth Assessment Report (AR4), that "Warming of the climate system is unequivocal" and "Most of the observed increase in global average temperatures since the mid-20th century is *very likely* due to the observed increase in anthropogenic GHG concentrations" (IPCC 2007, AR4 Summary for Policymakers, pp. 2, 5; emphasis in the original). Yet even as the scientific consensus has grown stronger, the prospects for action grow dimmer. The UNFCCC has, thus far, failed to produce an agreement sufficient to meet the 2°C goal (UNEP 2010) and, under the 2009 Copenhagen Accord, now seeks voluntary pledges from individual nations rather than a binding international treaty. However, the prospects for passage of policies that would limit emissions in key nations, including the United States, are poor.

To fulfill their mission negotiators and policymakers must be able to understand the dynamics of the climate and the relationship between emissions proposals and expected warming and other impacts. Historically, policymakers have had to rely on the results of the complex climate simulation models such as those used by the IPCC. Such models are essential in developing reliable scientific knowledge of climate change and its impacts, and are used to quantify the impact of and uncertainties in different scenarios for global GHG emissions (IPCC 2007, Edwards 2010). These models include advanced atmosphere-ocean general circulation models (AOGCMs) that include feedbacks among the biosphere, atmosphere and oceans.

However, although these models capture the best available scientific understanding of the climate, they are opaque and expensive. The cycle time for creating and running scenarios is too

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[1] unfccc.int/essential_background/convention/background/items/1349.php.

[2] The 2°C target was articulated in the Bali Declaration (www.climate.unsw.edu.au/news/2007/Bali.html). More recent statements by the UNFCCC Secretariat argue for no more than 1.5°C (unfccc.int/files/press/press_releases_advisories/application/pdf/pr20110606sbs.pdf).

long to be useful in the fast-paced environment of the UNFCCC negotiation process, government and executive briefings, and even for some purposes of the scientific community such as uncertainty analysis (IPCC 2007, WG1 Ch. 8-8). Consequently, the IPCC and others use Earth-system Models of Intermediate Complexity (EMICs) and Simple Climate Models (SCMs) as complements to the state-of-the-art AOGCMs. However, while EMICs and SCMs run quickly relative to the AOGCMs, they too are opaque and many still run far too slowly to be useful in in the negotiation process. Most importantly, existing models are generally neither available to nor usable by key constituencies including policymakers and negotiators, members of the media, educators, businesses, civil society and the general public.

Consequently, negotiators and other parties are forced to rely on their intuition to assess the likely impacts of proposals. However, intuition, even among experts, is highly unreliable when applied to understanding how proposals for emissions reductions affect likely future atmospheric GHG concentrations, temperatures, sea level, and other climate impacts.

First, the proposals offered by different nations in climate negotiations make different assumptions about future population and economic growth and are framed in incompatible terms, for example, changes in emissions relative to a base year or relative to a business-as-usual scenario; changes in emissions or in the emissions intensity of the economy or in emissions per capita. At a 2009 UNFCCC meeting in Bonn,

> "...delegates complained that their heads were spinning as they were trying to understand the science and assumptions underlying the increasing number of proposals tabled for Annex I countries' emission reduction ranges. "They all seem to use different base years and assumptions: how can we make any sense of them?" commented one negotiator." (Negotiations Bulletin, 9 April 2009, www.iisd.ca/vol12/enb12403e.html).

Second, decision makers should consider the impact of uncertainty, requiring multiple simulations of climate models under different assumptions, while decades of research show widespread errors and biases in people's intuitive ability to assess uncertainty (e.g., Kahneman, Slovic, and Tversky 1982, Kahneman and Tversky 2000, Gilovic, Griffin and Kahneman 2002).

Third, and perhaps most important, our mental models lead to pervasive, systematic and consequential errors in our assessments of likely climate dynamics (Sterman 2011, 2008;

Sterman and Booth Sweeney 2007, 2002; Moxnes and Saysel 2009). These errors are caused neither by poor training in science nor by the complexity of the climate: even highly educated people with significant training in Science, Technology, Engineering or Mathematics (STEM) consistently err in understanding much simpler and more familiar systems such as bathtubs, bank accounts and compound interest (Booth Sweeney and Sterman 2000, 2007, Cronin, Gonzalez and Sterman 2009, Brunstein *et al.* 2010). The research documents widespread, robust difficulties in understanding processes of accumulation (stocks and flows), feedback, time delays and nonlinearities (Sterman 1994), all of which are important in understanding the dynamics of the climate-economy system. Common errors include violations of mass balance, use of correlational reasoning, use of open-loop mental models that omit basic feedbacks, and linear projections of exponential processes. Because these errors are not the consequence of unfamiliarity with climate science they cannot be corrected simply by presenting people with more information on climate change, nor with graphs and tables showing the results of models. Interactive learning, through which people can use simulation models as “management flight simulators” to discover, for themselves, how complex systems behave is required to improve people’s mental models (Corell *et al.* 2009, Sterman 2010, 2000; Morecroft and Sterman 1994).

Poor understanding of the relationship between GHG emissions and their likely climate impacts not only afflicts the public, but the negotiators themselves. In 2008, Christiana Figueres, then lead negotiator for Costa Rica, and named to lead the UNFCCC in 2010, commented

> “Currently, in the UNFCCC negotiation process, the concrete environmental consequences of the various positions are not clear to all of us….There is a dangerous void of understanding of the short and long term impacts of the espoused …unwillingness to act on behalf of the Parties” (personal communication, Sept. 2008).

The C-ROADS (Climate Rapid Overview And Decision Support) model is designed to address these issues. The purpose of C-ROADS is to build shared understanding of climate dynamics and the risks of climate change, in a way that is solidly grounded in the best available science and rigorously nonpartisan, but that is simultaneously accessible to, understandable by, and useful to policymakers, negotiators, business leaders, educators, and the public at large. Without such a capability, the most technically advanced models and analysis have little impact.

The C-ROADS model provides a capability to assess proposals for emissions abatement at the level of individual nations or regional blocs. The model provides estimates of the likely impacts of these policies consistent with the best available science. The choice of policy is entirely up to the user. Users are free to create any emissions scenarios they wish for their own nation and those of others, based on their assessment of the risks of climate change, the costs of abatement, geopolitical strategy, and equity across nations and generations.

C-ROADS has several attributes that make it useful for a scientifically objective and commonly shared climate policy design and assessment platform. C-ROADS:

- is based on the best available peer-reviewed science and calibrated to state-of-the-art large scale climate models;
- tracks the Kyoto greenhouse gases, including CO_2, CH_4, N_2O, SF_6, halocarbons, aerosols and black carbon;
- distinguishes emissions from fossil fuels from deforestation/afforestation (REDD+) impacts;
- allows users to select from a number of different scenarios for business as usual, and to define their own scenarios;
- reports the resulting atmospheric CO_2 and CO_2e concentrations, global mean temperature change, sea level rise, per capita emissions, and cumulative emissions for the scenarios defined by the user;
- is easy to use, running on a laptop computer in seconds so users immediately see the impact of national or regional emissions reduction proposals;
- allows users to assess the impact of uncertainty in climate processes such as climate sensitivity, climate-carbon cycle feedbacks, and sea level rise from ice sheet dynamics;
- allows users to perform attribution experiments, and identify national and regional contributions to climate change;
- is fully documented, with all equations and assumptions available to all users.

C-ROADS is used in policy making and scenario testing by senior legislators and their staff, environment ministers and their advisors, the UN, CEOs, and climate policymakers in the US and China. It facilitates validity testing of scenarios created by other parties, and provides an independent, neutral process to ensure that different assumptions and scenarios can be made available to all parties. C-ROADS is also used in education, through *World Climate,* an interactive role-play simulation of the UNFCCC negotiations (Sterman *et al*. 2011). C-ROADS is available, at no cost, through climateinteractive.org.

Here we describe the structure of and data sources for the C-ROADS model and compare its behavior to data and to simulations of an ensemble of the large climate simulation models used by the IPCC and others. We describe how C-ROADS is being used by key UNFCCC parties, including the United States, China and the United Nations. To illustrate, we use the model to evaluate current proposals for emissions reductions offered by the nations of the world under the 2009 Copenhagen Accord, showing that current proposals fall short of what is required to limit warming to no more than 2°C above preindustrial levels. We close with discussion of model limitations and potential extensions.

2. Model structure

C-ROADS is a continuous time compartment (box) model of the greenhouse gas cycles and climate. C-ROADS includes an explicit carbon cycle, the budget for and atmospheric stocks of other GHGs, radiative forcing, global mean surface temperature, sea level rise and surface ocean pH (Fig. 1). The simulation begins in 1850 and is driven by historical emissions through the present day. Users provide scenarios for CO_2 and other GHG emissions from the present through 2100 for individual countries and regional blocs. Emissions can be specified at different levels of aggregation, including global totals, or 3, 6, or 15 different nations and regional blocs.

2.1 Carbon cycle

The core carbon cycle and climate sector of C-ROADS evolved from the FREE (Feedback Rich Energy-Economy) model developed by Fiddaman (1997, 2002, 2007). The carbon cycle is a one-dimensional compartment (box) model based on Goudriaan and Ketner (1984) and Oeschger *et al.* (1975) and similar to other widely used SCMs (Simple Climate Models) and EMICS (Earth-system Models of Intermediate Complexity) such as those in Nordhaus 1992, Socolow and Lam 2007, and Solomon *et al.* 2009, 2010.

Fig. 2 shows the structure of the model carbon cycle. Atmospheric CO_2 is increased by anthropogenic emissions, by oxidation of atmospheric methane, by natural emissions from the biosphere and CO_2 exchange with the ocean. CO_2 is removed from the atmosphere as it dissolves in the ocean and is taken up by biomass through net primary production. Biomass leads to flux of carbon into atmospheric CO_2 and CH_4 stocks. C-ROADS couples the atmosphere-mixed ocean layer interactions and net primary production of the Goudriaan and Ketner (1984) and IMAGE 1.0 models (Rotmans 1990) with a diffusive ocean based on Oeschger *et al.* (1975). Goudriaan and Ketner (1984) and the IMAGE model (Rotmans 1990) have detailed biospheres, partitioned into leaves, branches, stems, roots, litter, humus, and charcoal. To simplify, we aggregate these categories into two compartments: stocks of biomass (leaves, branches, stems, roots) and humus (litter, humus), both with first-order kinetics. The results are reasonably consistent with other partitions of the biosphere and with the one-compartment biosphere of Oeschger *et al.* (1975) and Bolin (1986).

Net primary production (NPP), the flux from the atmosphere to biomass, grows logarithmically with atmospheric CO_2 (Wullschleger *et al.* 1995), and is also negatively affected by temperature (Friedlingstein *et al.* 2006). We specify:

$$NPP = NPP_0(1 + \beta_C \ln(C_a / C_{a_0}))(1 - \beta_{T_L} \Delta T) \qquad (1)$$

where NPP and NPP_0 are current and initial net primary production, C_a and C_{a_0} are the current and initial stocks of carbon in the atmosphere, β_C is the strength of the CO_2 fertilization feedback, β_{T_L} is the strength of the temperature effect on NPP and ΔT is the temperature increase relative to initial (preindustrial) levels.

The dependence of NPP on temperature captures an important climate-carbon cycle feedback. The IPCC reported in AR4 that “Assessed upper ranges for temperature projections are larger than in the TAR [Third Assessment Report]…mainly because the broader range of models now available suggests stronger climate-carbon cycle feedbacks” (IPCC 2007, WG1 Summary for Policymakers, p. 13). Those positive feedbacks add 20-224 ppm to atmospheric CO_2 concentrations in 2100 under the SRES A2 scenario compared to models without such feedbacks (IPCC 2007, WG1, p. 501; see also Friedlingstein *et al.* 2006). However, the IPCC also noted “Models used to date do not include uncertainties in climate-carbon cycle feedback… because a basis in published literature is lacking” (WG1 SPM, p. 14). Since the effect of warming on NPP is poorly constrained by the data we assume a simple form for the temperature feedback: the term $(1 - \beta_{T_L}\Delta T)$ reduces NPP relative to what it otherwise would be, with an effect that is linear in the temperature increase. The linear effect can be thought of as the first term in the Taylor series approximation to the full, nonlinear impact of ΔT on NPP, an approximation that is valid for small values of $\beta_{T_L}\Delta T$.

The equilibrium concentration of carbon in the mixed layer of the ocean depends on the atmospheric concentration and the buffering effect in the ocean created by carbonate chemistry, $CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^= + 2H^+$.
The equilibrium concentration of dissolved inorganic carbon in the mixed layer, C_m, is

$$C_m = C_{m^*}\left(\frac{C_a}{C_{a_0}}\right)^{\frac{1}{\zeta}} \tag{2}$$

where C_{m^*} is the reference carbon concentration in the mixed layer, C_a and C_{a_0} are the actual and initial concentrations of atmospheric carbon, and ζ is the buffer or Revelle factor. The Revelle factor is typically about 10. As a result, the partial pressure of CO_2 in the ocean rises about 10 times faster than the total concentration of carbon (Fung, 1991): the ocean, while it initially contains about 60 times as much carbon as the preindustrial atmosphere, behaves as if it were only 6 times as large. The concentration of carbon in the mixed layer is assumed to adjust to its equilibrium value with a time constant of 1 year. The buffer factor ζ rises with atmospheric CO_2 (Goudriaan and Ketner 1984, Rotmans 1990): the ocean's marginal capacity to store CO_2 diminishes as the atmospheric concentration rises:

$$\zeta = \zeta_0 + \delta_b \ln\left(\frac{C_a}{C_{a_0}}\right) \tag{3}$$

where ζ_0 is the reference value of the Revelle factor and δ_b is the sensitivity of ζ to atmospheric CO_2 relative to its initial concentration.

The solubility of CO_2 in seawater also depends negatively on temperature (Fung 1991), forming another potentially important climate-carbon cycle feedback. As with the effect of temperature on NPP, we approximate the effect with a linear function of temperature increase relative to preindustrial levels,

$$C_{m^*} = C_{m_0}(1 - \beta_{T_O}\Delta T) \tag{4}$$

where C_{m_0} is the initial concentration of carbon in the mixed layer and β_{T_O} is the sensitivity of the equilibrium carbon concentration in the ocean to temperature.

The ocean is represented by a five-layer eddy-diffusion structure based on Oeschger *et al.* (1975). C-ROADS employs a 100 meter mixed layer, and deep layers of 300, 300, 1300 and 1800 m (for an average ocean depth of 3800 m). The net flux of carbon from layer i to j is

$$\frac{dC_{ij}}{dt} = e(C_i / d_i - C_j / d_j) / \langle d_{ij} \rangle \tag{5}$$

where d_i is the thickness of layer i, $<d_{ij}>$ is the mean thickness of layers i, j, and e is the eddy diffusion parameter. Simulation experiments show there is no material difference in the atmosphere-ocean flux between the five-layer ocean and more disaggregate structures, including an 11-layer ocean, at least through the model time horizon of 2100.

We calibrate the temperature feedback parameters on NPP and ocean uptake, β_{T_L} and β_{T_O}, to yield values consistent with Friedlingstein *et al.* (2006). The joint impact of these temperature feedbacks raises atmospheric CO_2 by 42 ppm in 2100 for the A2 scenario, towards the lower end of the 20-200 ppm range in Friedlingstein *et al.* (2006). Users may vary the strength of the temperature-carbon cycle feedbacks and receive immediate results (Fig. 5).

2.2 Other GHGs

C-ROADS explicitly models the budgets and atmospheric stocks of other well–mixed GHGs, including methane (CH_4), nitrous oxide (N_2O), SF_6 and other fluorinated gases (PFCs and HFCs). The atmospheric lifetimes of the PFCs are very long relative to the time horizon of C-ROADS so these are aggregated into a single compartment weighted by their CF_4-equivalents. The lifetimes of the HFCs, on the other hand, are shorter and more diverse, so we represent the nine most important species of HFC individually, each with its own budget, atmospheric stock and lifetime. The model includes natural fluxes of CH_4, N_2O and the PFCs (specifically, CF_4); these are estimated from the MAGICC model (Meinshausen *et al.* 2008, Wigley 2008). Atmospheric lifetimes and radiative forcing coefficients are from IPCC AR4, WG1, Table 2.14.

Temperature not only affects emissions and uptake of CO_2, but also affects the methane cycle. Total methane emissions, E, consist of anthropogenic and natural fluxes, E^A and E^N:

$$E = E^A + E^N \tag{6}$$

$$E^N = E_0^N(1 + \beta_M \Delta T) + \beta_P MAX(0, \Delta T - \Delta T^*) . \tag{7}$$

C-ROADS includes two feedbacks to natural methane emissions. First, higher temperatures increase anaerobic bacterial respiration in from tropical, temperate and boreal forests, peat bogs, and other biomes, increasing CH_4 release above the preindustrial rate E^N_0, with a sensitivity determined by β_M. Second, warming accelerates release of CH_4 through melting of permafrost and potential outgassing of methane clathrates and hydrates. We assume that emissions from permafrost and clathrates are nonlinear, with zero impact when ΔT is below a threshold, ΔT^*, then rising linearly with temperature with impact β_P. The gain of these feedbacks and the nonlinear threshold for the permafrost and clathrate effect are poorly constrained by data. We conservatively set the gain of these effects to zero, meaning C-ROADS, like other models that omit these poorly understood feedbacks, likely underestimates future temperature increases and other climate change impacts for any given emissions scenario. To explore the impact of these feedbacks, users may set the values for these parameters and receive immediate results (Fig. 5).

Sulfate aerosols and black carbon are short-lived so we do not model their atmospheric concentrations as explicit stock and flow structures. The net contribution to radiative forcing from aerosols and black carbon are therefore treated as exogenous inputs, under user control.

C-ROADS also includes the contribution to radiative forcing arising from the gases regulated under the Montreal Protocol (chlorofluorocarbons). We optimistically assume that emissions of these gases will follow the limits set by the Montreal Protocol, as amended. The resulting concentrations and contribution to forcing are therefore treated exogenously, using data and projections from Bullister (2009), Daniel *et al.* (2007), and Hansen *et al.* (1998).

2.3 Radiative forcing

Global mean surface temperature is determined by the heat content of the surface and mixed layer of the ocean (treated as a single compartment, H_m). The rate of change in the heat content of that layer is net radiative forcing from all GHGs and other sources, F_T, less the long wave radiation to space, R, less net heat transfer from the atmosphere and surface ocean to the top layer of the deep ocean dH_{md_1}/dt:

$$\frac{dH_m}{dt} = F_T - R - \frac{dH_{md_1}}{dt} \tag{8}$$

$$F_T = F_{CO_2} + F_{other} \tag{9}$$

Heat transfer across ocean layers is analogous to the flux of carbon (eq. 5). Radiative forcing from CO_2 rises logarithmically with its concentration:

$$F_{CO_2} = \gamma \ln\left(\frac{C_a}{C_{a_0}}\right) \tag{10}$$

where C_a and C_{a_0} are the current and initial CO_2 levels in the atmosphere and γ is the forcing from CO_2 at the initial concentration. We assume the flux of long wave radiation to space is linear in temperature, a reasonable approximation over the range of variation in ΔT across scenarios, at least through the model time horizon of 2100:

$$R = \frac{\gamma \ln 2 \Delta T}{S} \tag{11}$$

where S is climate sensitivity, the temperature increase in equilibrium resulting from a doubling of CO_2 relative to the preindustrial level. $S = 3°C$ in the base case, but users can easily vary it in sensitivity testing (Fig. 5).

Radiative forcing from sources other than CO_2, F_{other}, includes the contributions from CH_4, N_2O, SF_6, the PFCs, HFCs and Montreal Protocol gases, sulfate aerosols, black carbon, and changes in insolation and global average albedo. Net forcing from CH_4 and N_2O is less than the sum of their individual contributions due to their overlapping absorption spectra. Forcings from changes in insolation, volcanoes, and albedo are included using the GISS data for the historical period (Hansen *et al.* 1998, 2005, as updated) and user-defined scenarios for the future. Note that although net forcing is computed explicitly from the concentrations of each GHG, aerosols, black carbon, and other sources, for convenience, C-ROADS also provides graphs and tables showing total CO_2 equivalent (CO_2e) emissions and concentrations using the 100-year GWP values for the non-CO_2 gases.

2.4 Climate Change Impacts: Sea Level Rise and Ocean Acidification

C-ROADS estimates sea level rise (SLR) using the model in Vermeer and Rahmstorf (2009), which augments the original Vermeer (2007) semi-parametric model. As discussed in Vermeer and Rahmstorf (2009), their estimates of the sensitivity of SLR to warming are based on the SLR observed in the historical record and therefore capture the impact of thermal expansion and reductions in terrestrial ice mass observed to date, but may underestimate future contributions to SLR due to the possibility of a nonlinear increase in ice discharge from the Greenland and Antarctic ice sheets with higher temperatures. Accelerated ice discharge could be caused, for example, by positive feedbacks among the glacier grounding line, melting, and ocean circulation (Rignot and Jacobs 2002, Pritchard *et al.* 2009, Jacobs *et al.* 2011). We include this possibility through a user-defined sensitivity parameter. Thus the rate of change in SLR is

$$\frac{dSLR}{dt} = (\alpha_0 + \beta_I)(\Delta T - \Delta T_0) + \alpha_1 \frac{d\Delta T}{dt} \tag{12}$$

where ΔT_0 is the temperature at which sea level is in equilibrium with the climate, α_1 and α_2 are the effects of warming and the rate of change of warming estimated in Vermeer and Rahmstorf (2009), and β_I is the additional rate of increase in sea level per °C from ice discharge not captured in the historical data. By definition, $\beta_I = 0$ prior to the present time; users can set any value for the future in sensitivity tests (Fig. 5).

Explicit modeling of ocean pH is complex. Bernie *et al.* (2010) found a third-order polynomial function of atmospheric CO_2 concentration provides a good approximation to the pH of the mixed layer using a simple model of ocean chemistry and the HadCM3LCGCM model, up through atmospheric CO_2 level of at least 1000 ppm. We use their polynomial approximation to estimate the pH of the mixed layer.

2.5 GHG emissions scenarios

To fulfill its purpose as an aid to policymakers, C-ROADS offers users the ability to specify scenarios for future GHG emissions at multiple levels of aggregation. Users provide scenarios for anthropogenic CO_2 emissions, emissions of other GHGs, and assumptions about emissions from REDD+ policies (Reductions in Emissions from Deforestation and Land Degradation) and future afforestation programs for individual nations or groups of nations.

Users select the level of regional aggregation for emissions and can switch among levels of aggregation at any time. Currently, users may choose to provide emissions inputs for one, three, six, or fifteen different nations and blocs of nations (Table 1). For example, the six-party option specifies emissions for China, the European Union, India, the United States, all other developed economies, and all other developing countries. Historical and projected population, real GDP, and GHG emissions are drawn from Assadoorian *et al*. (2006), Boden *et al*. (2010), Houghton (2006), Maddison (2008), Mayer *et al*. (2000), Olivier and Berdowski (2001), Stern and Kaufmann (1998), and van Aardenne *et al*. (2001).

The model provides graphical and tabular output and reports for each level of aggregation, including, globally and for each nation or bloc, emissions and cumulative emissions, emissions per capita, the emissions intensity of the economy (tCO_2 per dollar of real GDP), and each nation's or bloc's share of global emissions and cumulative emissions. The model reports these metrics for both CO_2 and CO_2e emissions and concentrations.

Users can choose from a wide range of scenarios for business as usual (BAU) developed by the IPCC and others, including the IPCC SRES A1FI, A1B, A1T, A2, B1, and B2 scenarios (Nakicenovic and Swart 2000) and nine scenarios from EMF22 (Clarke *et al*. 2009). Users can also specify their own scenario.

Users can enter future emissions for each nation or bloc in one of three modes: as a table with graphical display from within the C-ROADS software, from an Excel spreadsheet, or manually. In the manual mode, users choose when the policy starts, then specify emissions, for each nation or bloc, in three user-selected target years. For example, a user might specify that the policy begins in 2015, then provide values for emissions for the years 2020, 2050 and 2100. Users also have a variety of options in specifying how emissions are set in each target year, including:

1. relative to a user-selected base year value such as 1990 or 2005 (e.g., emissions in 2020 will be 18% below the 2005 value);
2. relative to the reference scenario (e.g., emissions in 2020 will be 30% below the projected BAU value for that year);
3. relative to the carbon intensity of the economy of that nation or bloc (e.g., emissions in 2020 will reflect a 45% reduction in the carbon intensity of the economy relative to 2005);
4. relative to the per capita emissions of that nation or bloc (e.g., emissions in 2050 will reflect 10% growth in emissions per capita over the 2005 level for that nation or bloc).

Input modes, target years and emissions in each target year can be different for each nation and bloc. For example, one can set emissions for the US to be 17% below the 2005 value by 2020 and at the same time specify the emissions for China to capture a 45% reduction in China's emissions intensity by 2020. The variety of emissions input modes, targets and target years gives users maximum flexibility in representing the proposals of different nations in the form those nations present them, despite the use of targets presented relative to different reference years, different reference scenarios, and using different metrics such as absolute emissions, emissions intensity of the economy, or emissions per capita.

2.6 User Interface

The C-ROADS user interface is designed for ease of use and to enable rapid experiments with different policies and parameters. Fig. 3 shows the main screen, through which users can select the level of aggregation, the reference scenario, load prior simulations, control display options, and access instructions, a video tutorial on model use, full model documentation and technical reference, interactive diagrams of model structure, and other information giving them full access to the model assumptions. Users can also review prior simulations, carry out Monte-Carlo simulations to assess the sensitivity of results to uncertainty in any parameters, using predefined or user-defined parameter sets, and analyze the impact of any one nation's proposals to global outcomes via a contribution analysis in which a given scenario is run again with that nation's or bloc's contribution set to the BAU case in effect for that scenario.

Once users select the level of aggregation and reference scenario, the model presents the screen shown in Fig. 4. Here users define emissions pathways for each nation and bloc, as described in section 2.5, including pathways for emissions of CO_2 from fossil fuels, from REDD+ and afforestation policies, emissions of other GHGs, and other forcings, including aerosols, black carbon, and changes in insolation and surface albedo.

Users can select from dozens of graphs and tables to display, by nation/bloc or globally, population and GDP, emissions of CO_2 and other gases, emissions per capita, the emissions intensity of the economy, and other inputs, along with outputs including CO_2 and CO2e concentrations, CO_2 removal from the atmosphere, global mean surface temperature, sea level rise, ocean pH, and other indicators. Users can easily save simulations for later analysis, and export the graphs and tables of results to other applications.

The interface also offers an interactive sensitivity analysis capability (Fig. 5). Here users can alter the values of key parameters, one at a time or in combination, and get immediate results showing how GHG concentrations, warming, sea level rise and ocean pH are affected by alternative assumptions. The interactive sensitivity analysis feature is complementary to the formal Monte-Carlo sensitivity analysis capability available via the main screen. Through interactive experimentation with the values of key parameters users improve their understanding of climate dynamics and the response of the climate to key uncertainties in a way that puts them in control of their own learning and builds intuition better than merely examining confidence bands or probability distributions in static reports. The sensitivity option allows users to vary parameters including climate sensitivity, the strength of CO_2 fertilization, the eddy diffusion process that moves carbon and heat from the surface to the deep ocean, and the strengths of climate-carbon cycle feedbacks including impacts of warming on net primary production, ocean CO_2 uptake, enhanced methanogenesis from increased bacterial and fungal respiration with warming, and methane release from clathrates and melting of permafrost.

3. Fit to Data and Model Intercomparison

C-ROADS simulations begin in 1850. The model is driven by historic emissions of CO_2 and other GHGs, and includes the GISS time series for forcing arising from volcanoes and other non-GHG sources (available from 1880). Fig. 6 and Table 2 compare the behavior of C-ROADS to data for the period 1850-2010, including CO_2 and CH_4 concentrations, global mean surface temperature, and sea level. The model tracks the historical evolution of the climate well. For example, for CO_2 concentration, $R^2 = 0.995$ with a Mean Absolute Percent Error (MAPE) of 0.63% and Root Mean Square Error (RMSE) of 2.25 ppm. The bias (Theil U^M) is 2% and most of the MSE arises from unequal covariation, Theil U^C, (point-by-point differences between simulated and actual values). The fit for the temperature anomaly, ΔT, is also good, with RMSE = 0.13°C and low bias. Nearly all of the MSE is concentrated in U^C and arises from the year-by-year variations in temperature in the data not captured by the model. The fits for CH_4 and sea level rise also exhibit low RMSE and bias.

To test the parameterization of C-ROADS further, we also compare its behavior to the projected behavior of more comprehensive AOGCMs. Fig. 7 and Table 3 compare C-ROADS to the temperature projections reported in AR4 across a range of SRES scenarios. The projected temperature in 2100 matches the AR4 outcomes with an average error of less than 0.1°C over a wide range of future emissions paths, from the carbon-intensive world of A1FI to the low emissions world of B1. The differences between the AR4 and C-ROADS values are all well within the *likely* (66% chance) range of AR4 model outcomes. Similarly, Fig. 8 shows close agreement between C-ROADS and MAGICC for A1FI, A1B, and B1 between 2000-2100. Compared to MAGICC, C-ROADS slightly underestimates warming for A1FI and overestimates it for B1, but the RMSE is less than 0.1°C in all three cases. Note that the AR4 and MAGICC projections differ for the same scenarios, so it is not possible to fit both exactly. For example, C-ROADS is about 0.1°C high relative to the AR4 projection for A1FI (Fig. 7) but 0.1°C low relative to MAGICC projection (Fig. 8). The discrepancy between AR4 and MAGICC has been noted by the IPCC, although the source remains unclear.

The full model documentation (see climateinteractive.org) compares C-ROADS to historical data for N_2O, other GHGs, and radiative forcing, and presents additional model intercomparison tests against other scenarios and other models, including MAGICC, BERN (Joos *et al*. 2001) and ISAM (Kheshgi and Jain 2003).

4. Applications

C-ROADS is used by a variety of negotiators, policymakers, scientists, business leaders, educators and others. Senior members of the US government, including legislators and members of the executive branch have used C-ROADS. The US Department of State Office of the Special Envoy for Climate Change uses C-ROADS to analyze proposals made by various nations under the UNFCCC process, the Major Economies Forum on Energy and Climate, and other bilateral and multilateral negotiations. They have developed an in-house capability to use the model. Dr. Jonathan Pershing, the Deputy Special Envoy, commented

> "The results [of C-ROADS] have been very helpful to our team here at the U.S. State Department….The simulator's quick and accurate calculation of atmospheric carbon dioxide levels and temperatures has been a great asset to us. …I have made use of the results in both internal discussions, and in the international negotiations…." (personal communication).

Former staff member, Dr. Benjamin Zaitchik, elaborates:

> "It's quite important for us to discuss emissions reduction goals in terms of climate response; policy makers and negotiators need to have a reasonable sense of what a particular action will mean for global climate, when considered in the context of other

> actions and policies around the world. Previously, we would make these calculations offline. We'd download emissions projections from a reliable modeling source, input them to an excel spreadsheet to adjust for various policy options, and then enter each proposed global emissions path into a model like MAGICC to estimate the climate response. This method worked, but it was time consuming and opaque: in the end we had a set of static graphs that we could bring into a meeting, but we couldn't make quick adjustments on the fly. With C-ROADS, we can adjust policy assumptions in real-time, through an intuitive interface. This makes it much easier to assess the environmental integrity of various proposed emissions targets and to discuss how complementary emissions targets might achieve a climate goal, or to evaluate how changes in an emissions targets might affect global temperature through the 21st century" (personal communication).

C-ROADS is also used in China, through Tsinghua University, where it has been disaggregated to include drivers of CO_2 emissions at the provincial level using assumptions about total energy use and fuel mix.

C-ROADS analysis was included in a United Nations Environment Program assessment of "the emissions gap" (UNEP 2010). The gap is the difference between global GHG emissions resulting from the current pledges offered by the nations of the world under the Copenhagen Accord and the emissions reductions needed to limit expected warming to 1.5-2°C above preindustrial levels. The study found

> A "gap" is expected in 2020 between emission levels consistent with a 2° C limit and those resulting from the Copenhagen Accord pledges. The size of the gap depends on the likelihood of a particular temperature limit, and how the pledges are implemented. If the aim is to have a "likely" chance (greater than 66 per cent) of staying below the 2° C temperature limit, the gap would range from 5-9 $GtCO_2e$, depending on how the pledges are implemented.

Where UNEP (2010) reports the gap only through 2020, the C-ROADS gap analysis shows that, while emissions between now and 2020 are important, emissions after 2020 largely determine the level of warming and other climate impacts. As seen in Fig. 9, there is a large and growing gap after 2020 between emissions under the confirmed proposals and the emissions path needed limit expected warming to the 1.5-2°C goal. With all confirmed proposals to date, emissions fall below the BAU path and nearly stabilize by 2080. However, emissions remain far above the rate at which GHGs are removed from the atmosphere, so concentrations continue to rise, reaching 1125 ppm CO_2e by 2100. The steady increase in concentrations pushes expected temperature increase to 4.3°C above preindustrial levels by 2100 (compared to the BAU value of

5°C), raises sea level 1.22 meters above the year 2000 value, and lowers the pH of the mixed layer of the ocean to roughly 7.8. Fig. 9 and Table 3 also show the projected impacts of all potential proposals to date (potential proposals include proposals a nation has discussed but are not formal pledges, or that are conditional on actions by other nations). Assuming all confirmed and potential proposals are fully implemented roughly stabilizes GHG emissions near current rates of approximately 50 $GtCO_2e$/year. However, because emissions remain higher than the net removal of GHGs from the atmosphere, GHG concentrations reach 674-726 ppm CO_2e (depending on whether the declines specified in the proposals continue after the pledge time horizon ends). Even with the full implementation of all potential proposals, expected warming remains approximately 3°C, sea level rises more than one meter, and the pH of the mixed layer drops to about 7.9. To limit expected warming to the 2°C target, emissions must fall approximately 90% below the BAU path by 2050 (73% below 2005 levels). Nevertheless, the additional warming leads to nearly 0.9 meters of sea level rise and lowers the pH of the mixed layer to about 8 by 2100.

The results in Fig. 9 and Table 3 are optimistic as they assume the base case climate sensitivity of 3°C, the relatively low gain of the temperature-CO_2 feedbacks described above, zero gain for the impact of temperature on CH_4 emissions, including zero additional emissions from melting permafrost or clathrates, and no increase in sea level from accelerating ice sheet loss with rising temperatures.

The climate scoreboard simulation is made available in the model and via the interactive "Climate Scoreboard" widget (Fig. 10; climatescoreboard.org). The size of the emissions gap changes, and the scoreboard is updated, with new and revised pledges, and as scientific understanding of climate dynamics improves.

C-ROADS is also used in education. It is the core model in the Climate CoLab (Malone, Abelson, Karger, Klein and Sterman 2011), which "seeks to harness the collective intelligence of contributors from all over the world to address global climate change" (climatecolab.org). Open to anyone with Internet access, teams can create proposals to address the risks of climate change, simulate their proposals using C-ROADS and other models, and debate the merits of each proposal. People can also run C-ROADS experiments in C-Learn, the simplified, 3-region online version of the simulation (climateinteractive.org).

C-ROADS is also used in an interactive role-play simulation of the global climate negotiations entitled *World Climate* (Sterman *et al*. 2011). Participants play the roles of major GHG emitting nations and negotiate proposals to reduce emissions, using C-ROADS to provide immediate feedback on the implications of their proposals for atmospheric GHG concentrations, changes in global mean surface temperature, sea level rise and other impacts. The negotiation role-play enables participants to explore the dynamics of the climate and impacts of proposed policies in a way that is consistent with the best available peer-reviewed science but that does not prescribe what should be done. *World Climate* has been used successfully with diverse groups, including students, business executives and political leaders.

5. Limitations and extensions

C-ROADS has proven to be a useful tool enabling decision-makers and other leaders to quickly assess important climate impacts of particular national, regional or global emissions scenarios. Like all models, C-ROADS has limitations that present opportunities for extensions. These include three main areas: (i) enhancements to the structure of the carbon cycle and climate, (ii) inclusion of additional climate impacts, and (iii) expansion of the model boundary to include determinants of energy use and GHG emissions.

The modeling philosophy we follow is to ensure that the structure and assumptions of C-ROADS represent accepted, peer-reviewed science. Thus, as described above, we include a variety of climate-carbon cycle feedbacks, but set the gains of these feedbacks to zero in the base case because they are, at present, poorly constrained by data. Similarly, we conservatively assume no acceleration in ice discharge from Greenland or Antarctica ice sheets beyond what has been observed to date in the historical record. Consequently, C-ROADS is likely to underestimate future warming, sea level rise, and other impacts. However, users are able to test any values they wish for these feedbacks. We revise the model as knowledge of climate-carbon cycle feedbacks and ice sheet dynamics improves.

A second category of potential enhancement is inclusion of a broader array of climate impacts, including the effects of a warming world on water availability, agricultural production, species extinction, extreme weather events, human health, and more. Many such impacts exhibit significant spatial heterogeneity. However, C-ROADS, like other one-dimensional SCMs, cannot provide information on impacts at regional or subregional scales. It may be possible to link the output of C-ROADS to more detailed spatially resolved impact estimates derived from AOGCMS and other models. Such downscaling would need to be done in a computationally efficient fashion to preserve the ability of C-ROADS to run nearly instantly on ordinary laptop machines. We are exploring ways to couple C-ROADS to downscaled results.

A third category is expansion of the model boundary so that GHG emissions are determined endogenously. The original FREE model upon which C-ROADS is based (Fiddaman 1997, 2002, 2007), although far simpler, did constitute a global integrated assessment model, including endogenous economic growth, energy production and costs, and a climate damage function. However, these issues are poorly constrained by data and contentious (e.g., Weitzman 2009). Hence C-ROADS takes future population, economic growth, and GHG emissions as scenario inputs specified by the user and omits the costs of policy options and climate change damage. Many C-ROADS users, particularly those involved in negotiations, value the ability to specify pledges and proposals exogenously. But GHG emissions are not under the control of policymakers; they result from complex interactions of energy demand, production, prices, technology, learning and scale economies, regulations and government policies.

To address these issues, we have developed a new model, En-ROADS, that endogenously generates energy use, fuel mix, and CO_2 emissions. Energy production and consumption, by fuel type, are determined by stocks of energy producing and consuming capital. The model includes construction and planning delays for the development of new energy sources, and the possibility of retrofits and early retirement for existing capital stocks. The costs of each energy source are endogenous, including depletion of fossil fuel resources that increases marginal costs, and the impact of R&D, learning curves, scale economies, and other feedbacks that can lower costs. As in C-ROADS, En-ROADS simulates essentially instantly on an ordinary laptop and enables users to implement a wide range of policies including carbon prices, subsidies for specific technologies, and assumed major technical breakthroughs. Users can also try any values they wish for key parameters such as the strength of experience curves, the lifetimes and construction times for new plant, and so on. At the moment the two models are separate to maximize transparency and computation speed. Ultimately they may be integrated. The combination of C-ROADS, which shows the likely impacts of emissions pathways, and models like En-ROADS, which explore the costs and benefits of different policies, with a broader array of climate impacts would help policymakers and others explore the costs and benefits of mitigation, adaptation, and inaction, helping to build shared understanding, grounded in the best available science, of the choices we face.

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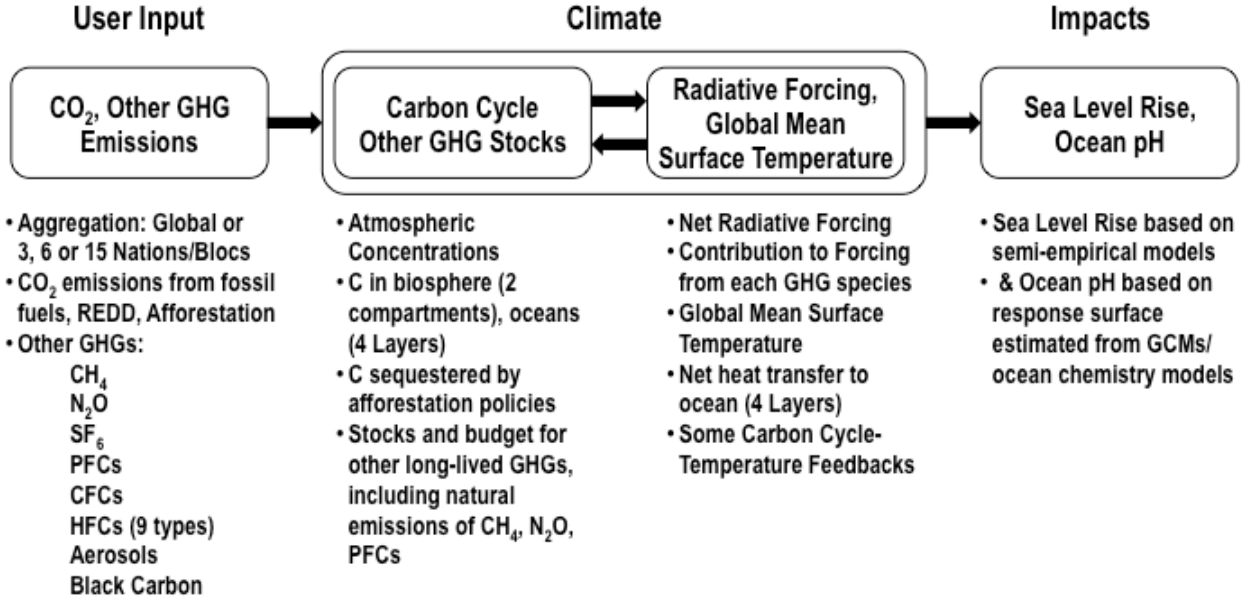


Figure 1. C-ROADS Overview. User-specified scenarios for GHG emissions affect atmospheric concentrations and the climate, which in turn drive impacts including sea level and ocean pH. The model includes climate-carbon cycle feedbacks.

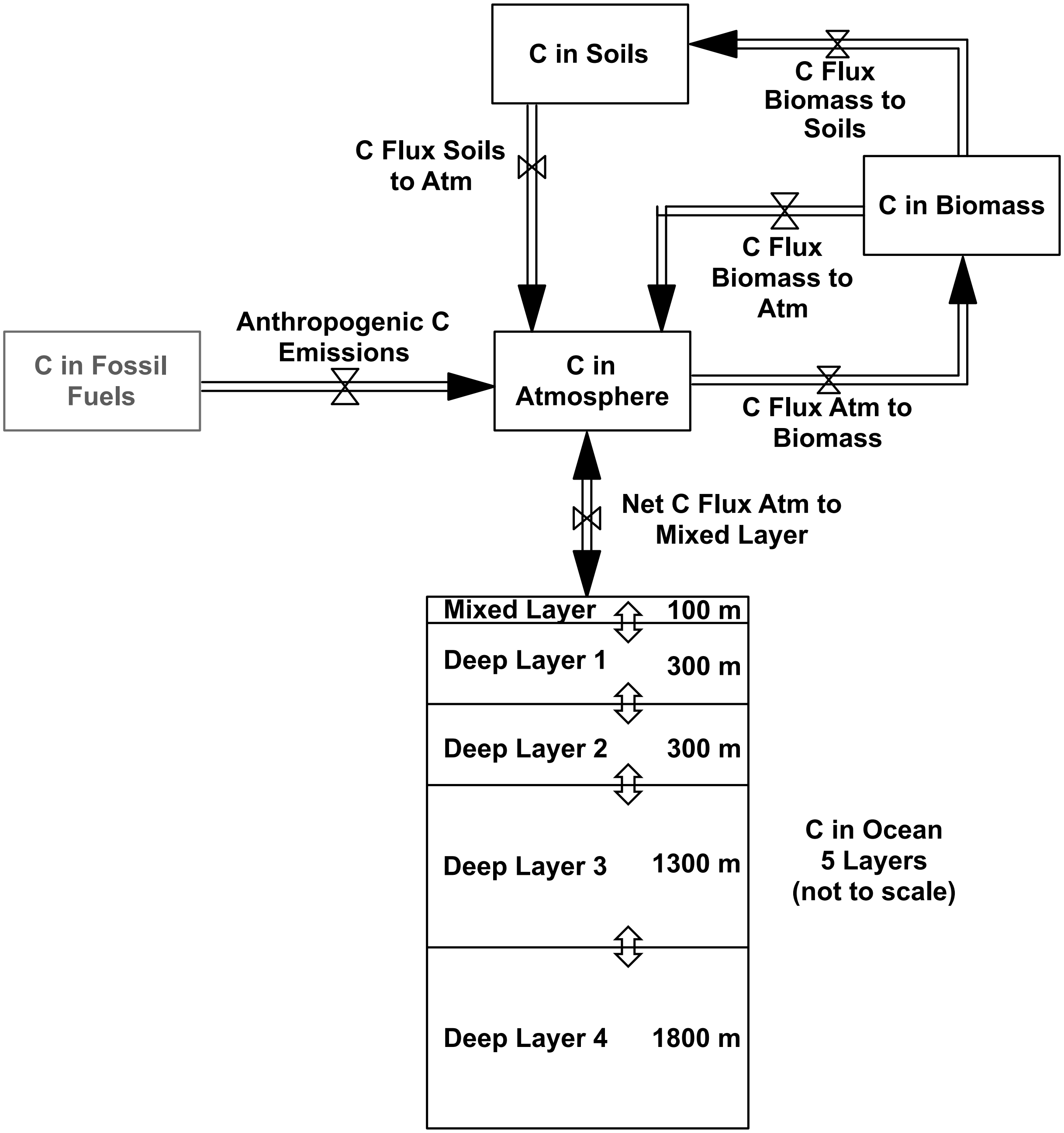


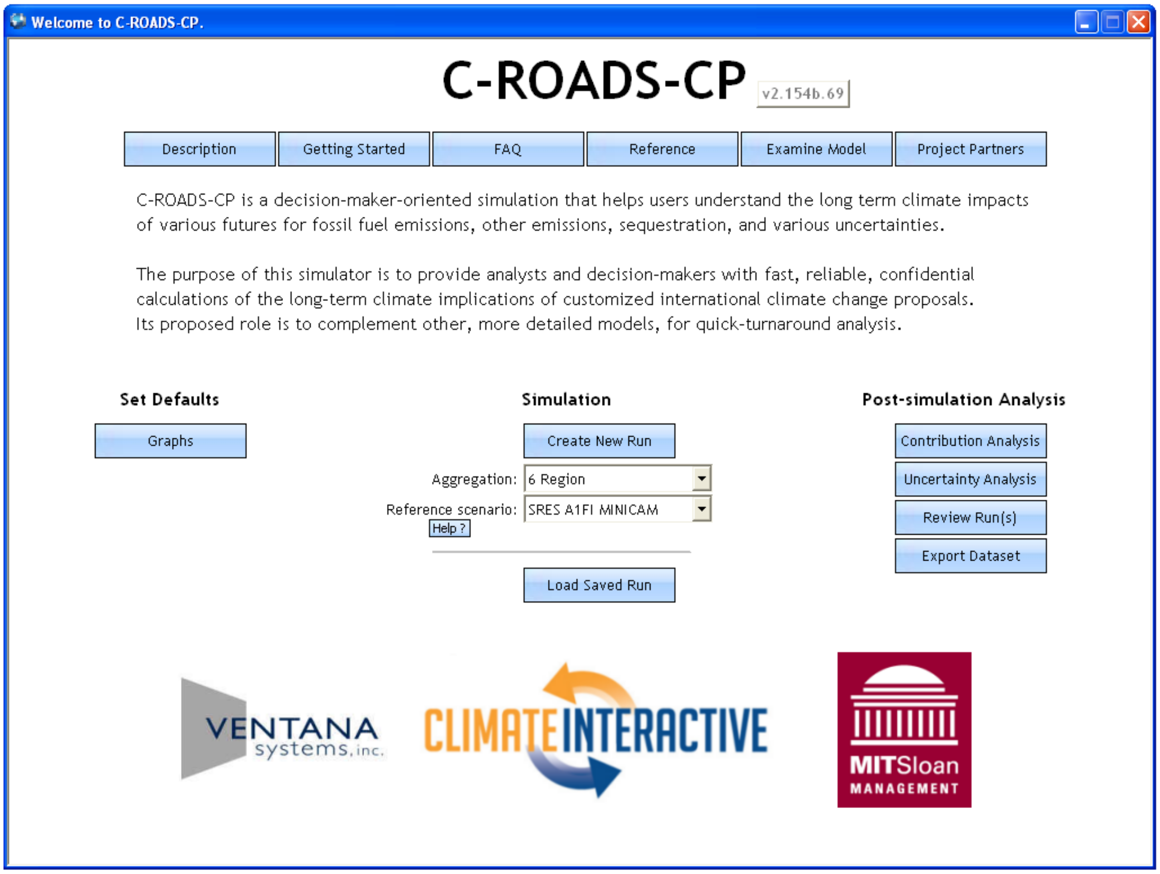
Figure 2. C-ROADS carbon cycle. Stocks of C in fossil fuels (grey) not treated explicitly. CH_4 fluxes and atmospheric stock and C fluxes and stocks due to deforestation and afforestation are represented explicitly but are aggregated in this simplified view.

3 Regions[a]	6 Regions	15 Regions
Developed All developed nations **Developing A** Rapidly developing nations (Brazil, China, India, Indonesia, Mexico, South Africa and other large developing Asian nations) **Developing B** Rest of world: least developed nations in Africa, Asia, Latin America, Middle East, Oceania	**China** **European Union** **India** **United States** **Other Developed Nations** Australia, Canada, Japan, New Zealand, Russia/FSU/ Eastern Europe, South Korea **Other Developing Nations** Brazil, Indonesia, Mexico, South Africa; Other Africa, Asia, Latin America, Middle East, Oceania	**Australia** **Brazil** **Canada** **China** **European Union** **India** **Indonesia** **Japan** **Mexico** **Russia** **South Africa** **South Korea** **United States** **Developed non MEF[b] nations** Other Eastern Europe & FSU, New Zealand **Developing non MEF nations** Other Africa, Asia, Latin America, Middle East, Oceania

[a] The three region level of aggregation is available in C-Learn, the free, online version of C-ROADS (climateinteractive.org).

[b] Major Economies Forum on Energy and Climate; www.majoreconomiesforum.org.

Table 1. Levels of aggregation in C-ROADS. In addition to the global level of aggregation, users may choose to enter emissions pathways for 3, 6 or 15 nation/region levels of aggregation.



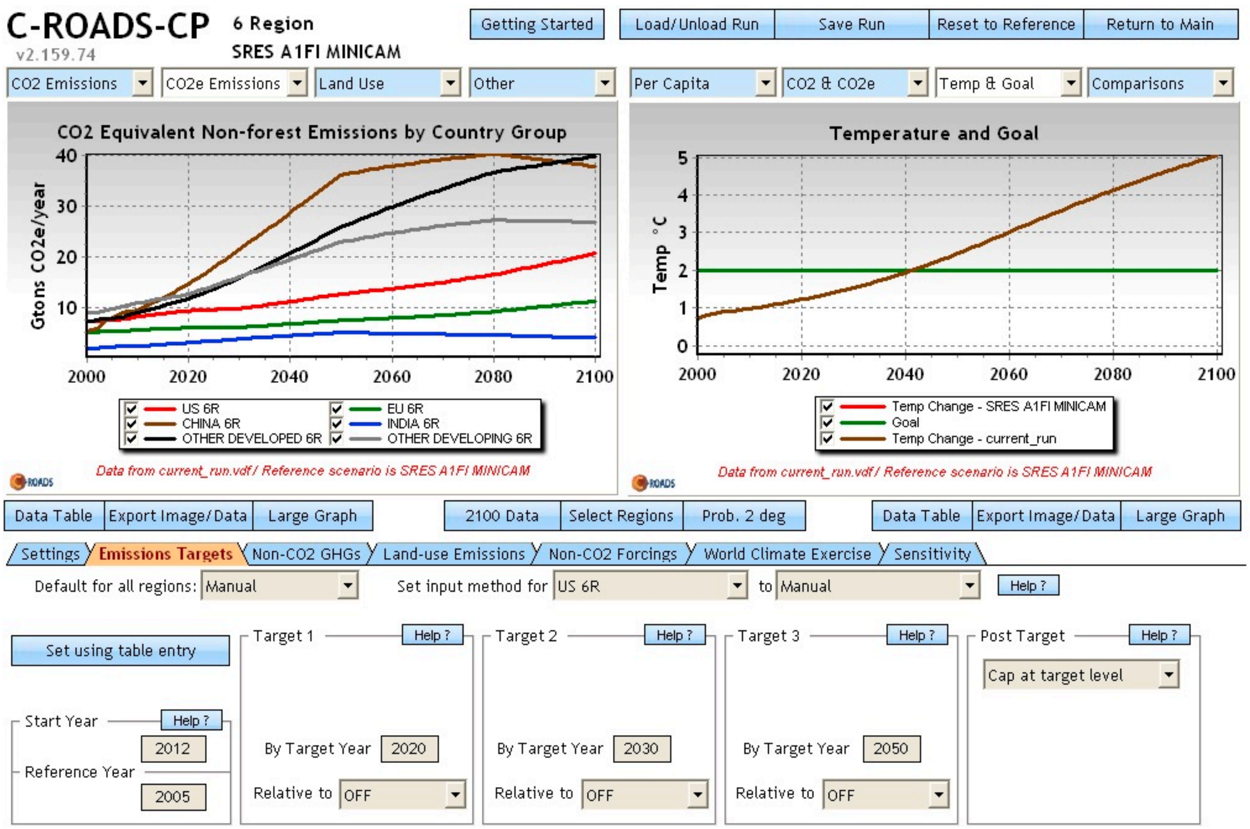
C-ROADS-CP is a decision-maker-oriented simulation that helps users understand the long term climate impacts of various futures for fossil fuel emissions, other emissions, sequestration, and various uncertainties.

The purpose of this simulator is to provide analysts and decision-makers with fast, reliable, confidential calculations of the long-term climate implications of customized international climate change proposals. Its proposed role is to complement other, more detailed models, for quick-turnaround analysis.

Aggregation: 6 Region

Reference scenario: SRES A1FI MINICAM

Figure 3. C-ROADS interface: Main overview screen. Here users can get a description of the model, examine model assumptions, select the level of aggregation and reference scenario, and load prior simulations.



Default for all regions: Manual

Set input method for US 6R to Manual

Start Year 2012

Reference Year 2005

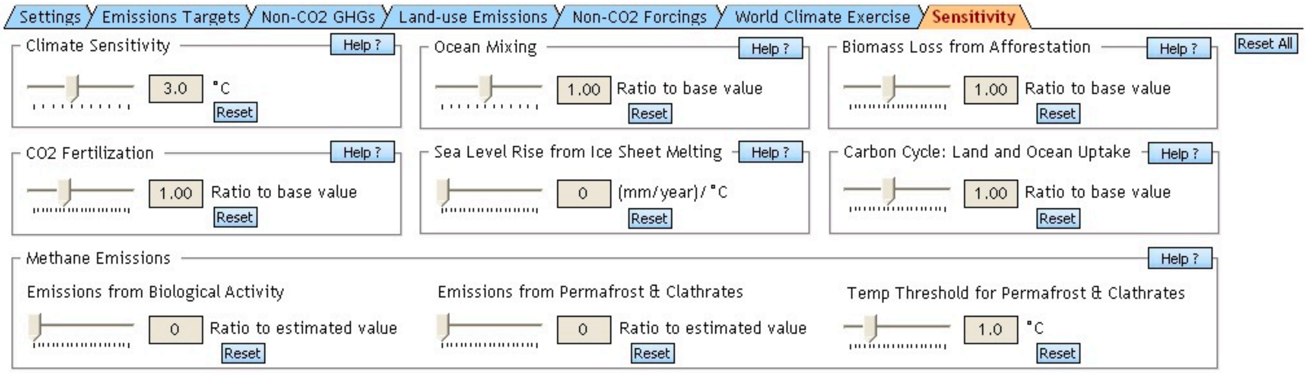
Target 1
By Target Year 2020
Relative to OFF

Target 2
By Target Year 2030
Relative to OFF

Target 3
By Target Year 2050
Relative to OFF

Post Target
Cap at target level

Figure 4. C-ROADS interface: Here users can set emissions policies for the major emitter nations and regional blocs. The graphs displayed in this image show emissions for several major countries and the resulting global mean surface temperature, compared to a 2°C goal. By selecting options from the menus, users can enter, for any nation or bloc, any emissions path they wish, set assumptions about land use (deforestation/afforestation) and other GHGs, and display a wide range of outputs, including emissions, GHG concentrations, temperature change, sea level, per capita emissions, cumulative emissions, etc.



Climate Sensitivity: 3.0 °C

Ocean Mixing: 1.00 Ratio to base value

Biomass Loss from Afforestation: 1.00 Ratio to base value

CO2 Fertilization: 1.00 Ratio to base value

Sea Level Rise from Ice Sheet Melting: 0 (mm/year)/°C

Carbon Cycle: Land and Ocean Uptake: 1.00 Ratio to base value

Methane Emissions

Emissions from Biological Activity: 0 Ratio to estimated value

Emissions from Permafrost & Clathrates: 0 Ratio to estimated value

Temp Threshold for Permafrost & Clathrates: 1.0 °C

Figure 5. Interactive sensitivity analysis. Users can vary the values of key parameters and receive immediate results. The parameters available in the sensitivity tab include climate sensitivity, S (eq. 11), the strength of CO_2 fertilization, β_C (eq. 1), the eddy diffusion parameter, e, affecting transport of carbon and heat to the deep ocean (eq. 5), the strengths of various climate-carbon cycle feedbacks including the effects of temperature on NPP, β_{T_L} (eq. 1), on the ocean's ability to store carbon, β_{T_O} (eq. 4), on methane emissions from biological activity and from permafrost/clathrates, β_M, β_P, and ΔT^* (eq. 7), and the sensitivity of sea level rise to accelerated ice sheet discharge, β_I (eq. 12).

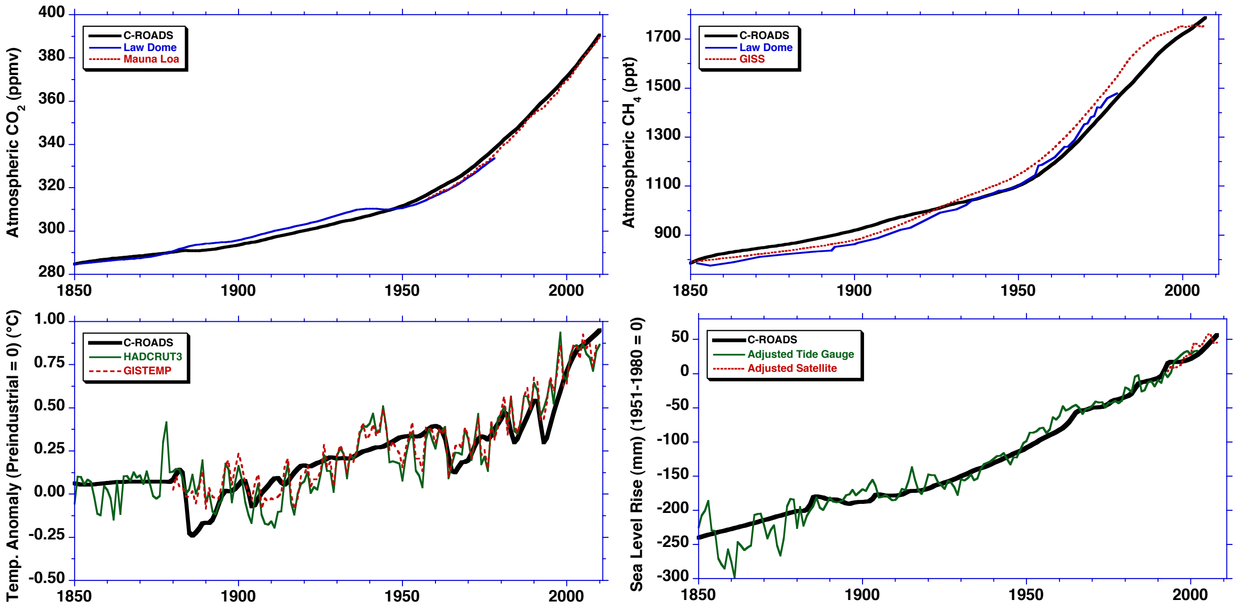


Figure 6. C-ROADS fit to historical data. Clockwise from top left: Atmospheric CO_2 vs. Law Dome and Mauna Loa data, CH_4 concentration vs. Law Dome and GISS data, Temperature Anomaly vs. HADCRUT3 and GISTEMP data, Sea Level Rise vs. tide gauge and satellite data, adjusted for impact of dams (Vermeer and Rahmstorf 2009).

	CO_2 (ppm)	CH_4 (ppt)[a]	Temperature Anomaly (°C)[b]	Sea Level Rise (mm)
Years	1850-2007	1850-2000	1850-2010	1850-2008
R^2	0.995	0.989	0.747	0.960
MAPE	0.63%	3.39%	NA[c]	NA[c]
RMSE	2.25	48.5	0.133	18.3
Theil Inequalities:[d]				
U^M	0.02	0.10	0.00	0.00
U^S	0.24	0.48	0.03	0.11
U^C	0.75	0.42	0.97	0.89

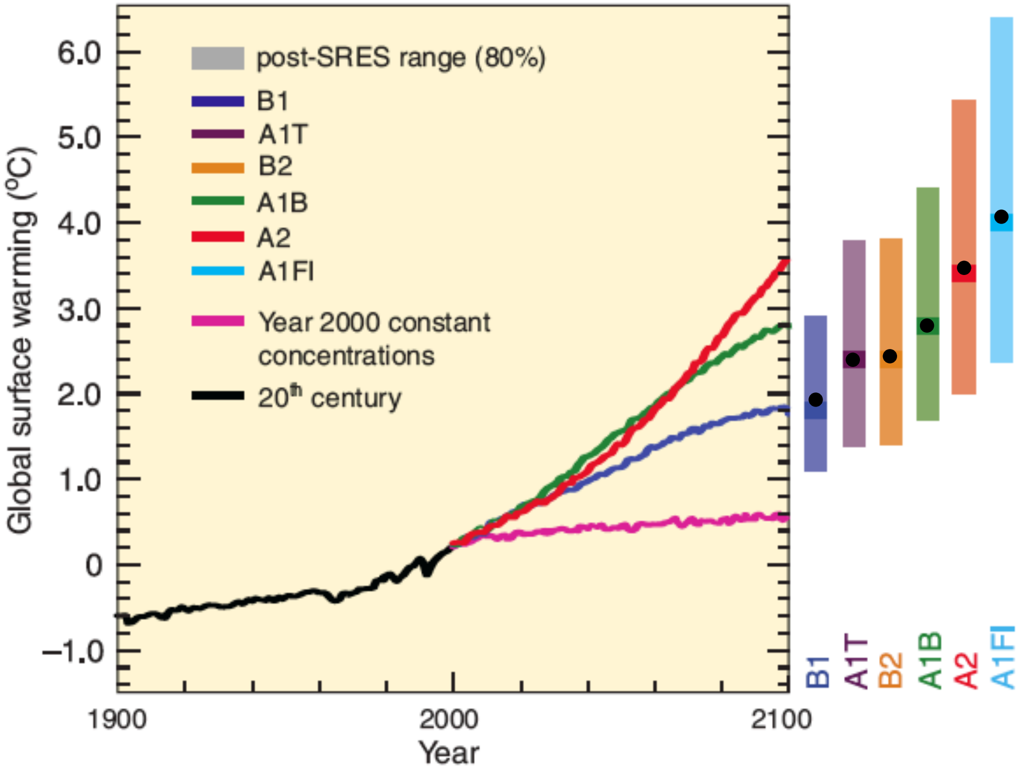
[a] C-ROADS simulated CH_4 compared to GISS data. Results for Law Dome data are similar.

[b] C-ROADS simulated ΔT compared to HADCRUT3 data. Results for GISTEMP are similar.

[c] MAPE (Mean Absolute Percent Error) not defined for ΔT and SLR because the data vary from negative to positive, yielding undefined % errors when the data cross zero.

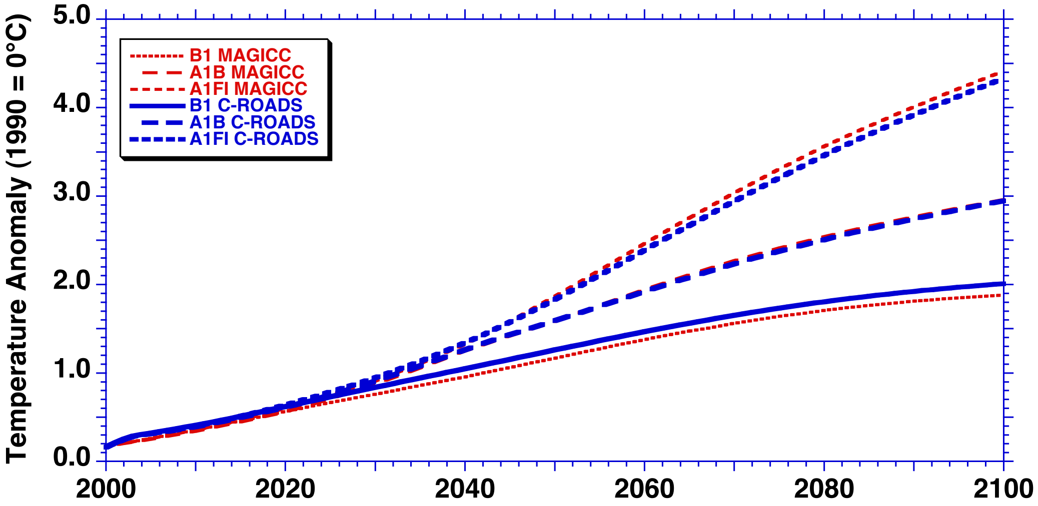
[d] Theil's inequality statistics decompose the MSE into 3 components: the fraction of the MSE due to (i) bias (unequal means of simulated and actual data), U^M; (ii) unequal variances for simulated and actual data, U^S; and (iii) unequal covariation between simulated and actual data, U^C. Due to rounding, U^M, U^S, and U^C may not sum to one.

Table 2. Goodness of fit metrics. Additional comparisons including fits for N_2O, other GHGs, and radiative forcing available in technical documentation (climateinteractive.org).



	Temperature Change (°C at 2090-2099 relative to 1980-1999)	
IPCC SRES Scenario	Best Estimate (*Likely* Range)	C-ROADS
B1	1.8 (1.1-2.9)	1.96
A1T	2.4 (1.4-3.8)	2.43
B2	2.4 (1.4-3.8)	2.47
A1B	2.8 (1.7-4.4)	2.83
A2	3.4 (2.0-5.4)	3.51
A1FI	4.0 (2.4-6.4)	4.11

Figure 7. Model intercomparison: projected warming by 2100. The graph and bars show temperature projections for 2100 and *likely* range (0 = average for 1980-1999) from IPCC AR4 (SPM Fig. 5). The black circles show the results from C-ROADS.



	A1FI	A1B	B1
R^2	0.998	0.996	0.993
RMSE (°C)	0.080°C	0.059°C	0.096°C
U^M	0.207	0.014	0.427
U^S	0.212	0.014	0.275
U^C	0.582	0.972	0.298

Figure 8. Model intercomparison: projected warming 2000-2100 in MAGICC compared to C-ROADS, for A1FI, A1B and B1 (Temperature Anomaly = 0°C in 1990).

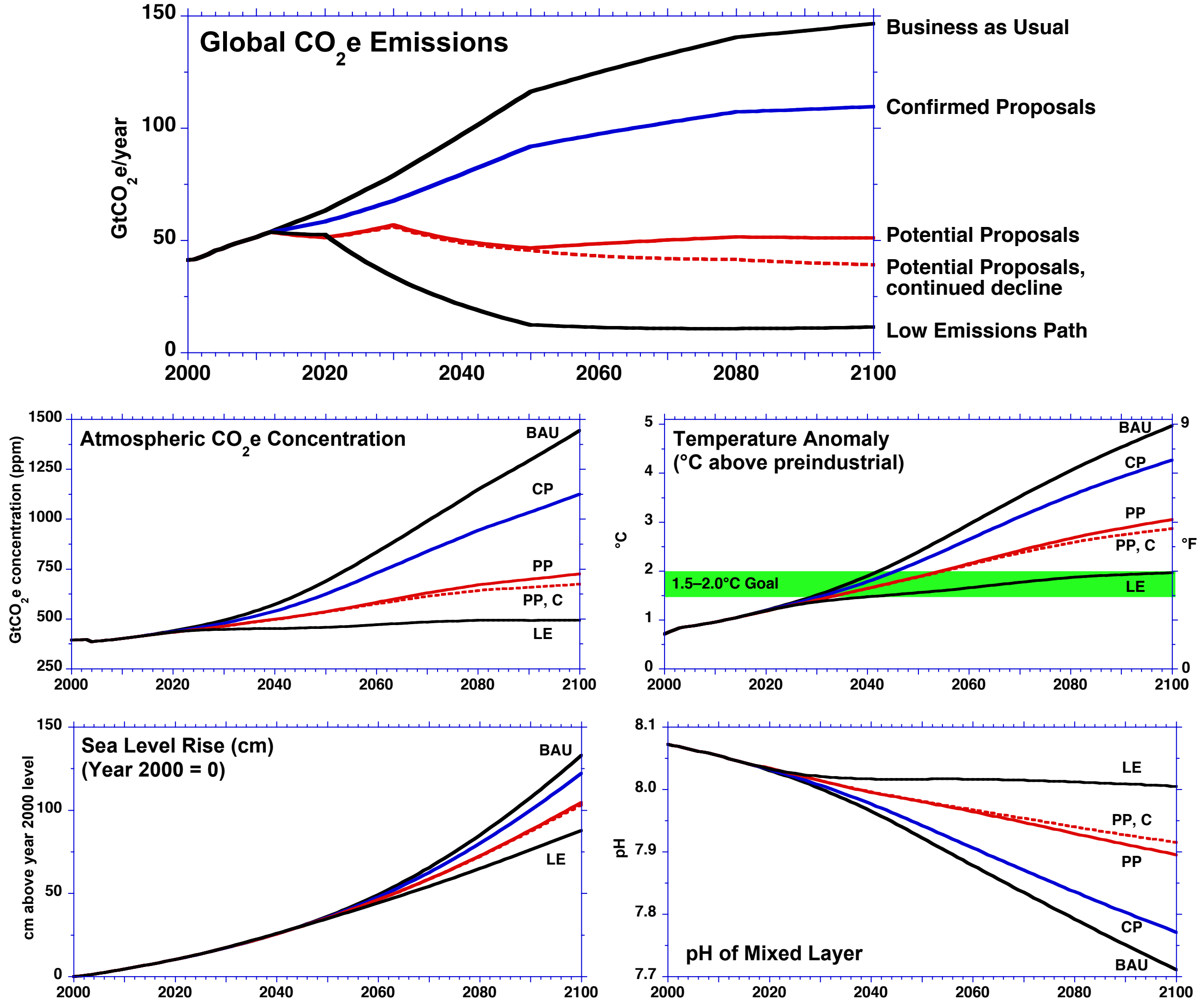
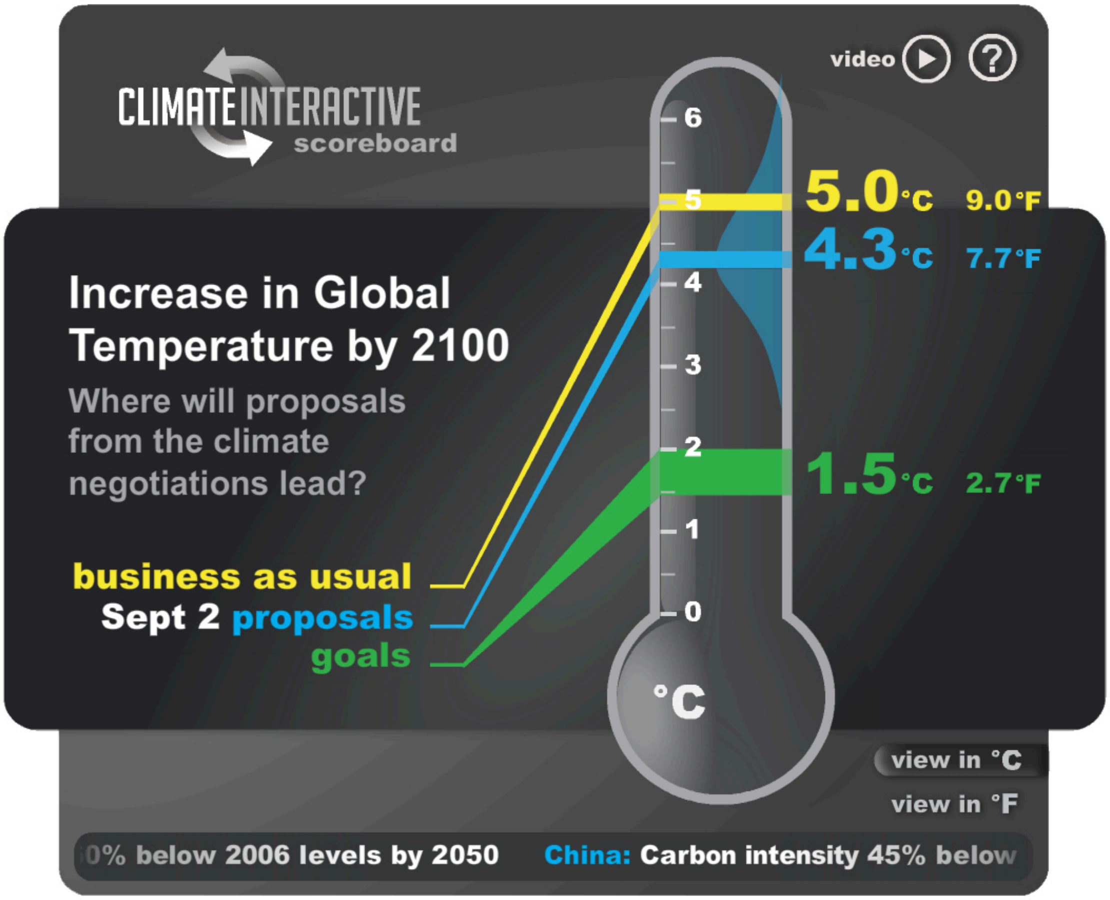


Figure 9. The Climate Scoreboard. C-ROADS simulations showing the expected impact of the publicly available emission reduction proposals of individual nations under the Copenhagen Accord, as of Sept. 2011. Global CO_2e emissions and the resulting atmospheric concentrations, expected global mean temperature increase, sea level rise, and pH of the mixed layer of the ocean shown for the BAU case (A1FI) and for total confirmed proposals, potential proposals, and potential proposals assuming continued emissions decline after the pledge horizon. Potential proposals include speculative proposals and proposals conditional on action by other nations. The "Low Emissions Path" meets the goal of ≤ 2°C of expected warming by 2100. Full documentation for individual pledges available at climatescoreboard.org. The assessment is continuously updated as new proposals are put forward.

	Impacts in 2100				
Scenario	**Emissions ($GtCO_2e$/yr)**	**Atm. Conc. (ppm CO_2e)**	**Temperature Anomaly (°C above preind.)**	**Sea Level Rise (cm; yr 2000 = 0)**	**pH of Mixed Layer**
BAU (A1FI)	147	1444	5.0	133	7.71
Confirmed Proposals	108	1125	4.3	122	7.77
Potential Proposals	51	726	3.0	105	7.90
Pot. Proposals, cont. decline	39	674	2.9	103	7.92
Low Emissions Path	11	494	2.0	88	8.01

Table 3. Climate Scoreboard results. Expected impacts of confirmed and potential proposals under the Copenhagen Accord as of Sept. 2011. Definitions as in Fig. 9.



Increase in Global Temperature by 2100

Where will proposals from the climate negotiations lead?

0% below 2006 levels by 2050 China: Carbon intensity 45% below

Figure 10. The Climate Scoreboard widget (climatescoreboard.org) summarizes the C-ROADS pledge analysis in Fig. 9 and Table 3 in an interactive widget that can be embedded in websites, blogs, and social media pages.