Environmental Modelling & Software 44 (2013) 122–135

Contents lists available at SciVerse ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Management flight simulators to support climate negotiations☆

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

[a] *MIT Sloan School of Management, 100 Main Street, Room E62-436, Cambridge, MA 02139, USA*
[b] *Ventana Systems, Bozeman, MT, USA*
[c] *Climate Interactive, Washington, DC, USA*

A R T I C L E I N F O

Article history:
Received 7 September 2011
Received in revised form
24 May 2012
Accepted 6 June 2012
Available online 25 July 2012

Keywords:
Climate change
Climate policy
System dynamics
Decision support
Interactive simulation

A B S T R A C T

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 policy making 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.

Software availability

Name of software: C-ROADS
Developers: Climate Interactive, MIT Sloan School of Management, Ventana Systems
First available year: 2009
Software requirements: Runs under Windows® XP, 2003, Vista, 7; requires Excel
Program language: Stand-alone application; developed in Vensim, Sable
Availability and cost: Free from climateinteractive.org
Primary contact: Stephanie McCauley
E-mail: info@climateinteractive.org

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

☆ Thematic Issue on Innovative Approaches to Global Change Modelling.
* Corresponding author. MIT Sloan School of Management, 100 Main Street, Room E62-436, Cambridge, MA 02139, USA.
E-mail address: jsterman@mit.edu (J.D. Sterman).

[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).

1364-8152/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.envsoft.2012.06.004

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, 2011) and, under the 2009 Copenhagen Accord, reaffirmed at the 2011 Durban meeting, now seeks voluntary pledges from individual nations rather than a binding international treaty. However, the prospects for passage of policies to reduce 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 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 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." (Earth Negotiations Bulletin, 9 April 2009, http://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 et al., 1982; Kahneman and Tversky, 2000; Gilovic et al., 2002).

Third, and perhaps most important, our mental models lead to pervasive, systematic and consequential errors in our assessments of likely climate dynamics (Sterman, 2008, 2011; Sterman and Booth Sweeney, 2002, 2007; 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 et al., 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, 2000, 2011; 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 executive secretary of 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 (BAU), 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 http://www.climateinteractive.org.

Like all models, C-ROADS has limitations and is not appropriate for all purposes. So that the model can run in about a second on standard laptops, the carbon cycle and climate sectors of the model are globally aggregated (although the model represents GHG emissions at the level of 15 countries/regional blocs). C-ROADS is therefore a member of the class of Simple Climate Models (SCMs). Other interactive SCMs available for use by nonspecialists include Azar and Johansson (2010) and Matthews (2011), both freely available online. Such SCMs are complementary to models such as AOGCMs, and dependent on them for calibration. Like all globally aggregated SCMs, C-ROADS cannot be used to assess climate change impacts at national/regional or smaller scales, including local changes in temperature, precipitation, winds, etc. As with any model, users must be aware of the key assumptions, including model boundary and level of aggregation, so that the model is used appropriately.

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 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 that, in all cases, sum to total global emissions.

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 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

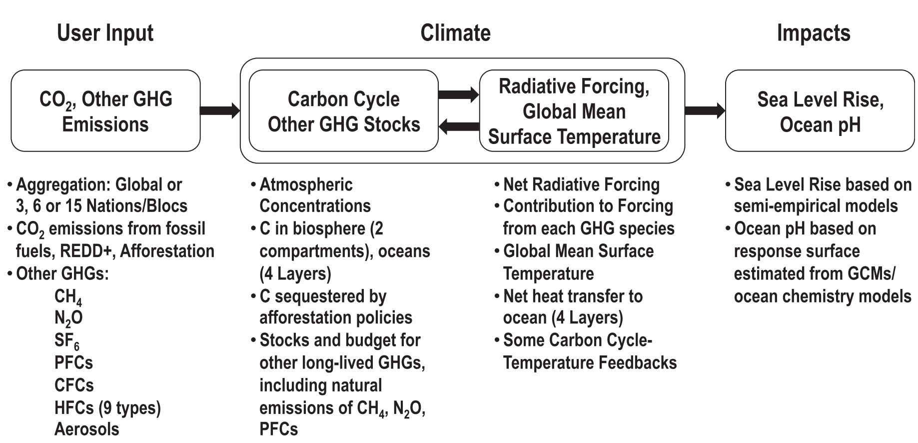


Fig. 1. C-ROADS Overview. User-specified scenarios for GHG emissions affect atmospheric concentrations and the climate, which in turn drive impacts including sea level and ocean pH. The model includes climate–carbon cycle feedbacks.

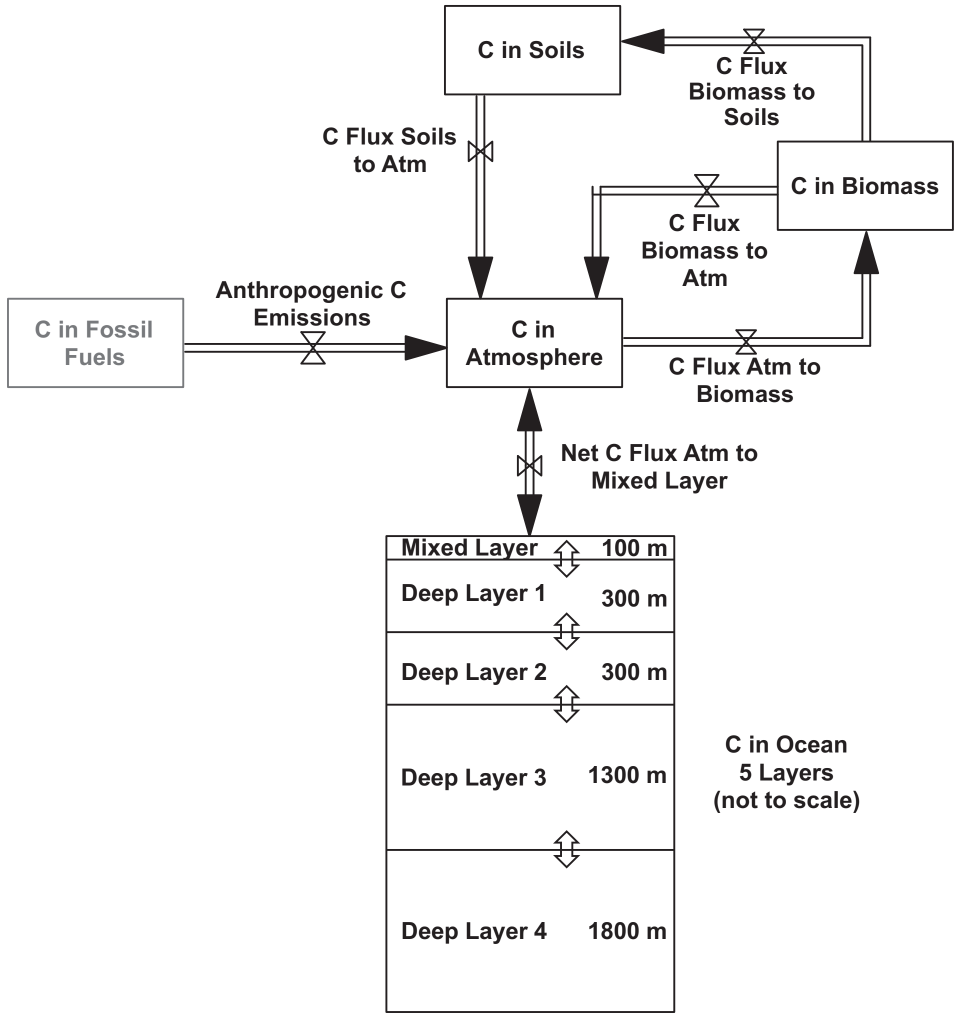


Fig. 2. C-ROADS carbon cycle. Stocks of C in fossil fuels (gray) not treated explicitly. CH_4 fluxes and atmospheric stock and C fluxes and stocks due to deforestation and afforestation are represented explicitly but are aggregated in this simplified view.

(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:

$$\mathrm{NPP} = \mathrm{NPP}_0\left(1 + \beta_C \ln(C_a/C_{a_0})\right)\left(1 - \beta_{T_L}\Delta T\right) \tag{1}$$

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

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

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,

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

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 m 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

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

where d_i is the thickness of layer i, $\langle d_{ij}\rangle$ is the mean thickness of layers i *and* 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, toward 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 (see below).

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:

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

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

C-ROADS includes two feedbacks to natural methane emissions. First, higher temperatures increase anaerobic bacterial respiration in tropical, temperate and boreal forests, peat bogs, and other biomes, increasing CH_4 release above the preindustrial rate E_0^N, 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 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 :

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

Net radiative forcing, F_T, consists of net forcing from CO_2, F_{CO_2}, plus the sum of forcings from other GHGs and sources, F_{other}:

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

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.

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, 2005a,b, as updated) and user-defined scenarios for the future. Note that net forcing is computed explicitly from the concentrations of each GHG, and in turn these GHGs are modeled explicitly, each with its own emissions budget, cycle, atmospheric stock and atmospheric lifetime. However, for reporting purposes only, C-ROADS also provides graphs and tables showing total CO_2 equivalent (CO_2e) emissions, computed using the 100-year GWP values for the non-CO_2 gases. We also report CO_2e concentrations, computed by inverting Eq. (10) to solve for the CO_2 concentration required to yield net radiative forcing, F_T, assuming the concentrations of all other GHGs are zero.

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 Rahmstorf's (2007) semi-parametric model. As Vermeer and Rahmstorf discuss, 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

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

where ΔT_0 is the temperature at which sea level is in equilibrium with the climate, α_0 and α_1 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.

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 levels 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

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.

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

other developing countries. Historical and projected population, real GDP, and GHG emissions are drawn from Asadoorian 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 higher levels of aggregation are useful in educational contexts (Sterman et al., 2011). The 15 nation/region option allows users to specify emissions paths for 13 individual nations (including the EU) that together comprise approximately 80% of current global CO_2 emissions, plus two additional blocs representing all other developed and all other developing nations. The model does not separately specify emissions from all parties to the UNFCCC (now nearly 200). Users interested in examining the impact of emissions from individual nations not explicitly represented can do so by developing a spreadsheet specifying and summing the emissions projections for these nations; C-ROADS can then read such files directly.

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 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 17% 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 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, including targets presented relative to different reference years and 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 experimentation 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

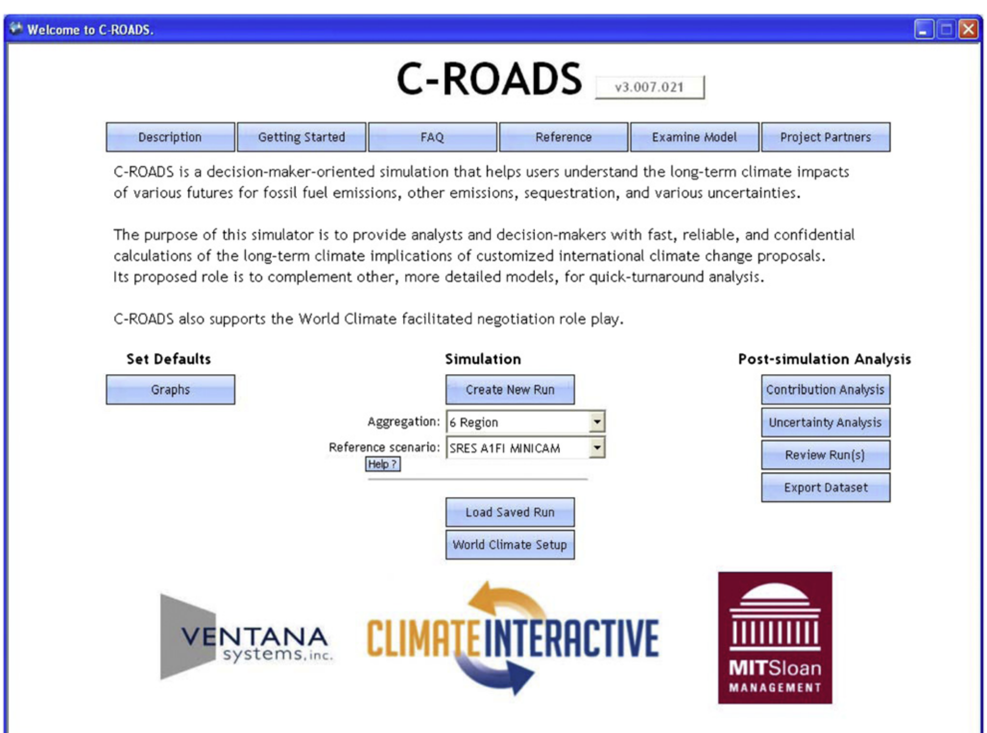


Fig. 3. C-ROADS interface: Main overview screen. Here users can get a description of the model, examine model assumptions, select the level of aggregation and reference scenario, and load prior simulations.

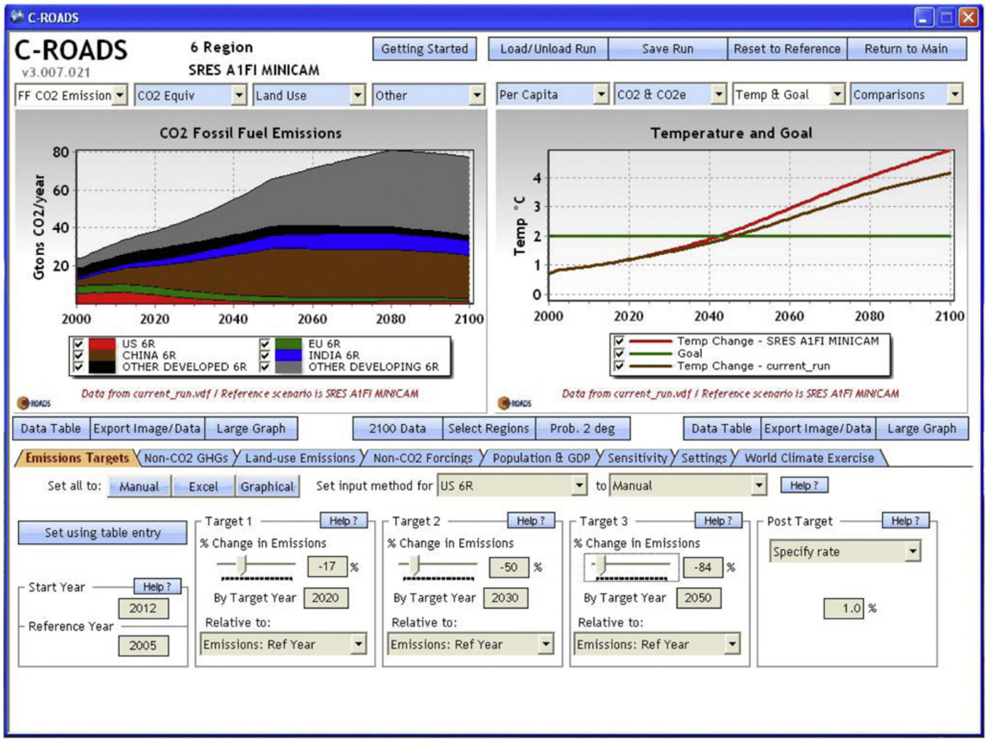


Fig. 4. C-ROADS interface: Here users can set emissions policies for the major emitter nations and regional blocs. Emissions for each nation or bloc are set using the sliders at the bottom of the screen; here the values for the US are shown. The graph on the left shows CO_2 emissions for several major countries. The graph on the right shows the resulting mean surface temperature anomaly compared to BAU and 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.

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 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 CO_2 emissions 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, including 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 CO_2e 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

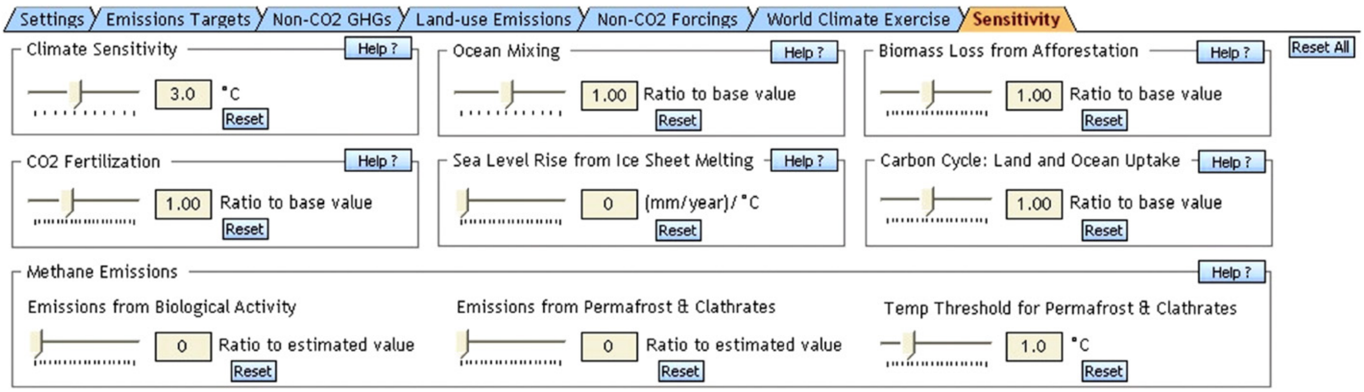


Fig. 5. Interactive sensitivity analysis. Users can vary the values of key parameters and receive immediate results. The parameters available in the sensitivity tab include climate sensitivity, S (Eq. (11)), the strength of CO_2 fertilization, β_C (Eq. (1)), the eddy diffusion parameter, *e*, affecting 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)).

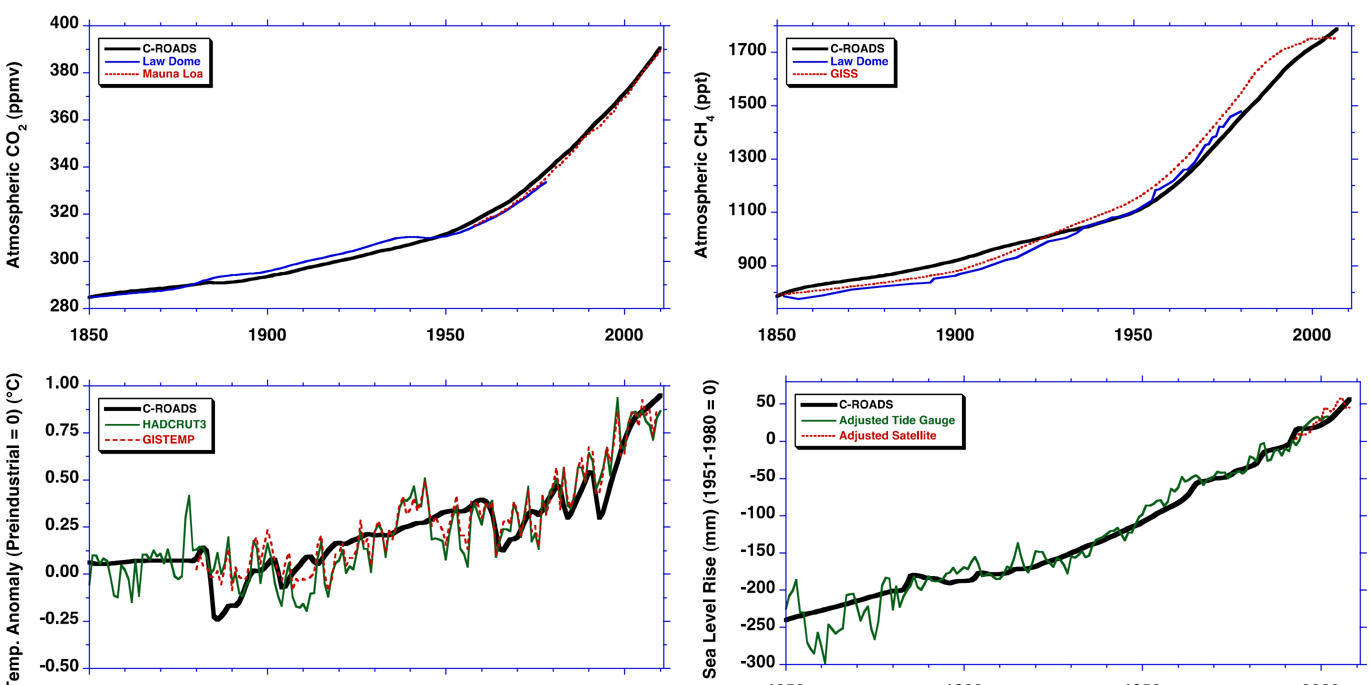


Fig. 6. C-ROADS fit to historical data. Clockwise from top left: Atmospheric CO_2 vs. Law Dome and Mauna Loa data, CH_4 concentration vs. Law Dome and GISS data, temperature Anomaly vs. HADCRUT3 and GISTEMP data, sea level Rise vs. tide gauge and satellite data, adjusted for the impact of dams (Vermeer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

the year-by-year variations in historical temperature 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 and 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).[3]

The full model documentation (see http://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).

[3] The discrepancy between AR4 and MAGICC has been noted by the IPCC, although the source remains unclear.

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

	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 base year defining zero is arbitrary.
[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.

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.

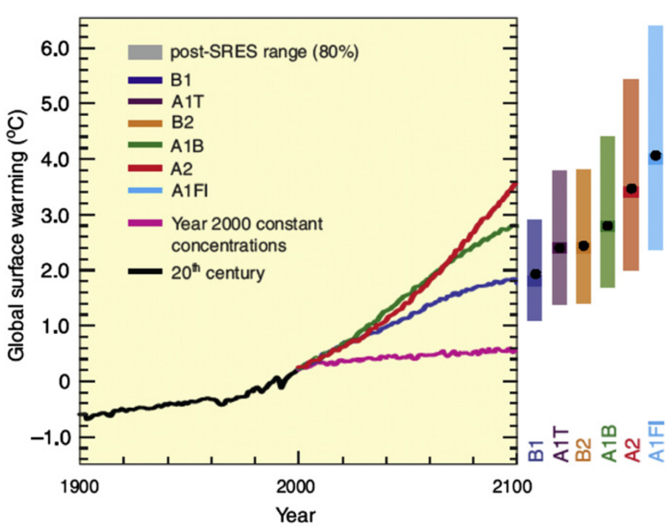
C-ROADS is also used in China, through Tsinghua University, where it has been disaggregated to include drivers of CO_2 emissions at the provincial level using assumptions about total energy use and fuel mix.

C-ROADS analysis was included in a United Nations Environment Program assessment of "the emissions gap" (UNEP, 2010, 2011). 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 percent) of staying below the 2 °C temperature limit, the gap would range from 5 to 9 $GtCO_2e$, depending on how the pledges are implemented."

Where UNEP (2010, 2011) 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. However, many nations do not specify their pledges beyond the year 2020. To address this issue, our post-2020 gap analysis considers several scenarios, distinguishing between "confirmed proposals" and "potential proposals" (Fig. 9). Confirmed proposals include those formally made under the Copenhagen Accord. The more optimistic potential proposals scenario includes quasi-official statements or policies under consideration, for instance the China Energy Research Institute's statement that China's emissions could peak by 2030 (CERI, 2009). For both the confirmed and potential proposals scenarios we assume the emissions of each nation or bloc offering a proposal remain constant at the level of the final year specified in the proposal. An additional scenario, "potential proposals-continued decline", is more optimistic, assuming that a nation's emissions continue to fall after the last year specified at the rate of decline in the proposal. The methods and assumptions used in our assessment of each nation's pledges and each scenario are fully documented and available at climatescoreboard.org.

Results (Fig. 9, Table 3) show 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 as of December 2011, after the Durban conference, 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 grow to more than 1200 ppm CO_2e by 2100. The steady increase in concentrations pushes expected temperature increase to 4.5 °C above preindustrial levels by 2100 (compared to 5 °C under BAU), lowers the pH of the mixed layer of the ocean to roughly 7.75 and raises sea level in 2100 more than 1.2 m above the year 2000 value. Of course sea level rise would continue for centuries or millennia even if radiative balance were achieved by 2100 (Solomon et al., 2009, 2010). However, as the contribution of ice sheet melt to future SLR is highly uncertain, we do not report long run SLR or the time required for equilibration. Fig. 9 and Table 3 also show the projected impacts of the more optimistic potential proposal



IPCC SRES Scenario	Temperature Change (°C at 2090-2099 relative to 1980-1999) 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

Fig. 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.

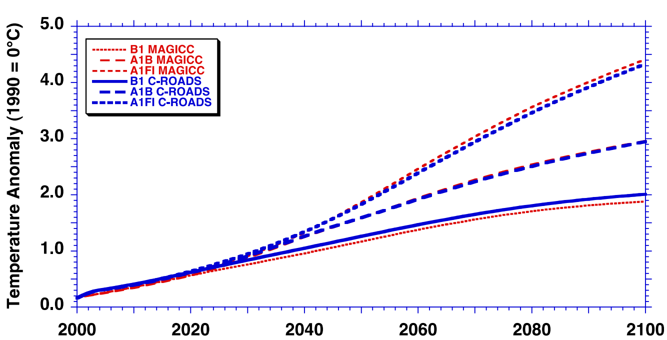
Table 3
Climate scoreboard results. Expected impacts of confirmed and potential proposals under the Copenhagen Accord, as of Dec. 2011. Definitions as in Fig. 9.

Scenario	Impacts in 2100				
	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)	146	1438	5.0	132	7.71
Confirmed proposals	121	1209	4.5	124	7.75
Potential proposals	74	852	3.5	109	7.85
Pot. proposals, cont. decline	60	785	3.3	107	7.87
Low emissions path	11	495	2.0	88	8.00

scenarios under which GHG emissions in 2100 fall substantially compared to the confirmed proposal scenario. However, because emissions remain higher than the net removal of GHGs from the atmosphere, GHG concentrations reach 785–850 ppm CO_2e, expected warming remains approximately 3.3–3.5 °C, the pH of the mixed layer drops to about 7.9, and sea level rises about 1.1 m. 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 m of sea level rise and lowers the pH of the mixed layer to about 8 by 2100.

The differences between the confirmed scenario (pledges under the UNFCCC or approved in national legislation) and the potential scenarios (including unofficial proposals) illuminate the uncertainty around future emissions after 2020. The results show that even in a very lenient interpretation of post-2020 actions (potential proposals, continued decline) the pledges and proposals for emissions reductions now being publicly discussed are not sufficient to stabilize atmospheric GHG concentrations or limit expected temperature increase to 2 °C. 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 permafrost or clathrates, and no increase in sea level from accelerating ice sheet loss with rising temperatures.

The climate scoreboard simulation is available in the model and via the interactive "Climate Scoreboard" widget (Fig. 10; climatescoreboard.org). The scoreboard analysis is updated when



	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

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

new pledges are made, existing pledges are revised, and as the model is updated based on improving scientific understanding of climate dynamics.

C-ROADS is also used in education. It is the core model in the Climate CoLab (Malone et al., 2011), which "seeks to harness the collective intelligence of contributors from all over the world to address global climate change" (http://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 (http://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.

Some caveats are in order: As a globally aggregated SCM, C-ROADS projects global averages for GHG concentrations, temperature increase, sea level rise and ocean pH, but cannot assess climate impacts at the national or subnational level including changes in precipitation, wind speed, storm intensity, etc. The model allows users to specify emissions pathways for CO_2 from fossil fuels, from REDD+ policies, and for emissions of other GHGs explicitly at the level of individual nations or regional blocs, including the 13 largest emitters, which account for about 80% of global emissions (Table 1). The rest of the world, however, is divided into two blocs, capturing all other developed and all other developing nations. Further, although C-ROADS is designed for nonspecialists, effective use of the tool, as with any model, requires knowledge of the relevant climate science and policy issues. Appropriate use of the sensitivity analysis capability of the model (Fig. 5) requires users to understand concepts such as climate sensitivity and CO_2 fertilization, along with understanding of the current best estimates for each parameter and the distribution of possible values around those estimates.

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

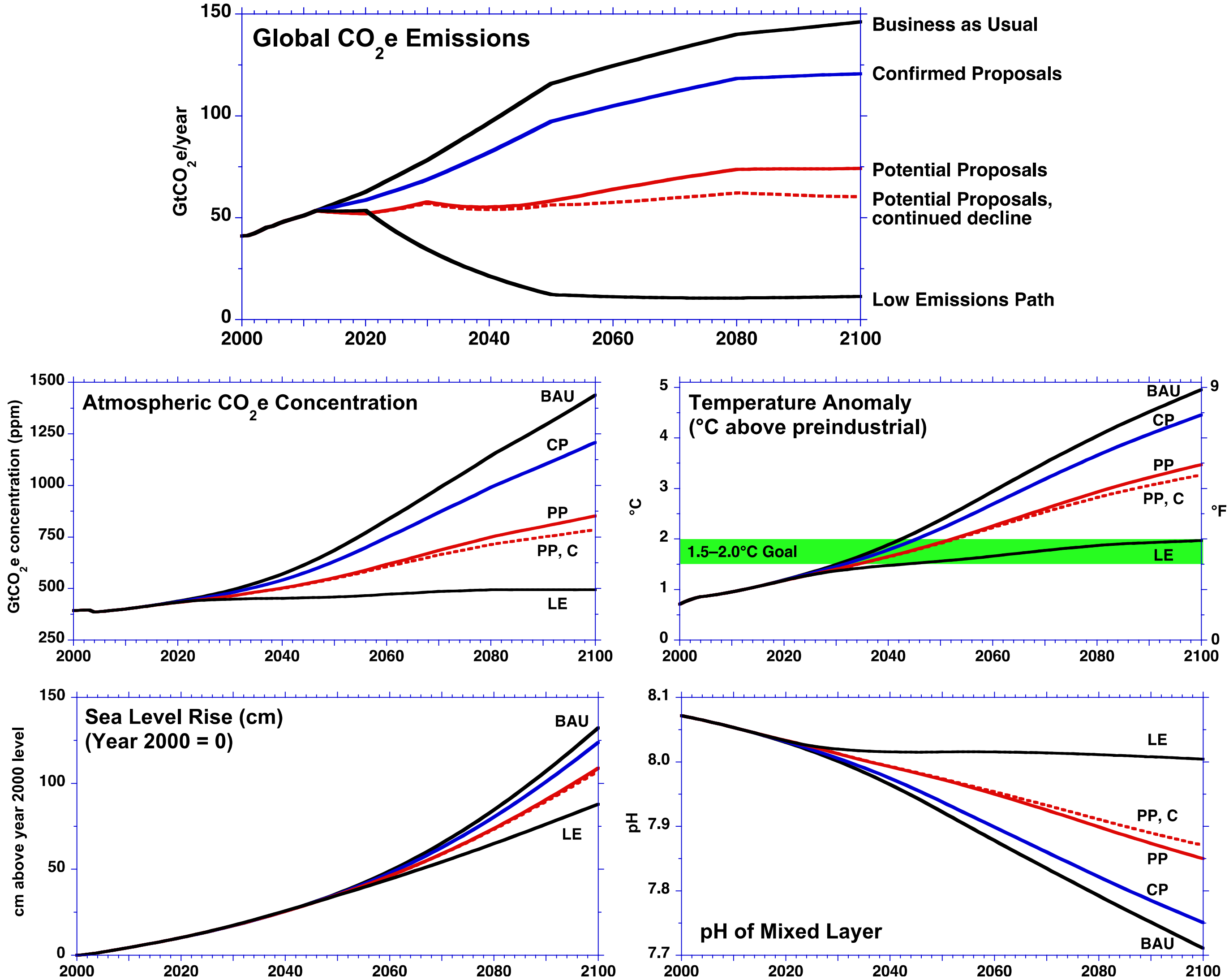


Fig. 9. The climate scoreboard. C-ROADS simulations showing the expected impact of the publicly available emission reduction proposals of individual nations under the Copenhagen Accord, as updated in Cancún and Durban, as of December 2011. Global CO_2e emissions and resulting atmospheric concentrations, 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" limits expected warming to 2 °C by 2100. Full documentation available at climatescoreboard.org. Updates are posted as pledges are revised or new proposals offered.

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 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. 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 spatially resolved impact estimates derived from AOGMS 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 laptops. We are exploring ways to couple C-ROADS to downscaled results. Eventually, as computer power increases, it may be possible to include regional disaggregation directly in C-ROADS while preserving the ability of the model to run quickly.

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

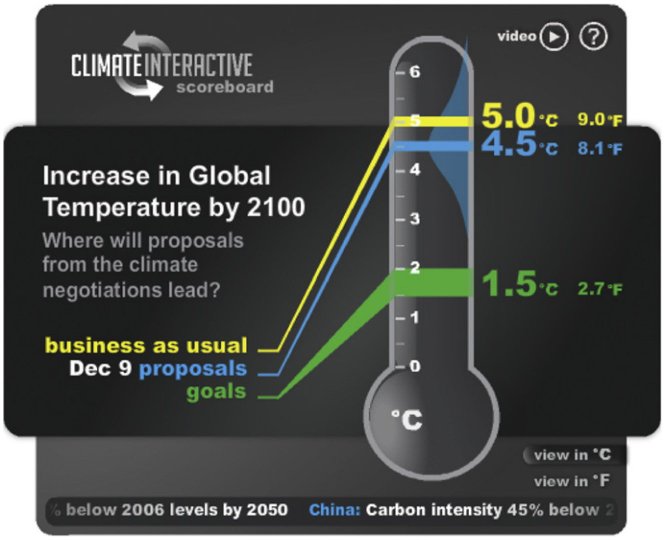


Fig. 10. The climate scoreboard widget (climatescoreboard.org) summarizes the C-ROADS pledge analysis in Fig. 9 and Table 3 in an interactive widget that can be embedded in websites, blogs, and social media pages.

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. However, 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. More comprehensive models should endogenously generate energy use, fuel mix, and GHG emissions from a representation of the economy incorporating stocks of energy producing and consuming capital, construction and planning delays, and the possibility of retrofits and early retirement. The costs of each energy source should be 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. We have developed a globally aggregated model, denoted En-ROADS, that incorporates these structures while maintaining the ability to run essentially instantly on an ordinary laptop and enabling users to implement a wide range of policies and sensitivity tests. A full description is beyond the scope of this paper; interested readers are referred to http://www.climateinteractive.org/ for details.

References

Asadoorian, M., Sarofim, C., Reilly, J., Paltsev, S., Forest, C., 2006. Historical Anthropogenic Emissions Inventories for Greenhouse Gases and Major Criteria Pollutants. Massachusetts Institute of Technology (MIT). Joint Program on the Science and Policy of Global Change Technical Note No. 8. http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt203.pdf.

Azar, C., Johansson, D., 2010. The Chalmers Climate Calculator. Available at: www.chalmers.se/ee/ccc2; See also uppsalainitiativet.blogspot.com/2010/02/chalmers-climate-calculator-del-i-om.html.

Bernie, D., Lowe, J., Tyrrell, T., Legge, O., 2010. Influence of mitigation policy on ocean acidification. Geophysical Research Letters 37, L15704.

Boden, T., Marland, G., Andres, R., 2010. Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy. cdiac.ornl.gov/ftp/ndp030/CSV-FILES/nation.1751_2008.csv.

Bolin, B., 1986. Requirements for a satisfactory model of the global carbon cycle and current status of modeling efforts. In: Trabalka, J., Reichle, D. (Eds.), The Changing Carbon Cycle: a Global Analysis. Springer, New York.

Booth Sweeney, L., Sterman, J., 2000. Bathtub dynamics: initial results of a systems thinking inventory. System Dynamics Review 16 (4), 249–294.

Booth Sweeney, L., Sterman, J., 2007. Thinking about systems: students' and their teachers' conceptions of natural and social systems. System Dynamics Review 23 (2–3), 285–312.

Brunstein, A., Gonzalez, C., Kanter, S., 2010. Effects of domain experience in the stock-flow failure. System Dynamics Review 26 (4), 347–354.

Bullister, J., 2009. NOAA/PMEL. Atmospheric CFC, CCl4, and SF6 History Update, Retrieved 10/27/2009 from cdiac.ornl.gov/oceans/new_atmCFC.html.

CERI (China Energy Research Institute), 2009. 2050 China Energy and CO_2 Emissions Report. Science Press, Beijing (in Chinese). Cited in Zheng, N. et al. (2010) Comparative Analysis of Modeling Studies on China's Future Energy and Emissions Outlook, Lawrence Berkeley National Laboratory, Report LBNL-4032E.

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: overview of the EMF 22 international scenarios. Energy Economics 31, S64–S81.

Corell, R., Lee, K., Stern, P., 2009. Informing Decisions in a Changing Climate. National Research Council. National Academies Press, Washington, DC. nap.edu.

Cronin, M., Gonzalez, C., Sterman, J., 2009. Why don't well-educated adults understand accumulation? A challenge to researchers, educators, and citizens. Organizational Behavior and Human Decision Processes 108 (1), 116–130.

Daniel, J., Velders, G., et al., 2007. Halocarbon scenarios, ozone depletion potentials, and global warming potentials. Ch. 8. In: Scientific Assessment of Ozone Depletion: 2006. WMO (World Meteorological Organization) Global Ozone Research and Monitoring Project, Geneva. Report 50. www.esrl.noaa.gov/csd/assessments/ozone/2006/chapters/chapter8.pdf.

Edwards, P., 2010. A Vast Machine. MIT Press, Cambridge.

Fiddaman, T., 1997. Feedback Complexity in Integrated Climate–Economy Models. Ph.D. dissertation, Massachusetts Institute of Technology.

Fiddaman, T., 2002. Exploring policy options with a behavioral climate-economy model. System Dynamics Review 18 (2), 243–267.

Fiddaman, T., 2007. Dynamics of climate policy. System Dynamics Review 23 (1), 21–34.

Friedlingstein, P., Cox, P., Betts, R., et al., 2006. Climate–carbon cycle feedback analysis: results from the C4MIP model intercomparison. Journal of Climate 19, 3337–3353.

Fung, I., 1991. Models of oceanic and terrestrial sinks of anthropogenic CO_2: a review of the contemporary carbon cycle. In: Oremland, R. (Ed.), Biogeochemistry of Global Change. Chapman & Hall, New York.

Gilovic, T., Griffin, D., Kahneman, D., 2002. Heuristics and Biases: the Psychology of Intuitive Judgment. Cambridge University Press, Cambridge UK.

Goudriaan, J., Ketner, P., 1984. A simulation study for the global carbon cycle, including man's impact on the biosphere. Climatic Change 6, 167–192.

Hansen, J., Nazarenko, L., et al., 2005a. Earth's energy imbalance: confirmation and implications. Science 308, 1431–1435. Also. data.giss.nasa.gov.

Hansen, J., Sato, M., et al., 2005b. Efficacy of climate forcings. Journal of Geophysical Research 110.

Hansen, J., Sato, M., et al., 1998. Climate forcings in the industrial era. Proceedings of the National Academy of Sciences 95, 12753–12758.

Houghton, R., 2006. Carbon Flux to the Atmosphere from Land-Use Changes: 1850–2005. The Woods Hole Research Center. Carbon Dioxide Information Analysis Center (CDIAC). cdiac.ornl.gov/trends/landuse/houghton/1850-2005.txt.

IPCC, 2007. Climate Change 2007: the Physical Science Basis. Cambridge University Press, Cambridge, UK. ipcc.ch.

Jacobs, S., Jenkins, A., Giulivi, C., Dutrieux, P., 2011. Stronger ocean circulation and increased melting under Pine Island glacier ice shelf. Nature Geoscience 4, 519–523.

Joos, F., Prentice, I., Sitch, S., Meyer, R., Hooss, G., Plattner, G., Gerber, S., Hasselmann, K., 2001. Global warming feedbacks on terrestrial carbon uptake under the intergovernmental panel on climate change (IPCC) emissions scenarios. Global Biogeochemical Cycles 15, 891–908.

Kahneman, D., Slovic, P., Tversky, A., 1982. Judgment Under Uncertainty: Heuristics and Biases. Cambridge University Press, Cambridge UK.

Kahneman, D., Tversky, A., 2000. Choices, Values and Frames. Cambridge University Press, Cambridge UK.

Kheshgi, H., Jain, A., 2003. Projecting future climate change: implications of carbon cycle model intercomparisons. Global Biogeochemical Cycles 17, 1047. http://dx.doi.org/10.1029/2001GB001842.

Maddison, A., 2008. Historical Statistics for the World Economy: 1–2006 AD. Conference Board and Groningen Growth and Development Centre, Total Economy Database. www.ggdc.net/MADDISON/oriindex.htm.

Malone, T., Abelson, H., Karger, D., Klein, M., Sterman, J., 2011. The Climate CoLab. climatecolab.org.

Matthews, B., 2011. Java Climate Model. Available at: jcm.climatemodel.info.

Mayer, M., Hyman, R., Harnisch, J., Reilly, J., 2000. Emissions Inventories and Time Trends for Greenhouse Gases and Other Pollutants. Massachusetts Institute of Technology (MIT). Joint Program on the Science and Policy of Global Change, Technical Note No. 1. globalchange.mit.edu/files/document/MITJPSPGC_TechNote1.pdf.

Meinshausen, M., Raper, S., Wigley, T., 2008. Emulating IPCC AR4 atmosphere-ocean and carbon cycle models for projecting global-mean, hemispheric and land/ocean temperatures: MAGICC 6.0. Atmospheric Chemistry and Physics Discussions 8, 6153–6272.

Morecroft, J., Sterman, J., 1994. Modeling for Learning Organizations. Productivity Press, Portland, OR.

Moxnes, E., Saysel, A., 2009. Misperceptions of global climate change: information policies. Climatic Change 93 (1–2), 15–37.

Nakicenovic, N., Swart, R., 2000. Special Report on Emissions Scenarios. Cambridge University Press, Cambridge, United Kingdom.
Oeschger, H., Siegenthaler, U., et al., 1975. A box diffusion model to study the carbon dioxide exchange in nature. Tellus 27 (2), 167–192.
Olivier, J., Berdowski, J., 2001. Global emissions sources and sinks. In: Berdowski, J., Guicherit, R., Heij, B. (Eds.), The Climate System. A.A. Balkema Publishers/Swets & Zeitlinger Publishers, Lisse, The Netherlands, ISBN 90 5809 255 0, pp. 33–78.
Pritchard, H., Arthern, R., Vaughan, D., Edwards, L., 2009. Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets. Nature 461, 971–975.
Rahmstorf, S., 2007. Sea-level rise a semi-empirical approach to projecting future sea level rise. Science 315, 368–370.
Rignot, E., Jacobs, S., 2002. Rapid bottom melting widespread near Antarctic ice sheet grounding lines. Science 296, 2020–2023.
Rotmans, J., 1990. IMAGE: an Integrated Model to Assess the Greenhouse Effect. Kluwer Academic Publishers, Boston.
Socolow, R., Lam, S., 2007. Good enough tools for global warming policy-making. Philosophical Transactions of the Royal Society A 365, 897–934.
Solomon, S., Plattner, G., Knutti, R., Friedlingstein, P., 2009. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences 106 (6), 1704–1709.
Solomon, S., Daniel, J., Sanford, T., Murphy, D., Plattner, G., Knutti, R., Friedlingstein, P., 2010. Persistence of climate changes due to a range of greenhouse gases. Proceedings of the National Academy of Sciences 107, 18354–18359.
Sterman, J., 1994. Learning in and about complex systems. System Dynamics Review 10 (2–3), 291–330.
Sterman, J., 2000. Business Dynamics. Irwin McGraw Hill, Boston, MA.
Sterman, J., 2008. Risk communication on climate: mental models and mass balance. Science 322, 532–533.
Sterman, J., 2011. Communicating climate change risks in a skeptical world. Climatic Change 108, 811–826.
Sterman, J., Booth Sweeney, L., 2002. Cloudy skies: assessing public understanding of climate change. System Dynamics Review 18 (2), 207–240.
Sterman, J., Booth Sweeney, L., 2007. Understanding public complacency about climate change: adults' mental models of climate change violate conservation of matter. Climatic Change 80, 213–238.
Sterman, J., Fiddaman, T., Franck, T., et al., 2011. World Climate: a Role-Play Simulation of Global Climate Negotiations. Working Paper. MIT Sloan School of Management. jsterman.scripts.mit.edu/docs/World Climate.pdf.
Stern, D., Kaufmann, R., 1998. Annual estimates of global anthropogenic methane emissions: 1860–1994. In: Trends Online: a Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn.. http://dx.doi.org/10.3334/CDIAC/tge.001. cdiac.ornl.gov/trends/meth/ch4.htm
UNEP, 2010. The Emissions Gap Report. United Nations Environment Programme (UNEP). Available at: www.unep.org/publications/ebooks/emissionsgapreport/.
UNEP, 2011. Bridging the Emissions Gap. United Nations Environment Programme (UNEP). Available at: www.unep.org/publications/ebooks/bridgingemissionsgap.
van Aardenne, J., Dentener, F., Olivier, J., et al., 2001. A 1 × 1 degree resolution dataset of historical anthropogenic trace gas emissions for the period 1890–1990. Global Biogeochemical Cycles 15 (4), 909–928.
Vermeer, M., Rahmstorf, S., 2009. Global sea level linked to global temperature. Proceedings of the National Academy of Sciences 106 (51), 21527–21532.
Weitzman, M., 2009. On modeling and interpreting the economics of catastrophic climate change. Review of Economics and Statistics 91 (1), 1–19.
Wigley, T., 2008. MAGICC/SCENGEN 5.3: User Manual (V2). www.cgd.ucar.edu/cas/wigley/magicc/.
Wullschleger, S., Post, W., et al., 1995. On the potential for a CO_2 fertilization effect in forests: estimates of the biotic growth factor based on 58 controlled-exposure studies. In: Woodwell, G., Mackenzie, F. (Eds.), Biotic Feedbacks in the Global Climatic System. Oxford Univ. Press, New York, pp. 85–107.