C-ROADS Simulator Reference Guide

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# Background

## Purpose and intended use

The purpose of the C-ROADS (Climate-Rapid Overview and Decision Support) simulator is to improve public and decision-maker understanding of the long-term implications of possible greenhouse gas emissions futures by allowing access to a rigorous – but rapid and user-friendly – computer simulation of the impacts of greenhouse gas emissions and land use decision-making on global temperature and sea level rise.

Research shows that many people, including highly educated adults with substantial training in science, technology, engineering, or mathematics, misunderstand the fundamental dynamics of the accumulation of carbon and heat in the atmosphere (Brehmer, 1989; Sterman, 2008). Such misunderstandings can prevent decision-makers from recognizing the long-term climate impacts likely to emerge from specific policy decisions.

As a result of these misunderstandings, many people’s intuitive predictions of the response of the global climate system to emissions cuts are not accurate and often underestimate the degree of emissions reductions needed to stabilize atmospheric carbon dioxide levels. These misunderstandings also lead people to underestimate the lag time between changes in emissions and changes in global mean temperature.

Furthermore, people charged with making decisions related to climate change – climate professionals, corporate and government leaders, and citizens – may understand the emissions reduction proposals of individual nations (such as those proposed under the United Nations Framework Convention on Climate Change process) but lack tools for assessing the likely collective impact of those individual proposals on future atmospheric greenhouse gas concentrations, temperature changes, and other climate impacts.

These challenges to effective decision-making in regard to climate change are typical of the challenges facing decision-makers in other dynamically complex systems. Research shows that people often make suboptimal, biased decisions in dynamically complex systems characterized by multiple positive and negative feedbacks, time delays, and nonlinear cause-and-effect relationships (Brehmer, 1989; Kleinmuntz and Thomas,1987; Sterman, 1989). In such situations, computer simulations offer laboratories for learning and experimentation and can help improve decision-making (Morecroft and Sterman, Eds., 1994; Sterman, 2000). Critical climate policy decisions will be made at the local, national, and global scales in the coming months and years. Key stakeholders need transparent tools grounded in the best available science to provide decision support for real-time exploration of different policy options (Corell *et al.*, 2009).

Our conversations with stakeholders, such as negotiators tasked with reaching global climate agreements or leaders working to influence those agreements, suggest that even within very high-level policy-making discussions, the ability to understand the aggregate effects of national, regional, or sectoral mitigation commitments on atmospheric CO2 level and temperature is limited by the scarcity of simple, real-time decision-support tools. The C-ROADS simulator is a tool intended to close this gap.

**Thus, the purpose of C-ROADS is to improve public and decision-maker understanding of the long-term implications of international emissions and sequestration futures with a rapid-iteration, interactive tool as a path to effective action that stabilizes the climate.**

We created C-ROADS to provide a transparent, accessible, real-time decision-support tool that encapsulates the insights of more complex models. The simulator helps decision-makers improve their understanding of the planetary system’s responses to changes in greenhouse gas (GHG) emissions, including CO2 from fossil fuel use, CO2 emissions from land use practices, and changes in other greenhouse gases.

C-ROADS has been used in strategic planning sessions for decision-makers from government, business, civil society, and in interactive role-playing policy exercises[[1]](#footnote-1). An online version for broad use is also available.

C-ROADS provides a consistent basis for analysis and comparison of policy options, grounded in well-accepted science. By visually and numerically conveying the projected aggregated impact of national-level commitments to GHG emission reductions, the model allows users to see and understand the gap between ‘policies on the table’ and actions needed to stabilize GHG concentrations and limit the risks of “dangerous anthropogenic interference” in the climate. In this way, C-ROADS offers decision-makers a way to determine if they are on track towards their goals, and to discover – if they are not on track – what additional measures would be sufficient to meet those goals.

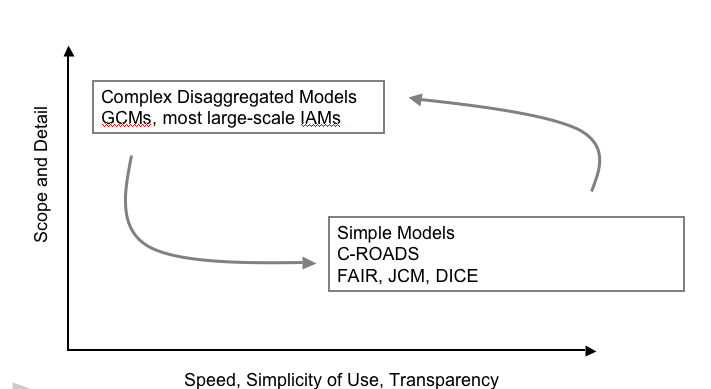
The C-ROADS simulator allows for fast-turnaround, hands-on use by decision-makers. It emphasizes:

* Transparency: equations are available, easily auditable, and presented graphically.
* Understanding: model behavior can be traced through the chain of causality to origins; we don’t say “because the model says so.”
* Flexibility: the model supports a wide variety of user-specified scenarios at varying levels of complexity.
* Consistency: the simulator is consistent with historic data, the structure and insights from larger models, and the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5).
* Accessibility: the model runs with a user-friendly graphical interface on a laptop computer, in real time.
* Robustness: the model captures uncertainty around the climate outcomes associated with emissions decisions.

The C-ROADS simulator is not a substitute for larger integrated assessment models (IAMs) or detailed climate models, such as General Circulation Models (GCMs). Instead, it captures some of the key insights from such models and makes them available for rapid policy experimentation. This is important for negotiators and other stakeholders who need to appreciate the consequences of possible emissions reductions commitments quickly and accurately.

Figure 1.1 shows one way of representing C-ROADS in the context of other tools to help navigate climate complexity. Other more complex and disaggregated models are important for giving decision-makers information on possible futures with higher degrees of spatial resolution and more details on climate impacts and economic considerations than simple models such as C-ROADS. Simple models thus complement these more disaggregated models, allowing users to gain general insights that can be refined with more complex models as needed. In turn, the insights of more complex models can be incorporated into simple models (as has been done for C-ROADS) in order to improve the performance of the simpler models and enhancing their ability to bring analysis and scenario testing into policy debate, negotiation, and decision-making in real time.

Figure . C-ROADS Complements Other Tools For Navigating Climate Complexity



## Overview

The C-ROADS simulator was constructed according to the principles of System Dynamics (SD), which is a methodology for the creation of simulation models that help people improve their understanding of complex situations and how they evolve over time. The method was developed by Jay Forrester at the Massachusetts Institute of Technology in the 1950’s and described in his book Industrial Dynamics (Forrester, 1961). SD was the methodology used to create the World3 simulation model that provided the basis for the book *The Limits To Growth* (Meadows *et al.*, 1972). System dynamics has been described more recently by John Sterman in *Business Dynamics* (Sterman, 2000).

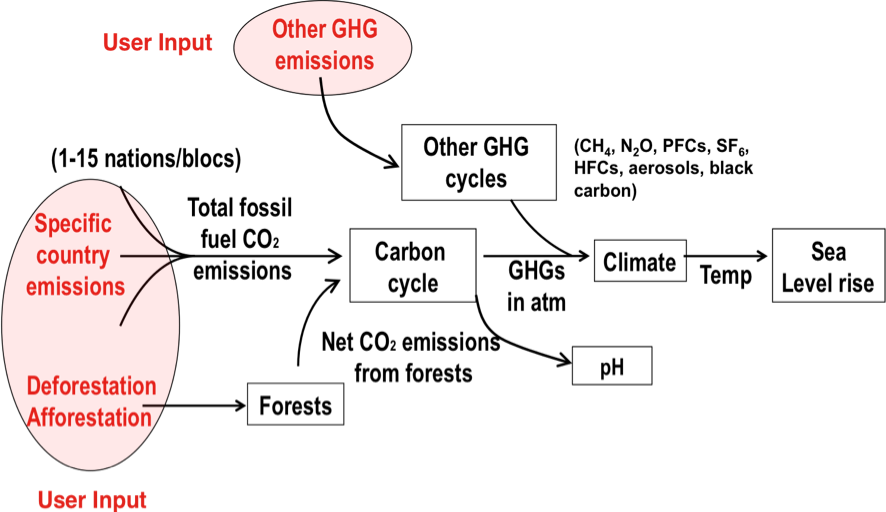
System dynamics computer simulations, including the C-ROADS simulator, consist of linked sets of differential equations that describe a dynamic system in terms of accumulations (stocks) and changes to those stocks (inflows and outflows). Feedback, delays, and non-linear responses are all included in the simulation. System dynamics simulations help users understand the observed behavior of systems and anticipate future behavior under a variety of scenarios.

The C-ROADS simulator is the product of many years of effort, beginning as the graduate research of Tom Fiddaman (Fiddaman, 1997), under the direction of John Sterman, and continued by Tom Fiddaman at Ventana Systems and Lori Siegel, Andrew Jones, and Elizabeth Sawin for Climate Interactive.

The simulation model is based on the biogeophysical and integrated assessment literature and includes representations of the carbon cycle, other GHGs, radiative forcing, global mean surface temperature, and sea level change. Consistent with the principles articulated by, e.g., Socolow and Lam, 2007, the simulation is grounded in the established literature yet remains simple enough to run quickly on a laptop computer.

The basic structure of the C-ROADS simulator is shown in Figure 1.2. Fossil fuel carbon dioxide emissions scenarios for individual nations or groups of nations are aggregated into total fossil fuel CO2 emissions. These combine with additional uptake and/or release of CO2 from land use decisions to form the input to the carbon cycle sector of the model. CO2 concentrations thus determined combine with the influence on net radiative forcing of other well-mixed GHGs (CH4, N2O, PFCs, SF6, and HFCs) via their explicit cycles, to determine the global temperature change, which in turn determines sea level rise.

Figure . Schematic View of C-ROADS Structure



The model uses historical data through the most recent available figures, including country-level CO2 emissions from fossil fuels (FF) (1850-2016: CDIAC - Boden *et al*., 2017, Global Carbon Budget – Le Quere *et al*, 2017, and PRIMAP-hist – Gütschow *et al*, 2018), CO2 emissions from changes in land use (1850-2015: Houghton and Nassikas, 2017), and GDP and population (1850-2016: Maddison, 2008 and World Bank, 2017). Other well-mixed GHGs historical data, from PRIMAP-hist (Gütschow *et al*, 2018), extend through 2015. PRIMAP-hist only provides the total HFC for each country so the allocation of each HFC type is determined from data provided by the European Commission Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. (2014).

Business As Usual Reference Scenario (RS) CO2 and other well-mixed gas emissions, population, and GDP default projections are all calibrated to be consistent with the IPCC AR5 SSP4/RCP8.5 scenario in terms of rates yet accounting for divergences in recent years’ data from the IPCC projections. Users may change the assumptions driving population, GDP per capita, and emissions per GDP to adjust the RS. Global RCP trajectories for calibration are also available.

The core carbon cycle and climate sector of the model is based on Dr. Tom Fiddaman’s MIT dissertation (Fiddaman, 1997). The model structure draws heavily from Goudriaan and Ketner (1984) and Oeschger and Siegenthaler *et al.* (1975). The sea level rise sector is based on Rahmstorf, 2007. In the current version of the simulation, temperature feedbacks to the carbon cycle are not included, nor are the economic costs of policy options or of potential climate impacts.

Model users determine the path of net GHG emissions (CO2 from FF and land use, CH4, N2O, PFCs, SF6, HFCs, and CO2 sequestration from afforestation) at the country or regional level, through 2100. The model calculates the path of atmospheric CO2 and other GHG concentrations, global mean surface temperature, sea level rise, and ocean pH changes resulting from these emissions.

The user can choose the level of regional aggregation. Currently, users may choose to provide emissions inputs for one, three, six, or fifteen different blocs of countries, depending on the purpose of the session. Outputs may be viewed for any of these aggregation levels. Other key variables, such as per capita emissions, energy and carbon intensity of the economy (e.g., tonnes C per dollar of real GDP), and cumulative emissions, are also displayed.

The model allows users to test a wide range of proposals for future emissions. Users can specify emissions reductions as a chosen annual rate, a target in a given year based on emissions, emissions intensity, or emissions per capita, all of which may be relative to a reference year or reference scenario, or a global target to be achieved by equitable emissions intensity or per capita. Besides specifying changes to the trajectories, it is also possible to specify CO2 emissions by Excel spreadsheet inputs or by graphical inputs. Similarly, the user may graphically input the CO2equivalent (CO2eq) emissions, such that each gas changes proportionally to the RS of each well-mixed greenhouse gas. Finally, the user may specify the reduction in emissions on a linear basis to be calculated as a percent of emissions in a reference year. With these options, users may simulate specific sets of commitments, such as those under discussion by national governments, or those proposed by academic or advocacy groups.

# Model structure overview

C-ROADS simulations run from the year 1850 through the year 2100. Model values are updated every 0.25 years. The model stores and can plot and print the output for every time step or for other time intervals, as desired.

C-ROADS simulator is a synthesis of several sub-models.

* Regional CO2 Emissions;
* Other greenhouse gases (CH4, N2O, PFCs, SF6, and HFCs);
* Land use;
* Carbon cycle;
* Global Average Surface Temperature; and
* Sea level rise
* pH.

Various platforms use C-ROADS, with user interface controls geared toward various audiences.

# Formulation[[2]](#footnote-2)

## Introduction

The **Regional CO2 Emissions** sector captures the historical and projected CO2 fossil fuel (FF) emissions for nations or regions and aggregates those emissions into the global CO2 fossil fuel emissions parameter that serves as input into the carbon cycle sub-model of C-ROADS. The *CO2 Fossil Fuel Emissions* variable is the final output of this sector and feeds into the carbon cycle sector. It is determined either by *Historical Emissions* or *Projected CO2 FF emissions,* depending upon the simulated year. The emissions sector has three primary functions within the C-ROADS simulator.

* It aggregates national or regional fossil fuel CO2 emissions into a single global emissions parameter to feed into the carbon sector sub-model.
* It allows the user a choice of the level of national/regional aggregation (defined in Section 3.3.4) and four main input modes (IMs) (defined in Section 3.4) for designating future emissions. It allows the user to graphically view and compare global CO2 fossil fuel emissions trajectories and national or regional per capita CO2 emissions under different scenarios.

The core structure of the **Regional Reference Scenario CO2 Emissions** sector is shown in Figure 3.1. Population projections are driven by UN projections, GDP projections are driven by population and GDP per capita, and emissions are driven by GDP and emissions per GDP. Parameters are set so that GDP projections are consistent with the IPCC’s AR5 Shared Socioeconomic Pathways (SSPs), particularly SSP4, and emissions are consistent with AR5 Representative Concentration Pathway (RCP) 8.5 projections, as defined in Section 3.3.3. Although consistent, historic data now extends beyond when the RCP scenarios were created such that the RS often diverges from RCP8.5.

RCP projections are obtained from the IASSA website <http://www.iiasa.ac.at/web-apps/tnt/RcpDb> (RCP2.6: van Vuuren *et al*, 2007;RCP4.5: Clarke, *et al*, 2007, Smith and Wigley, 2006, and Wise *et al*, 2009; RCP6.0: Fujino *et al*, 2006, Hijioka *et al*, 2008; and RCP8.5: Riahi *et al*, 2007).

Figure . Structure of Regional Reference Scenario CO2 Emissions



The stand-alone version of C-ROADS does not include calibration data. Another difference is that data variables are instead inputted as lookup tables. The model code is, therefore, adjusted accordingly, requiring *Time* in the equations.

## Sources of Historical Data

Historical national CO2 FF emissions were obtained from the Carbon Dioxide Information Analysis Center, Global Carbon Budget, and PRIMAP-hist (Boden *et al.*, 2017, Le Quere *et al*, 2017, and Gütschow *et al*, 2018). Historical population and GDP data in the Data Model are from the Conference Board and Groningen Growth and Development Centre for 1850-1959 (Maddison, 2008) and from the World Bank Indicators for 1960-2016 (World Bank, 2019). We aggregate these data to import into our data model of 180 countries, which then aggregates those data into the 20 COP blocs.

## Reference Scenario Calculation

This section presents the structure, inputs, and equations for RS CO2 FF emissions; similar structures determine the other GHGs as detailed in Section 3.8.2. Figure 3.2 through Figure 3.4 present population, GDP per capita, and GDP. Figure 3.4 shows CO2 per GDP rates of change driving CO2 FF per GDP over time, and, with population and GDP per capita, CO2 FF emissions over time.

### Population and GDP

Population defaults to use the UN’s medium fertility projections (UN, 2019) for 192 nations aggregated according to its COP bloc. However, it can be adjusted to a setting that is continuous between the low, medium, and high UN projections. For each of 20 COP regions, the starting rate converges to a minimum rate over the region-specified times aimed to achieve long term convergence of GDP per capita in terms of purchase power parity (PPP) and be consistent with SSP range. GDP is also presented in terms of market exchange rates (MER). The default time to reach the convergence rate and the default starting GDP per capita rate may be changed for each of the 20 regions; however, they may also be adjusted by 6 region inputted changes from the default.

.

Figure 3.2 Structure of RS Population

****

Figure 3.3 Structure of RS GDP per capita and GDP

****

| Table 3‑1 Population and GDP | | | |
| --- | --- | --- | --- |
| **Parameter** | **Definition** | | **Units** |
| **RS Population[COP]** | Population depends on chosen RS.  RS UN population[COP]\*million people | | million people |
| **RS UN population** | IF THEN ELSE(RS Population scenario<2, RS Weight to low\*UN Population LOW[COP]+(1-RS Weight to low)\*UN Population MED[COP], RS Weight to high\*UN Population HIGH[COP]+(1-RS Weight to high)\*UN Population MED[COP]) | | million people |
| **RS Weight to low** | 2 - Population scenario | | Dmnl |
| **RS Weight to high** | Population scenario – 2 | | Dmnl |
| **RS GDP PPP** | IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, Historic COP GDP [COP], RS GDP per capita[COP]\*RS population  [COP])/trillion PPP 2011 dollars | |  |
| **RS GDP[COP]** | Sets the RS GDP to be PPP.  RS GDP PPP[COP] | | T$ 2011 PPP/year |
| **RS GDP per capita rate [COP]** | GDP per capita rate of change over time, converging to long term annual rate defaulted to 1% per year.  INTEG(RS Change in GDP per capita rate[COP], RS Starting GDP per cap rate[COP]) | 1/year | |
| **RS Starting GDP per cap rate[COP]** | Projected GDP per capita rate in the year projections start, based on historic rates, adjustable by user controlled amounts.  MAX(Historic GDP per cap rate[COP],RS Minimum starting GDP per capita rate)+Increase in starting GDP per capita rate semi agg[Semi Agg]/"100 percent" | 1/year | |
| **Increase in starting GDP per capita rate semi agg** | User controlled inputs to change the starting projected GDP per capita rates, simplified to apply 6-region inputs to all 20 regions.  IF THEN ELSE(Change RS globally, Global increase in starting GDP per capita rate, Increase in starting GDP per capita rate semi agg semi agg[Semi Agg]) | Percent/year | |
| **Effective CO2 and GDP last historic year** | If Use BAU, forces projections of CO2 and GDP to start in the last BAU year of 2005, overriding the actual data from 2005-2016.  IF THEN ELSE(Use BAU, RCP first projection year,Last year of CO2 FF per GDP data) | Year | |
| **RS Change in GDP per capita rate [COP]** | IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, 0, RS GDP per capita rate Adjustment[COP]\*RS GDP per capita rate[COP]) | 1/year/year | |
| **RS Projected GDP per capita [COP]** | INTEG(RS Change in GDP per capita[COP], First projected GDP per capita[COP]) | $ 2011 PPP/year/ person | |
| **RS Change in GDP per capita [COP]** | IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, 0, RS GDP per capita rate[COP]\*RS Projected GDP per capita[COP]) | $ 2011 PPP/year/ person/year | |
| **First projected GDP per capita [COP]** | get data between times(Historic GDP per capita[COP],Effective CO2 and GDP last historic year, Interpolate) | $ 2005PPP/year/ person | |
| **Historic GDP per capita [COP]** | ZIDZ(Historic COP GDP[COP],Historic COP population[COP]) | $ 2005PPP/year/ person | |
| **RS GDP per capita [COP[** | IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, Historic GDP per capita[COP], RS Projected GDP per capita[COP]) | $ 2011 PPP/year/ person | |
| **RS GDP per capita MER[COP]** | RS GDP per capita[COP]/PPP 2011 to MER 2010 COP[COP] | $2010 MER/year/ person | |
| **RS GDP PPP[COP]** | RS GDP in purchase power parity (PPP).  IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, Historic COP GDP [COP], RS GDP per capita[COP]\*RS population[COP])/trillion PPP 2011 dollars | T$ 2011 PPP/year | |
| **RS GDP MER[COP]** | RS GDP in market exchange rates (MER).  RS GDP PPP[COP]/trillion MER 2010 dollars\*trillion PPP 2011 dollars/PPP 2011 to MER 2010 COP[COP] | T$ 2010 MER/year | |

### RS CO2 FF Emissions

Comparable to GDP per capita, RS CO2 FF emissions are determined as the product of population and GDP per capita and CO2 FF emissions per GDP. For each of 20 COP regions, the starting rate converges to a minimum rate over aggregated region-specified times aimed to achieve long term convergence of emissions per GDP. The default time to reach the convergence rate and the default starting emissions per GDP rate may be changed for each of the 20 regions; however, they may also be adjusted by 6 region inputted changes from the default.

Figure . Structure of Reference Scenario CO2 Emissions



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table ‑ Starting CO2 FF per GDP rate and Time to Reach Long Term Annual Rate of 0.5% | | | | |
| **Region** | **Recent CO2 per GDP rates default**  **(%/year)** | **BAU from 2012 CO2 FF per GDP Starting Rate (%/year)** | **RS CO2 per GDP time to reach convergence rate default (years)** | **BAU CO2 per GDP Time to reach convergence rate**  **(years)** |
| US | -1.9% | -1 | 25 | 20 |
| EU | -2.3% | -1 | 25 | 15 |
| Russia | -1.0% | -1 | 25 | 20 |
| Other Eastern Europe | -2.9% | -1 | 25 | 20 |
| Canada | -2.9% | -1 | 25 | 20 |
| Japan | -1.5% | -1 | 25 | 20 |
| Australia | -1.9% | -1 | 25 | 20 |
| New Zealand | -1.5% | -1 | 25 | 20 |
| South Korea | -1.5% | -1 | 25 | 20 |
| Mexico | -1.5% | -1.5 | 25 | 20 |
| China | -2.9% | -2.5 | 25 | 30 |
| India | -1.9% | -2 | 25 | 20 |
| Indonesia | -1.9% | -1.5 | 25 | 20 |
| Other Large Asia | -1.5% | -1.5 | 25 | 20 |
| Brazil | -1.5% | -1.5 | 25 | 20 |
| Other Latin America | -1.5% | -1.5 | 25 | 20 |
| Middle East | -1.5% | -1.5 | 25 | 20 |
| South Africa | -1.5% | -1.5 | 25 | 20 |
| Other Africa | -1.5% | -1.5 | 25 | 20 |
| Small Asia | -1.5% | -1.5 | 25 | 20 |

| Table 3‑3 RS CO2 FF Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **RS CO2 FF per GDP rate [COP]** | CO2 FF per GDP rate of change over time, converging to long term annual improvement defaulted to 0.3% per year.  INTEG(RS Change in CO2 FF per GDP rate[COP], IF THEN ELSE(Use BAU, RS Starting CO2 per GDP rate[COP], MIN(Recent CO2 per GDP rates[COP], RS Starting CO2 per GDP rate[COP])) | 1/year |
| **RS Change in CO2 FF per GDP rate[COP]** | IF THEN ELSE( Time<=Effective CO2 and GDP last historic year, 0, RS CO2 per GDP rate Adjustment[COP]\*RS CO2 FF per GDP rate[COP]) | 1/year/year |
| **Recent CO2 per GDP rates[COP]** | Rates of CO2 per GDP consistent with those calculated over the past decade. Adjusted by user inputted change from the default.  Recent CO2 per GDP rates default[COP]-Increase in starting CO2 per GDP reduction rate[Semi Agg]/"100 percent" | 1/year |
| **RS CO2 per GDP time to reach convergence rate** | MAX(One year, RS CO2 per GDP time to reach convergence rate default[Semi Agg]+Increase in GHG per GDP time to reach convergence rate[Semi Agg]) | Years |
| **RS CO2 per GDP rate Gap[COP]** | ZIDZ(RS Long term CO2 per GDP rate-RS CO2 FF per GDP rate[COP],RS CO2 FF per GDP rate  [COP]) | Dmnl |
| **RS CO2 per GDP rate Adjustment[COP]** | RS CO2 per GDP rate Gap[COP]/IF THEN ELSE(Use BAU, BAU CO2 per GDP Time to reach convergence rate[Semi Agg],RS CO2 per GDP time to reach convergence rate[Semi Agg]) | 1/year |
| **RS Projected CO2 FF per GDP[COP]** | INTEG(RS Change in CO2 FF per GDP[COP], First projected CO2 FF per GDP[COP]) | tonsCO2/T$ 2011 PPP |
| **RS Change in CO2 FF per GDP[COP]** | IF THEN ELSE(Time<=Effective CO2 and GDP last historic year, 0, RS CO2 FF per GDP rate[COP]\*RS Projected CO2 FF per GDP[COP]) | tonsCO2/T$ 2011 PPP/year |
| **First projected CO2 FF per GDP[COP]]** | get data between times(Historic CO2 per GDP[COP], Effective CO2 and GDP last historic year, Interpolate) | tonsCO2/T$ 2011 PPP |
| **Historic CO2 per GDP[COP]** | ZIDZ(Historic COP CO2[COP],Historic COP GDP[COP])\*TonCO2 per GtonCO2\*trillion PPP 2011 dollars | tonsCO2/T$ 2011 PPP |
| **RS CO2 FF per GDP[COP[** | IF THEN ELSE(Time<Last year of CO2 FF per GDP data, Historic CO2 per GDP[COP], RS Projected CO2 FF per GDP[COP]) | tonsCO2/T$ 2011 PPP |
| **RS CO2 FF per GDP MER[COP]** | RS CO2 FF per GDP[COP]\*PPP 2011 to MER 2010 COP[COP]\*trillion MER dollars/trillion PPP dollars | tonsCO2/T$ 2005 MER |
| **RS Calculated CO2 FF emissions[COP]** | IF THEN ELSE( Time<=Effective CO2 and GDP last historic year, Historic COP CO2[COP], RS population[COP]\*RS GDP per capita[COP]\*RS CO2 FF per GDP[COP]/ TonCO2 per GtonCO2/trillion PPP 2011 dollars) | GtonsCO2/year |

### External Calibration Scenarios

When *Choose RS* = 1, the global emissions of each GHG follow the selected RCP scenario. Likewise, when *Test RCP for nonCO2* = 1, the global emissions of each nonCO2 GHG follow the selected RCP scenario. C-ROADS provides calibration scenarios from RCP. The reported output from which these inputs are derived is more aggregated (less detailed) than C-ROADS’ COP regions, and therefore it was necessary to downscale the output to match. However, it is only the global values that matter for calibration of the GHG and climate system; regional values were used to guide parametric estimates for building the RS in Section 3.3.

RCP output is available for 4 scenarios to achieve 4 different radiative forcings by the end of the century (RCP2.6, RCP4.5, RCP6.0, and RCP8.5). Regions are R5ASIA, R5LAM, R5MAF, R5OECD, R5REF, and World.

| Table ‑ Scenario Inputs | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| Choose RS | Specifies global emissions and other forcings to follow those of the selected RCP scenario if set to 1 ; Otherwise, Calculated according to UN population and assumptions about rates of GDP per capita, and emissions per GDP, consistent with AR5 RCP8.5 but updated to reflect trends of GDP per capita and CO2 per GDP over the last decade. | 0-1 | 0 | Dmnl |
| Test RCP for nonCO2FF GHGs | Specifies global emissions of nonCO2 to follow those of the selected RCP scenario if set to 1 | 0-1 | 0 | Dmnl |
| RCP SelectedScenarios | Chosen RCP Scenario | 1-4 | 4 | Dmnl |
|  | Used when Choose RS = 1 for the global emissions of each GHG or when Test RCP for nonCO2 = 1 for the global emissions of each nonCO2 GHG.  1 = RCP26  2 = RCP45  3 = RCP60  4 = RCP85 | | | |

Table 3‑5 COP-RCP Region Mapping

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| COP RCP mapping | R5ASIA | R5LAM | R5MAF | R5OECD | R5REF | World |
| OECD US | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD EU27 | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD Russia | 0 | 0 | 0 | 0 | 1 | 1 |
| Other Eastern Europe | 0 | 0 | 0 | 0 | 1 | 1 |
| OECD Canada | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD Japan | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD Australia | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD New Zealand | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD South Korea | 0 | 0 | 0 | 1 | 0 | 1 |
| OECD Mexico | 0 | 1 | 0 | 0 | 0 | 1 |
| G77 China | 1 | 0 | 0 | 0 | 0 | 1 |
| G77 India | 1 | 0 | 0 | 0 | 0 | 1 |
| G77 Indonesia | 1 | 0 | 0 | 0 | 0 | 1 |
| G77 Other Large Asia | 1 | 0 | 0 | 0 | 0 | 1 |
| G77 Brazil | 0 | 1 | 0 | 0 | 0 | 1 |
| G77 Other Latin America | 0 | 1 | 0 | 0 | 0 | 1 |
| G77 Middle East | 0 | 0 | 1 | 0 | 0 | 1 |
| G77 South Africa | 0 | 0 | 1 | 0 | 0 | 1 |
| G77 Other Africa | 0 | 0 | 1 | 0 | 0 | 1 |
| G77 Small Asia | 1 | 0 | 0 | 0 | 0 | 1 |

|  |  |  |
| --- | --- | --- |
| Table 3‑6 RS CO2 FF Emissions Calculated Parameters | | |
| **RS CO2 FF emissions[COP]** | Annual RS CO2 FF emissions from each COP bloc. The default uses the emissions consistent with RCP8.5 but updated to reflect trends of GDP per capita and CO2 per GDP over the last decade, calculated for each region as the product of population, GDP per capita, and CO2 FF per GDP.  RS Calculated CO2 FF emissions[COP] | GtonsCO2/year |
| **RS CO2 FF trend[COP]** | Calculates the rate of change of the RS trajectory for each COP bloc:  FRAC TREND(RS CO2 FF emissions[COP],One year)  See Macro detail for FRAC TREND (Table 3‑7) | 1/year |
| **Global RS rate of change** | Calculates the rate of change of the global RS trajectory:  FRAC TREND(Global RS CO2 FF emissions ,One year)  See Macro detail for FRAC TREND (Table 3‑7) | 1/year |

Table 3‑7 presents the macro for FRAC TREND, which calculates the rate of change of a given variable over a specified trend time.

Table 3‑7 Macro Detail for FRAC TREND

|  |
| --- |
| :MACRO: FRAC TREND(input,trend time)  FRAC TREND = IF THEN ELSE( input > 0 :AND: smooth input > 0  ,LN(input/smooth input)/trend time, 0)  ~ 1/trend time  ~ |  smooth input = SMOOTH(input,trend time)  ~ input  ~ |  :END OF MACRO: |

### National Groupings

Emissions scenarios can be created by the user at a variety of levels of national aggregation, and the resulting emissions pathways can be evaluated at a variety of levels of aggregation as well. Table 3‑8 summarizes these groupings and labels, whereas *Table 3‑9* and *Table 3‑10* describe these groupings in more detail. Regardless of aggregation level at which scenarios are created and reported, the underlying model is based on data disaggregated into 20 regions, labeled as COP blocs. Model input choices affect those choices for each COP bloc within the given group.

Model output can be shown as a six-region grouping, which is the default for C-ROADS, as shown for the Reference Scenario (RS) Case in Figure 3.2 through Figure 3.9

* US,
* EU,
* China,
* India,
* Other Developed Countries,
* Other Developing Countries.

Users can also test scenarios in more detail using the 15-regions grouping of the Major Economies Forum (MEF).

Fossil fuel CO2 emissions can also be shown in a simplified view that aggregates nations into three classes:

* Developed Countries;
* Developing A Countries; and
* Developing B Countries.

The assignment of countries to these groups is shown in *Table 3‑10*. As a general approximation, the Developed Countries group corresponds to the Annex I countries within the UNFCCC process, the Developing Countries A group consists of the large developing countries with rising emissions, including China and India, and the Developing Countries B group consists of smaller developing countries, including the least developed countries and the small island states. This three level grouping is most useful with audiences seeking a general introduction to climate dynamics and for simplified role-playing exercises. Table 3‑11 presents the aggregation input choices.

Table 3‑8 Summary of Aggregation Level and Corresponding Labels

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Level of Aggregation** | **3 Regions** | **6 Regions** | **15 Regions** | **20 Regions** |
| Label | Aggregated Regions | Semi Agg | Economic Regions | COP Blocs |
| Countries/groups | * *Developed* * *Developing A* * *Developing B* | * *US* * *EU* * *Other Developed* * *China* * *India* * *Other Developing* | * *US* * *EU* * *Russia* * *Canada* * *Japan* * *Australia* * *South Korea* * *Mexico* * *China* * *India* * *Indonesia* * *Brazil* * *South Africa* * *Developed non MEF* * *Developing non MEF* | * *US* * *EU* * *Russia* * *Other Eastern Europe* * *Canada* * *Japan* * *Australia* * *New Zealand* * *South Korea* * *Mexico* * *China* * *India* * *Indonesia* * *Other Large Asia* * *Brazil* * *Other Latin America* * *Middle East* * *South Africa* * *Other Africa* * *Small Asia* |

*Table 3‑9 Regions of Interest for C-ROADS*

|  |  |  |  |
| --- | --- | --- | --- |
| **Six Regions** | **MEF Categories** | **MEF Regions** | **Individual Nations** |
| United States (US) | Developed Nations in MEF | United States (US) | United States (US) |
| European Union (EU) | European Union (EU) 27 (EU27) (plus Iceland, Norway and Switzerland) | Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the United Kingdom, Iceland, Norway and Switzerland. (includes former Czechoslovakia) |
| Other Developed Countries | Russia | Russia (includes fraction of former USSR) |
| Canada | Canada (includes rest of other North America) |
| Japan | Japan |
| Australia | Australia |
| South Korea | South Korea |
| Developed Non MEF | New Zealand | New Zealand |
| Other Eastern Europe | Albania, Bosnia & Herzegovinia, Croatia, Macedonia, Slovenia, Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (includes former Yugoslavia and fraction of former USSR) |
| China | Developing Nations in MEF | China | China |
| India | India | India |
| Other Developing Countries | Indonesia | Indonesia |
| Brazil | Brazil |
| South Africa | South Africa |
| Mexico | Mexico |
| Developing Non MEF | Other Large Developing Asia | Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore |
| Middle East | Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, South Arabia, Syria, Turkey, United Arab Emirates, Yemen, West Bank and Gaza (Occupied Territory) |
| Other Latin America | Argentina, Chile, Colombia, Peru, Uruguay, Venezuela, Bolivia, Costa Rica, Cuba, Dominican Rep., Ecuador, El Salvador, Guatemala, Haïti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Puerto Rico, Trinidad and Tobago. And Caribbean Islands |
| Other Africa | Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoro Islands, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea and Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zaire, Zambia, Zimbabwe, Mayotte, Saint Helena, West Sahara |
| Other Small Asia | Bangladesh, Burma, Nepal, Sri Lanka, Afghanistan, Cambodia, Laos, Mongolia, N. Korea, Vietnam, 23 Small East Asia nations |

*Table 3‑10 Additional Grouping Options*

|  |  |
| --- | --- |
| **Three Regions** | **Individual Nations** |
| Developed Countries | United States (US) |
| Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Spain, Sweden and the United Kingdom, Norway and Switzerland. (includes former Czechoslovakia) |
| Russia, Albania, Bosnia & Herzegovinia, Croatia, Macedonia, Slovenia, Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (includes former Yugoslavia and USSR) |
| Canada (includes rest of other North America) |
| Australia |
| New Zealand |
| Japan |
| South Korea |
| Developing A Countries | China |
| India |
| Indonesia, Philippines, Thailand, Taiwan, Hong Kong, Malaysia, Pakistan, Singapore |
| Brazil |
| South Africa |
| Mexico |
| Developing B Countries | Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, South Arabia, Syria, Turkey, United Arab Emirates, Yemen, West Bank and Gaza (Occupied Territory) |
| Argentina, Chile, Colombia, Peru, Uruguay, Venezuela, Bolivia, Costa Rica, Cuba, Dominican Rep., Ecuador, El Salvador, Guatemala, Haïti, Honduras, Jamaica, Nicaragua, Panama, Paraguay, Puerto Rico, Trinidad and Tobago. and Caribbean Islands |
| Algeria, Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoro Islands, Congo, Côte d'Ivoire, Djibouti, Equatorial Guinea, Eritrea and Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea Bissau, Kenya, Lesotho, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome & Principe, Senegal, Seychelles, Sierra Leone, Somalia, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zaire, Zambia, Zimbabwe, Mayotte, Saint Helena, West Sahara |
| Bangladesh, Burma, Nepal, Sri Lanka, Afghanistan, Cambodia, Laos, Mongolia, N. Korea, Vietnam, 23 Small East Asia nations |

Table 3‑11 Aggregate Level Inputs

| **Parameter** | **Definition** | **Range** | **Default Values** | **Units** |
| --- | --- | --- | --- | --- |
| Aggregate Switch | Aggregates nations according to user needs. | 0-3 | 1 | Dmnl |
|  | If set to 0, then inputs are set for 15 regions (13 MEF and 2 non MEF), as in Table 3‑9 | | | |
|  | If set to 1 (defaults), then inputs set for 6 economic regions as in Table 3‑9 | | | |
|  | If set to 2, then inputs are set globally | | | |
|  | If set to 3, then inputs are set inputs set for 3 aggregated regions as in Table3.10 | | | |
| Apply to CO2eq[COP] | Dictates the behavior of well-mixed GHGs (excluding CO2 land use). | 1-3 | 1 | Dmnl |
|  | 1= targets applied to non-land use CO2eq; each GHG changes by same proportion | | | |
|  | 2= targets applied to CO2 FF; other GHG's change by the same proportion as CO2 FF | | | |
|  | 3= targets applied to CO2 FF; other GHGs follow lookup table of proportionality to RS emissions, independent of CO2 FF | | | |
| Global apply to CO2eq choice | Allows the Apply to CO2eq to be chosen globally regardless of the aggregation level. | 0-1 | 0 | Dmnl |

Every variable that is labeled with the prefix "Regional" has the 20 COP regions mapped to the 15 economic regions

Every variable that is labeled with the prefix "Semi agg" has the 20 COP regions mapped to the 6 Semi-aggregated regions.

Every variable that is labeled with the prefix "Aggregated" has the 20 COP regions mapped to the 3 aggregaated regions.

| Table ‑ Aggregation Output | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **Economic Region Definition[COP, Economic regions]** | Tabbed array to define to which of the 15 economic regions (according to MEF) each of the COP blocs belongs, reflecting *Table 3‑9* | Dmnl |
| **Semi Agg Definition[COP,Semi Agg]** | Tabbed array to define to which of the 6 semi-aggregated regions each of the 20 COP blocs belongs, reflecting *Table 3‑9*. | Dmnl |
| **Aggregate Region Definition[COP,Aggregated Regions]** | Tabbed array to define to which of the 3 aggregated regions each of the COP blocs belongs, reflecting *Table 3‑9* | Dmnl |
| **Regional XXX[Economic regions]** | Aggregates variable XXX[COP] of 20 COP blocs into the 15 MEF regions.  Every variable that is labeled with the prefix "Regional" has the 20 COP regions mapped to these 15 MEF regions.  VECTOR SELECT(Economic Region Definition[COP!, Economic Regions], XXX[COP!]\*Economic Region Definition[COP!, Economic Regions], 0, VSSUM, VSERRATLEASTONE) | Units of disaggregated variable |
| **Semi Aggregated XXX[Semi Aggs]** | Aggregates variable XXX [COP] of 20 COP blocs into 6 regions.  Every variable that is labeled with the prefix "Semi agg" has the 20 COP regions mapped to these 6 Semi Agg regions.  VECTOR SELECT(Semi Agg Definition[COP!,Semi Agg], XXX[COP!]\*Semi Agg Definition[COP!, Semi Agg],0,VSSUM,VSERRATLEASTONE) | Units of disaggregated variable |
| **Aggregated XXX [Aggregated regions]** | Aggregates variable XXX[COP] of 20 COP blocs into 3 regions.  Every variable that is labeled with the prefix "Aggregated" has the 20 COP regions mapped to these 3 aggregated regions.  VECTOR SELECT(Aggregated Definition[COP!, Aggregated Regions],XXX[COP!]\*Aggregated Definition[COP!, Aggregated Regions], 0, VSSUM, VSERRATLEASTONE) | Units of disaggregated variable |
| **Global XXX** | Aggregates variable XXX[COP] of 20 COP blocs into 1 global region.  Every variable that is labeled with the prefix "Global" has the 20 COP regions mapped to the global level.  SUM(XXX[COP!]) | Units of disaggregated variable |

Figure . RS Population



Figure . RS GDP per Capita



Figure . RS GDP



Figure . RS CO2 FF per GDP



Figure . RS CO2 FF Emissions



## User Control of Population, GDP, and Emissions

The model allows users to test a wide range of scenario proposals for future emissions according to several Input Modes (IMs). With IM 1, users can specify emissions reductions at a chosen annual rate (e.g., x%/year, beginning in a specified year). Using IM 2, there are four target type options plus the no target option: 0) no target: 1) emissions reductions relative to a specified reference year (e.g., x% below 1990 by 2050); 2) emissions reductions relative to the chosen RS; 3) reductions in emissions intensity relative to a specified reference year; or 4) reductions in emissions per capita relative to a specified reference year. Users can select the years in which the scenarios would go into force, the target years, and other attributes to capture a wide range of scenario proposals. Besides specifying changes to the trajectories, it is possible to specify emissions by Excel spreadsheet inputs (IM 4). IM 6 allows the user to graphically input the CO2equivalent (CO2eq) emissions, such that each gas changes proportionally to the RS of each GHG, the trajectories of which are discussed in Section 3.8. With these options, users may simulate specific sets of commitments, such as those under discussion by national governments, or those proposed by academic or advocacy groups. The input mode numbering is no longer ordered integers because some have been omitted from previous versions due to becoming irrelevant.

Figure 3.10 illustrates how these IM determine the CO2 FF emissions. The following sections outline the six types of emissions input modes that the current version of C-ROADS can implement. More detailed information on the parameters, default settings, and key equations in the Regional CO2 Emissions sub-model are provided in Sections 3.4.1 through 3.4.4.

Figure . Structure of CO2 FF Emissions



Table 3‑13 Input Mode Inputs

| Parameter | Definition | Range | Default Values | Units |
| --- | --- | --- | --- | --- |
| Input mode[COP] | Defines input mode for each region depending on the level of aggregation. | 1-6 | 2 | Dmnl |
|  | 1 | Allows users to specify a peak year, before which emissions continue as RS, and after which emissions hold constant until another specified year, when emissions are reduced at an annual rate designated by the user. If the target type is set to 3, the changes apply to emissions per GDP instead of absolute emissions. | | |
|  | 2 | Allows users to specify the desired emissions level to be reached by a target year as a fraction of a reference year emissions level, as a fraction of the RS, as a result of a fraction of emissions intensity relative to that in a reference year or as a fraction of the RS intensity, or as a result of a fraction of emissions per capita relative to that in a reference year or as a fraction of the per capita of the RS. | | |
|  | 4 | CO2 FF emissions inputs are drawn from Microsoft Excel worksheets | | |
|  | 6 | Inputs global CO2 equivalent emissions, with the emissions of each GHG changed proportionally from the RS total CO2 equivalent emissions. | | |
| Same input switch | Determines whether all regions follow the same input mode. | 0-1 | 0 | Dmnl |
|  | 1 specifies that all regions use the same input mode, in which case *IM for each group* is used instead. | | | |
| IM for each group | Defines the Input mode for all COP blocs if *Same input switch* is set to 1 | 1-6 | 2 | Dmnl |
| CO2 makes up for other GHG limits | Forces the reductions of CO2 to be greater than specified to make up for those reductions not achieved by CH4 and/or N2O when their lower limits are reached. | 0-1 | 1 | Dmnl |
| Lower limit of CO2 FF emissions[COP] | Allows CO2 energy and industrial emissions to decrease to essentially 0 but avoids errors when determining rates of emissions change. |  | 1e-6 | GtonsCO2/year |

| Table 3‑14 CO2 FF Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **CO2 FF emissions unadjusted [COP]** | Annual CO2 emissions from fossil fuels and cement production, including bunker fuels, for each of the 20 COP blocs, in units of Gtons of CO2 per year. Trajectory depends on input mode. *Include country contributions* allows the user to exclude emissions from a country/region to test its contribution to the global impact.  IF THEN ELSE(Test inertia :AND: Threshold 2 Deg exceeded, Lower limit of CO2 FF emissions  , IF THEN ELSE(Input Mode[COP]=4, IM 4 FF CO2[COP]  ,IF THEN ELSE(Input Mode[COP]=6, IM 6 FF CO2[COP]  , IF THEN ELSE(Input Mode[COP]=1, IM 1 FF CO2[COP]  , IM 2 FF CO2[COP])))) | GtonsCO2/year |
| **CO2 FF emissions domestic[COP]** | If *CO2 makes up for other GHG limits* is set to 1 (default), reduces CO2 FF emissions unadjusted values by the amount that the nonCO2 emissions were specified to reduce but could not due to reaching their lower limits.  CO2 FF emissions unadjusted[COP]-CO2 makes up for other GHG limits\*(CH4 reductions needed by CO2 reductions[COP]+N2O reductions needed by CO2 reductions[COP]+SF6 reductions needed by CO2 reductions[COP]+PFC reductions needed by CO2 reductions[COP]) | GtonsCO2/year |
| **CO2 FF emissions[COP]** | MAX(Lower limit of CO2 FF emissions,CO2 FF emissions domestic[COP]-Annual GtonsCO2e supported from conditional pledges over time[COP]) | GtonsCO2/year |
| **RS emissions[COP]** | If Apply to CO2eq[cop] is set to 1, then the RS emissions includes all the nonforest CO2eq unless *DF follows GHGs*=1, in which case it includes all CO2eq emissions; otherwise it includes only CO2 FF emissions. The lower limit term (1e-6 GtonsCO2/year) avoids division by zero  MAX(IF THEN ELSE(Apply to CO2eq[COP]=1, IF THEN ELSE(Land use CO2 emissions follow GHGs[COP], RS CO2eq total[COP], RS CO2eq nonforest emissions[COP]), IF THEN ELSE(Land use CO2 emissions follow GHGs[COP], RS CO2 land use gross emissions[COP], 0)+RS CO2 FF emissions[COP]),Lower limit of CO2 FF emissions) | GtonsCO2/year |
| **CO2 FF emissions vs RS[COP]** | Calculates the ratio of actual CO2 FF emissions to RS so that the emissions of other GHGs may be proportionally changed when *Apply to CO2eq*=1 or 2.  ZIDZ(CO2 FF emissions[COP],RS CO2 FF emissions[COP]) | Dmnl |
| **Global CO2 FF Emissions** | Annual global emissions of CO2 from fossil fuels and cement production as sum of that from each COP bloc. However, if *Choose RS* = 1, the global emissions for the selected RCP scenario overrides that sum for projections.  IF THEN ELSE(Choose RS=1 :AND: Time>RCP first projection year, Selected RCP FF CO2 emissions [World], SUM(CO2 FF emissions[COP!])) | GtonsCO2/year |

Figure 3.11 Structure of Population

****

Figure 3.12 Structure of GDP

****

| Table 3‑15 Population Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **Population Growth Rate[COP]** | Annual change in population.  FRAC TREND(Population [COP],One year) | 1/year |
| **Global population Growth Rate** | Annual change in global population.  FRAC TREND(Global Population,One year) | 1/year |

| Table 3‑16 GDP Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **GDP[COP]** | RS GDP[COP]) | T$ 2011 PPP/year |
| **Gross world product** | Sum of GDP adjusted of all regions.  SUM(GDP[COP!]) | T$ 2011 PPP/year |
| **GDP Growth Rate[COP]** | Annual change in GDP.  FRAC TREND(GDP[COP],One year) | 1/year |
| **GWP Growth Rate** | Annual change in global world product.  FRAC TREND(Gross world product, One year) | 1/year |

### Input mode 1: Annual Change in Emissions

UnderInput mode 1 (IM 1), fossil fuel CO2 emissions grow at the RS rate until a year specified by the user when the growth of emissions stops. Emissions are then held constant until another specified year, when emissions are reduced at an annual rate designated by the user. This Input Mode allows for the testing of simple scenarios in which the growth, peak, and decline of regional emissions is controlled by the user. The model structure underlying IM 1 is shown in Figure 3.13. If the target type is set to 3, the changes apply to emissions per GDP instead of absolute emissions.

Figure . Structure of Input Mode 1



| Table ‑ Input Mode 1 FF CO2 Emissions Parameter Inputs | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| FF Stop Growth Year[COP] | Year when emissions (or emissions per GDP if the target type is set to 3) peak. | 2020-2100 | 2100 | Year |
| FF reduction start year[COP] | Year when emissions (or emissions per GDP if the target type is set to 3) start to decrease | 2020-2100 | 2100 | Year |
| Annual FF reduction[COP] | Annual rate at which emissions (or emissions per GDP if the target type is set to 3) decrease | 0-10 | 0 | %/year |

| Table ‑ Input mode 1 CO2 FF Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **IM 1 emissions[COP]** | ACTIVE INITIAL (IF THEN ELSE(Time<=FF stop growth year[COP],RS emissions[COP],Emissions with Stopped Growth[COP]\*IM 1 Relative Reduction[COP]), RS emissions[COP]) | GtonsCO2/year |
| **IM 1 emissions per GDP[COP]** | ACTIVE INITIAL (IF THEN ELSE(Time<=FF stop growth year[COP],RS emissions[COP]/GDP[COP],Emissions per GDP with Stopped Growth[COP]\*IM 1 Relative Reduction[COP]), RS emissions[COP]/GDP[COP]) | GtonsCO2/year |
| **IM 1 emissions from per GDP[COP]** | IM 1 emissions per GDP[COP]\*GDP[COP] | GtonsCO2/year |
| **IM 1 Emissions Reduction[COP]** | The relative emissions reduction at each time step compared to the reference year relative emissions, by definition 1, starting at the FF reduction start year for each COP bloc.  STEP(Annual FF emissions reduction[COP]/"100 percent"\*IM 1 Relative Reduction[COP],MAX(FF stop growth year[COP], FF reduction start year[COP])) | 1/year |
| **IM 1 Relative Reduction[COP]** | The relative emissions reduction at each time step compared to the reference year relative emissions, by definition 1, starting at the FF reduction start year for each COP bloc.  INTEG (IM 1 Emissions Reduction[COP],1) | Dmnl |
| **Emissions with Stopped Growth[COP]** | Emissions continue according to RS until the peak year, at which point they cap at that current level.  SAMPLE IF TRUE(Time <= FF stop growth year[COP]+TIME STEP, SMOOTH( RS emissions[COP],TIME STEP),RS emissions[COP]) | GtonsCO2/year |
| **Emissions per GDP with Stopped Growth[COP]** | Emissions per GDP continue according to RS until the peak year, at which point they cap at that current level.  SAMPLE IF TRUE (Time <= FF stop growth year[COP]+TIME STEP, Emissions with Stopped Growth[COP]/GDP[COP], Emissions with Stopped Growth[COP]/GDP[COP]) | GtonsCO2/year |
| **IM 1 Emissions vs RS[COP]** | For each bloc, the ratio of the target emissions to those of the RS.  XIDZ(IM 1 emissions[COP],RS emissions[COP], :NA:) | Dmnl |
| **IM 1 target type 2 Emissions vs RS[COP]** | For each bloc, the ratio of the target emissions to those of the RS from the emissions per GDP calculation.  XIDZ(IM 1 emissions from per GDP[COP],RS emissions[COP], :NA:) | Dmnl |
| **IM 1 FF CO2[COP]** | IF THEN ELSE(Final target type[COP]=3, IM 1 target type 2 Emissions vs RS[COP], IM 1 Emissions vs RS[COP])\*RS CO2 FF emissions[COP] | GtonsCO2/year |

### Input mode 2: Percent Change in Emissions by a Target Year

Input mode 2 (IM 2) allows users to specify the target level in a given *target year* and in two potential *interim target years* for each group of nations. The target type determines the nature of the target terms. For each region, the model defaults to a target type of 0, specifying that each trajectory follow the RS. The target levels are either in terms of 1) absolute emissions relative to a reference year; 2) absolute emissions relative to the RS in the target and/or interim target years; 3) *emissions intensity ref*, *i.e*., annual emissions per unit of GDP, relative to a reference year; Figure 3.14 shows the structure used to implement IM 2. Target types 3 and 4 depend on population and GDP, which are defined in Section 3.3.1.

When following target type 1, the model calculates a uniform annual rate sufficient to bring emissions from the current level to the specified level by the target year or interim target years. This exponential change is the default, but may be changed to be a linear or s-shape change, which exhibits rates of change that are slow, rapid, and then slow again. Beyond the target year, emissions remain capped at the level they have reached in the target year.

With target type 2, the model applies the change from RS linearly starting at 0 at the start year and rising to the full value of the percent change in the target year. For example, a 40% decrease starting in 2010 would be 0.3 times the RS value in 2030 and 0.6 times the RS in 2050. Beyond the target year, the percent of RS remains capped at the level reached in the target year.

When following target type 3, emissions and GDP changing at the same rate yield emissions per GDP intensity that remains constant. The carbon intensity target is relative to a reference year. Comparable to target type 2, the model applies the change in emissions intensity linearly starting at 0 at the start year and rising to the full value of the percent change in the target year. For example, 40% decrease from a reference year value of x by 2050 starting in 2010 would give an intensity of 0.3x in 2030 and an intensity of 0.6x in 2050. Beyond the target year, the emissions intensity remains capped at the level reached in the target year. Emissions intensity can decrease as a result of reduced annual emissions and/or increased GDP. Therefore, a reduction of emissions intensity does not necessarily translate to a reduction of emissions, and under many scenarios, decreasing emissions intensity in some regions does give rise to emissions growth.

With target type 4, the model applies the change from emissions intensity relative to the RS intensity linearly starting at 0 at the start year and rising to the full value of the percent change in the target year. Beyond the target year, the emissions intensity remains capped at the level reached in the target year.

For each target type, the emissions are constrained to not exceed the greater of the RS and RS adjusted by the ratio of GDP and population to their RS. For example, a percent greater than 0 for target type 2, assuming RS GDP and RS population, would have no effect on the actual emissions in the target year. The user may override the default post-target behavior with a continuation of the rate required to achieve the target level from the start or previous interim level, the resumption of the RS growth rate, or specified rate of change. An exception to this constraint is when testing global and three-region targets; then the model allows emissions to exceed RS.

Instead of addressing CO2 FF emissions independently from other greenhouse gases (GHGs), the user may choose to apply the changes to CO2 equivalents (CO2eq). The definition of CO2eq and method for applying IM 2 to CO2eq are further described in Section 3.8.

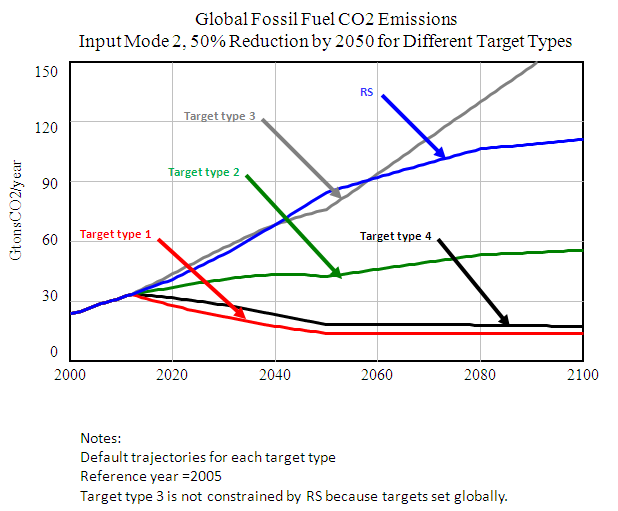
Figure 3.15 shows representative emissions under a scenario created using Input mode 2 with varying target types. In these scenarios, CO2 fossil fuel emissions (target types 1 and 2), emissions intensity (target type 3), or emissions per capita (target type 4), depending on the target type, reduce by 50% by 2050. Target types relative to a reference year, i.e., 1 and 3, default to use 2005 as the reference year. These trajectories are compared to that of the RS.

Figure . Structure of Input Mode 2



Figure . Representative Emissions Scenarios Created Using Input Mode 2

With Varying Target Types, Compared Against a Reference Scenario (RS)



| Table 3‑19 Input Mode 2 FF CO2 Emissions Parameter Inputs | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| Pct change in FF emissions Reg[COP] | Percent change in target measure by the target year, where the measure depends on the target type. | -99-200 | 0 | % |
| Pct interim change in FF emissions Reg[COP] | Percent change in target measure by the interim 1 target year, where the measure depends on the interim 1 target type. | -99-200 | 0 | % |
| Pct interim 2 change in FF emissions Reg[COP] | Percent change in interim 2 target measure by the target year, where the measure depends on the interim 2 target type. | -99-200 | 0 | % |
| Emissions reference year Reg[COP] | Year when emissions, intensity, or emissions per capita for target types 1, 3, or 4, respectively, are used to calculate future value based on the proportionality specified by the user. | 1990-2018 | 2005 | Year |
| Final target type Reg[COP] | Specifies that the nature of the target | 0-4 | 0 | Dmnl |
|  | 0 = no target | | | |
| REFYR | 1 = relative to a reference year emissions | | | |
| RS | 2 = relative to the RS | | | |
| INTENSITY REF | 3 = based on emissions intensity of GDP relative to a reference year intensity | | | |
| PER CAPITA REF | 4 = based on emissions per capita relative to a reference year emissions per capita | | | |
| Interim 1 target type Reg[COP] | Specifies that the nature of the interim 1, as for final target type | 0-4 | 0 | Dmnl |
| Interim 2 target type Reg[COP] | Specifies that the nature of the interim 2 target, as for final target type | 0-4 | 0 | Dmnl |
| FF change start year Reg[COP] | Year when the FF emissions begin to change | 2016-2100 | 2018 | Year |
| FF change interim 1 target year [COP] | Year when the first interim target emissions will be achieved | 2020-2100 | 2020 | Year |
| FF change interim 2 target year [COP] | Year when the second interim target emissions will be achieved | 2020-2100 | 2030 | Year |
| FF change target year Reg[COP] | Year when the desired change in emissions will be completed. | 2020-2100 | 2050 | Year |
| Ultimate Target[COP] | Overrides the default post-target trajectory | 0-3 | 0 | Dmnl |
| ULT INACTIVE | 0 = inactive |  |  |  |
| ULT SAME | 1 = Same rate required to get from start (or previous interim target if applicable) to target value | | | |
|  | 2 = Resumes RS growth | | | |
| ULT SPECIFIED | 3 = Specified rate | | | |
| Global ultimate target choice | Allows user to set post-target trajectory choice globally even when inputs are set to disaggregated level | 0-1 | 0 | Dmnl |
| Specified annual post target rate[COP] | For when Ultimate Target[COP] = ULT SPECIFIED (3), the user specifies the annual percent change from the target year to the final time. | -10-10 | 0 | Percent |
| Choose by aggregated region | Uses 3 region aggregated inputs for post target year trajectories. | 0-1 | 0 | Dmnl |
| Profile | 0=exponential, 1=linear, 2=s shape | 0-2 | 0 | Dmnl |
| Profile for s | 1=linear, 2=quadratic | 1-2 | 2 | Dmnl |
| Allow resumed growth | If set to 0, constrains the emissions by the previous target. Otherwise, emissions may grow from one target to the next. | 0-1 | 1 | Dmnl |
|  | 0=Forces emissions to not exceed those from the previous target |  |  |  |
|  | 1=Allows emissions to exceed those from the previous target |  |  |  |

| Table 3‑20 Input Mode 2 Supported Action Parameter Inputs | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| Annual GtonsCO2e in target year from Other Developed Supported Actions | The percentage change in emissions in the final year in a country that is supported by other regions. | -99-0 | 0 | Percent |
| Annual GtonsCO2e in target year from Supported Actions[Semi Agg] | Annual emissions reductions pledged by developed countries to be reduced in developing countries. |  | 0 | GtonsCO2/year |
| US |  |  | 0 |  |
| EU |  |  | 0 |  |
| Other Developed |  |  | 0 |  |

| Table 3‑21 Input Mode 2 Nationally Determined Contribution (NDC) and Mid-Century Strategy (MCS) Parameter Inputs | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| Choose pct of NDC globally |  | 0-1 | 0 | Dmnl |
| Test NDCs | Set to 1 to test NDCs as percent closing the gap between RS and full implementation of NDCs by NDC target year (2025/2030), and then Mid-century strategy (MCS) as a percent change by mid-century (defaulted to 2050) below the value in the NDC trajectory in the MCS target year or below the NDC reference year. | 0-1 | 0 | Dmnl |
| MCS target type | Specifies that the nature of the MCS Target. Comparable to target types for IM 2 if set to 1, i.e., relative to emissions in a common reference year. However, if set to 2 (default), relative to the NDC trajectory in the MCS target year. | 1-2 | 2 | Dmnl |
| MCS C neutral target year semi agg[Semi Agg] | Year when emissions will drop to near zero for CO2 and the minimum ratio to current levels for the other GHGs. |  | 2200 | Year |
| Percent of NDC by end of pledge period[Semi Agg] | Percent of NDC achieved. | 0-150 | 0 | Percent |
| Max percent reduction | Percent change in the target year to achieve zero emissions by then, set to less than 100% to avoid abrubt drop in the trajectory. |  | -97 | Percent |
| NDC reference year[COP] | Reference year for basis of MCS for reference year based pledges. |  |  | Year |
| NDC interim 1 target year [COP] | Interim 1 target year for NDC trajectories, corresponds with Interim 1 target year Reg |  | 2020 | Year |
| NDC target year[COP] | NDC target year for NDC trajectories, corresponds with Interim 2 target year Reg |  | 2025-2030 | Year |
| NDC interim fractional change from 2020 if CO2eq[COP] | Calculated reduction of gross CO2eq from RS if all on track to achieve 100% NDCs, based on default RS inputs. |  |  | Dmnl |
| **NDC interim fractional change from 2020 China CO2 only** | Calculated reduction of gross CO2 for China from RS if on track to achieve 100% NDCs but not extended to include nonCO2 GHGs, based on default RS inputs. |  |  | dmnl |
| NDC interim fractional change from NDC target year if CO2eq [COP] | Calculated reduction of gross CO2eq from RS if all achieve 100% NDCs, based on default RS inputs. |  |  | Dmnl |
| **NDC interim fractional change from NDC target year China CO2 only** | Calculated reduction of gross CO2 for China from RS if achieve 100% NDCs but not extended to include nonCO2 GHGs, based on default RS inputs. |  | - | Dmnl |
| **MCS pct change semi agg[Semi Agg]** | MCS percent change by the target year (defaulted to 2050) from the NDC reference year or from the value in NDC trajectory in the MCS target year (default). | 0-100 | 0 | Percent |
| **Global MCS pct change** | Global MCS percent change by the target year (defaulted to 2050) from the NDC reference year or from the value in NDC trajectory in the MCS target year (default). | 0-100 | 0 | Percent |

| Table 3‑22 Input mode 2 CO2 FF Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **Interim 1 target type[COP]** | IF THEN ELSE(Test NDCs:OR: Discrete success measure of NDC[Semi Agg], NDC target type, Interim 1 target type Reg[COP]) | Dmnl |
| **Interim 2 target type[COP]** | IF THEN ELSE(Test NDCs:OR: Discrete success measure of NDC[Semi Agg], NDC target type, Interim 2 target type Reg[COP]) | Dmnl |
| **Final target type[COP]** | IF THEN ELSE(Discrete success measure of NDC[Semi Agg], 0, IF THEN ELSE(Test NDCs,Final target type if test NDCs[COP],Final target type Reg[COP])) | Dmnl |
| **Interim 1 target type Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2, Global interim 1 target type, IF THEN ELSE(AGGREGATE SWITCH=1, Semi Agg interim 1 target type aux[Semi Agg], EcR interim 1 target type aux[Economic Regions])) | Dmnl |
| **Interim 2 target type Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2, Global interim 2 target type, IF THEN ELSE(AGGREGATE SWITCH=1, Semi Agg interim 2 target type aux[Semi Agg], EcR interim 2 target type aux[Economic Regions])) | Dmnl |
| **Final target type Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2 :OR: Choose target globally, Global final target type, IF THEN ELSE(AGGREGATE SWITCH=1, Semi Agg target type aux[Semi Agg], EcR target type aux[Economic Regions])) | Dmnl |
| **FF change interim 1 target year[COP]** | IF THEN ELSE(Test NDCs, NDC interim 1 target year[COP], FF change interim target year Reg[COP]) | Year |
| **FF change interim 2 target year[COP]** | IF THEN ELSE(Test NDCs, NDC target year[Semi Agg], FF change interim 2 target year Reg[COP]) | Year |
| **FF change target year[COP]** | IF THEN ELSE(Test NDCs, FF change target year if Test NDCs[COP], FF change target year Reg[COP]) | Year |
| **Pct interim change in FF emissions [COP]** | MAX(-Max percent reduction , IF THEN ELSE(Test NDCs, Actual NDC interim pct change from 2020[COP], Pct interim change in FF emissions Reg[COP])) | Percent |
| **Pct interim 2 change in FF emissions [COP]** | MAX(-Max percent reduction, IF THEN ELSE(Test NDCs, Actual NDC interim pct change from NDC target year[COP], Pct interim 2 change in FF emissions Reg[COP])) | Percent |
| **Pct change in FF emissions [COP]** | MAX(-Max percent reduction, IF THEN ELSE(Test NDCs, Pct change in FF emissions if MCS[COP], Pct change in FF emissions Reg[COP])) | Percent |
| **Pct interim change in FF emissions EcR[Economic Regions]** | Allows supported actions from other countries for MEF aggregation:  IF THEN ELSE((Pct interim change in FF emissions[Economic Regions] > 0) :AND: (Pct interim change in FF emissions from Supported Actions EcR[Economic Regions] < 0), Pct interim change in FF emissions from Supported Actions EcR[Economic Region],Pct interim change in US FF emissions + Pct interim change in FF emissions from Supported Actions EcR[Economic Regions]) | Percent |
| **Pct interim 2 change in FF emissions EcR[Economic Regions]** | Allows supported actions from other countries for MEF aggregation  IF THEN ELSE((Pct interim 2 change in FF emissions[Economic Regions] > 0) :AND: (Pct interim 2 change in FF emissions from Supported Actions EcR[Economic Regions] < 0), Pct interim 2 change in FF emissions from Supported Actions EcR[Economic Region],Pct interim 2 change in US FF emissions + Pct interim 2 change in FF emissions from Supported Actions EcR[Economic Regions]) | Percent |
| **Pct change in FF emissions EcR[Economic Regions]** | Allows supported actions from other countries for MEF aggregation:  IF THEN ELSE((Pct change in FF emissions[Economic Regions] > 0) :AND: (Pct change in FF emissions from Supported Actions EcR[Economic Regions] < 0), Pct change in FF emissions from Supported Actions EcR[Economic Region],Pct change in US FF emissions + Pct change in FF emissions from Supported Actions EcR[Economic Regions]) | Percent |
| **Pct interim change in FF emissions Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2, Pct interim change in global FF emissions, IF THEN ELSE(AGGREGATE SWITCH=1, Pct interim change in FF emissions Semi Agg[Semi Agg], Pct interim change in FF emissions EcR[Economic Regions])) | Percent |
| **Pct interim 2 change in FF emissions Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2, Pct interim 2 change in global FF emissions, IF THEN ELSE(AGGREGATE SWITCH=1, Pct interim 2 change in FF emissions Semi Agg[Semi Agg], Pct interim 2 change in FF emissions EcR[Economic Regions])) | Percent |
| **Pct change in FF emissions Reg[COP]** | IF THEN ELSE(AGGREGATE SWITCH=2, Pct change in global FF emissions, IF THEN ELSE(AGGREGATE SWITCH=1, Pct change in FF emissions Semi Agg[Semi Agg], Pct change in FF emissions EcR[Economic Regions])) | Percent |
| **Trajectory Calculations** | | |
| **Target Value[COP,target]** | The target value based on the percent change from the target base, where the based depends on the target type. | Dmnl |
| **Target Value[COP,t1]** | INITIAL(1+Pct interim 1 change in FF emissions[COP]/"100 percent") |  |
| **Target Value[COP,t2]** | INITIAL(1+Pct interim 2 change in FF emissions[COP]/"100 percent") |  |
| **Target Value[COP,t3]** | INITIAL(1+Pct change in FF emissions[COP]/"100 percent") |  |
| **Target Value[COP,t4]** | Sets the ultimate target, i.e., 2100 value, to follow default trajectory for given previous target type, to follow a rate if Ultimate target[COP] = 1 or 3, or to resume RS growth if Ultimate target[COP] = 2.  IF THEN ELSE (ultimate target[COP]=ULT INACTIVE, :NA:, IF THEN ELSE(ultimate target[COP]=ULT SAME :OR:ultimate target[COP]=ULT SPECIFIED, ultimate target value from rate[COP], Target Emissions vs RS at last set target[COP])) |  |
| **Target Type[COP,target]** |  | Dmnl |
| **Target Type[COP,t1]** | INITIAL(Interim 1 target type[COP]) |  |
| **Target Type[COP,t2]** | INITIAL(Interim 2 target type[COP]) |  |
| **Target Type[COP,t3]** | INITIAL(Final target type[COP]) |  |
| **Target Type[COP,t4]** | If there are no set targets, the ultimate target is inactive regardless of the input for it. If there is a set target and the ultimate target is set to 1 or 3, the target is relative to the reference year. If there is a set target and the ultimate target is set to 2, the target is relative to RS.  INITIAL(IF THEN ELSE(Last Set Target Year[COP]=:NA: :OR: ultimate target[COP]=0, 0, IF THEN ELSE(ultimate target[COP]=ULT SPECIFIED :OR: ultimate target[COP]=ULT SAME, REFYR, RS))) |  |
| **Target Year[COP,target]** |  | Year |
| **Target Year[COP,t1]** | INITIAL(FF change interim 1 target year[COP]) |  |
| **Target Year[COP,t2]** | INITIAL(FF change interim 2 target year[COP]) |  |
| **Target Year[COP,t3]** | INITIAL(FF change target year[COP]) |  |
| **Target Year[COP,t4]** | INITIAL(FINAL TIME) |  |
| **Target is Active[COP,Target]** | The target is active if and only if the target type is greater than 0 and the target year is greater than the start year.  INITIAL(IF THEN ELSE(Target Year[COP,Target]>Start Year[COP] :AND: Target Type[COP,Target]>0, 1, 0)) | Dmnl |
| **Effective Target Year[COP,Target]** | The effective target year is the specified year unless the target is not active, in which case it equals the inactive target year, set to be 4000 so that it is beyond the time of the model.    INITIAL(IF THEN ELSE(Target is Active[COP,Target],Target Year[COP,Target],Inactive Target Year)) | Year |
| **Start Year[COP]** | INITIAL(FF change start year[COP]) | Year |
| **Reference Year[COP]** | INITIAL(Emissions reference year[COP]) | Year |
| **Effective reference year[COP]** | Reference year needs to be less than start year  MIN(Reference Year[COP],Start Year[COP]) | Year |
| **Target Order[COP,Target]** | Determines the chronological order of the target years, in case the interim and final targets are not entered as such.  VECTOR SORT ORDER(Effective Target Year[COP,Target], ASCENDING ) | Dmnl |
| **Sorted target year[COP,Target]** | Puts the target years in chronological order.  VECTOR ELM MAP(Effective Target Year[COP,t1],Target Order[COP,Target]) | Year |
| **Sorted target type[COP,Target]** | Puts the corresponding target type for each sorted target year.  VECTOR ELM MAP(Target Type[COP,t1],Target Order[COP,Target]) | Dmnl |
| **Sorted target value[COP,Target]** | Puts the corresponding target value for each sorted target year.  VECTOR ELM MAP(Target Value[COP,t1],Target Order[COP,Target]) | dmnl |
| **Sorted target active[COP,Target]** | Puts the corresponding target active value for each sorted target year.  VECTOR ELM MAP(Target is Active[COP,t1],Target Order[COP,Target]) | dmnl |
| **Previous target year[COP,target]** |  | Year |
| **Previous target year[COP,t1]** | INITIAL(Start Year[COP]) |  |
| **Previous target year[COP,tNext]** | INITIAL(sorted target year[COP,tPrev]) |  |
| **RefYr trajectory if linear or exp[COP,Target]** | Calculates the fraction of the emissions to reference emissions at each time from the previous relevant year to the target value at the target year for a linear or s-shaped trajectory.  IF THEN ELSE(RefYr target[COP,Target]=:NA:,:NA:, RAMP FROM TO(previous emissions vs RefYr[COP,Target], RefYr target[COP,Target], previous target year[COP, Target], sorted target year[COP, Target], profile))  See Macro detail for RAMP FROM TO (Table 3‑25) | Dmnl |
| **RefYr trajectory if s shape[COP,Target]** | Calculates the fraction of the emissions to reference emissions at each time from the previous relevant year to the target value at the target year for an s-shaped trajectory.  IF THEN ELSE(RefYr target[COP,Target]=:NA:,:NA:  ,target realization s shape[COP,Target]\*RefYr target[COP,Target]+(1-target realization s shape[COP,Target])\*previous emissions vs RefYr[COP,Target])  See Macro detail for SSHAPE (Table 3‑26) | Dmnl |
| **Target realization[COP,Target]** | The model applies the change from the target base linearly starting at 0 at the start year and rising to the full value of the percent change in the target year. Used for target types 2-6.  MIN(1,MAX(0, XIDZ(Time-previous target year[COP,Target], sorted target year[COP,Target]-previous target year[COP,Target], STEP(1,sorted target year[COP,Target])))) | Dmnl |
| **RefYr target[COP,Target]** | The target value if the target type is emissions relative to the reference year.  IF THEN ELSE(sorted target type[COP,Target] = REFYR :AND: sorted target active[COP,Target]  , sorted target value[COP,Target], :NA: ) | Dmnl |
| **RS target[COP,Target]** | The target value if the target type is emissions relative to the RS.  IF THEN ELSE( sorted target type[COP,Target] = RS :AND: sorted target active[COP,Target], sorted target value[COP,Target], :NA: ) | Dmnl |
| **Intensity ref target[COP,Target]** | The target value if the target type is emissions intensity relative to the reference year.  IF THEN ELSE(sorted target type[COP,Target]=INTENSITY REF :AND: sorted target active[COP,Target], sorted target value[COP,Target], :NA:) | Dmnl |
| **Per capita ref target[COP,Target]** | The target value if the target type is emissions per capita relative to the reference year.  IF THEN ELSE(sorted target type[COP,Target]=PER CAPITA REF :AND: sorted target active[COP,Target], sorted target value[COP,Target], :NA:) | Dmnl |
| **Intensity RS target[COP,Target]** | The target value if the target type is emissions intensity relative to the RS.  IF THEN ELSE(sorted target type[COP,Target]=INTENSITY RS :AND: sorted target active[COP,Target], sorted target value[COP,Target], :NA:) | Dmnl |
| **Per capita RS target[COP,Target]** | The target value if the target type is emissions per capita relative to the RS.  IF THEN ELSE(sorted target type[COP,Target]=PER CAPITA RS :AND: sorted target active[COP,Target], sorted target value[COP,Target], :NA:) | Dmnl |
| **RefYr trajectory[COP,Target]** | For those targets that are relative to reference emissions, this calculates the fraction of the emissions to reference emissions from the previous relevant year to the target year depending on the profile chosen. It forces the s-shaped trajectory if the emissions increase from the relevant year to the target year. Unless an ultimate target is active to override the default, beyond the target year, the fraction of reference emissions remains constant.  IF THEN ELSE(RefYr target[COP,Target]=:NA:,:NA:, IF THEN ELSE(profile>1:OR: RefYr target[COP,Target]>previous emissions vs RefYr[COP,Target],RefYr trajectory if s shape[COP,Target], RefYr trajectory if linear or exp[COP,Target])) | Dmnl |
| **RS trajectory[COP,Target]** | For those targets that are relative to the RS, this calculates the fraction of the emissions to RS from the previous relevant year to the target year. The fraction starts at 0, i.e., no change from the previous relevant year’s emissions, and linearly increases to the full target fraction at the target year. Unless an ultimate target is active to override the default, beyond the target year, the fraction of RS remains constant.  IF THEN ELSE(RS target[COP,Target]=:NA:, :NA:,target realization[COP,Target]\*RS target[COP,Target]+(1-target realization[COP,Target])\*previous emissions vs RS[COP,Target]) | Dmnl |
| **Intensity ref trajectory[COP,Target]** | For those targets that are based on intensity relative to a reference year, this calculates the fraction of the emissions intensity from the previous relevant year to the target year. The fraction starts at 0, i.e., no change from the previous relevant year’s intensity, and linearly increases to the full target fraction at the target year. Unless an ultimate target is active to override the default, beyond the target year, the fraction of reference intensity remains constant.  IF THEN ELSE(Intensity ref target[COP,Target]=:NA:,:NA:, Target realization[COP,Target]\*Intensity ref target[COP,Target] + (1-Target realization[COP,Target])\*previous emissions intensity vs RefYr[COP,Target]) | Dmnl |
| **Per capita ref trajectory[COP,Target]** | For those targets that are based on emissions per capita relative to a reference year, this calculates the fraction of the emissions per capita from the previous relevant year to the target year. The fraction starts at 0, i.e., no change from the previous relevant year’s emissions per capita, and linearly increases to the full target fraction at the target year. Unless an ultimate target is active to override the default, beyond the target year, the fraction of reference emissions per capita remains constant.  IF THEN ELSE(Per capita ref target[COP,Target]=:NA:,:NA:,Target realization[COP,Target]\*Per capita ref target[COP,Target] + (1-Target realization[COP,Target])\*previous emissions per capita vs RefYr[COP,Target]) | Dmnl |
| **Intensity RS trajectory[COP,Target]** | For those targets that are based on emissions intensity relative to the RS, this calculates the fraction of the emissions intensity from the previous relevant year to the target year. The fraction starts at 0, i.e., no change from the previous relevant year’s emissions per capita, and linearly increases to the full target fraction at the target year. Unless an ultimate target is active to override the default, beyond the target year, the ratio to RS emissions intensity remains constant.  IF THEN ELSE(Intensity RS target[COP,Target]=:NA:,:NA:,Target realization[COP,Target]\*Intensity RS target[COP,Target] + (1-Target realization[COP,Target])\*previous intensity vs RS[COP,Target]) | Dmnl |
| **Per capita RS trajectory[COP,Target]** | For those targets that are based on emissions per capita relative to the RS, this calculates the fraction of the emissions per capita from the previous relevant year to the target year. The fraction starts at 0, i.e., no change from the previous relevant year’s emissions per capita, and linearly increases to the full target fraction at the target year. Unless an ultimate target is active to override the default, beyond the target year, the ratio to RS emissions per capita remains constant.  IF THEN ELSE(Per capita RS target[COP,Target]=:NA:,:NA:,Target realization[COP,Target]\*Per capita RS target[COP,Target] + (1-Target realization[COP,Target])\*previous emissions per capita vs RS[COP,Target]) | Dmnl |
| **refYr constrained emissions[COP,Target]** | Multiplies the trajectory of emissions/reference emissions by the reference emissions to yield the emissions trajectory.  IF THEN ELSE(RefYr trajectory[COP,Target]=:NA:,:NA:,reference emissions[COP,Target]\*RefYr trajectory[COP,Target]) | GtonsCO2/year |
| **RS constrained emissions[COP,Target]** | Multiplies the trajectory of emissions/reference scenario emissions by the reference scenario emissions to yield the emissions trajectory.  IF THEN ELSE(RS trajectory[COP,Target]=:NA:,:NA:,RS emissions[COP]\*RS trajectory[COP,Target]) | GtonsCO2/year |
| **Intensity ref constrained emissions[COP,Target]** | Multiplies the trajectory of emissions intensity/reference year emissions intensity by the reference year intensity and GDP, as defined in Section 3.3.1, to yield the emissions trajectory.  IF THEN ELSE(Intensity ref trajectory[COP,Target]=:NA:,:NA:,Reference intensity[COP]\*Intensity ref trajectory[COP,Target]\*GDP[COP]) | GtonsCO2/year |
| **Per capita ref constrained emissions[COP,Target]** | Multiplies the trajectory of emissions per capita/reference year emissions by the reference year emissions per capita and population adjusted, as defined in Section 3.3.1, to yield the emissions trajectory.  IF THEN ELSE(Per capita ref trajectory[COP,Target]=:NA:,:NA:,Reference per capita[COP]\*Per capita ref trajectory[COP,Target]\*Population[COP]) | GtonsCO2/year |
| **Intensity RS constrained emissions[COP,Target]** | Multiplies the trajectory of RS emissions intensity by the RS intensity and GDP adjusted, as defined in Section 3.3.1, to yield the emissions trajectory.  IF THEN ELSE(Intensity RS trajectory[COP,Target]=:NA:,:NA:  ,RS intensity[COP]\*Intensity RS trajectory[COP,Target]\*GDP[COP]) | GtonsCO2/year |
| **Per capita RS constrained emissions[COP,Target]** | Multiplies the trajectory of RS emissions per capita by the RS per capita and population adjusted, as defined in Section 3.3.1, to yield the emissions trajectory.  IF THEN ELSE(Per capita RS trajectory[COP,Target]=:NA:,:NA:  ,RS per capita[COP]\*Per capita RS trajectory[COP,Target]\*Population[COP]) | GtonsCO2/year |
| **Constrained emissions[COP,Target]** | Synthesizes into one variable the emissions trajectories as determined for the various types of targets.  IF THEN ELSE(:NOT: Sorted target active[COP,Target], RS emissions[COP]  ,IF THEN ELSE(Sorted target type[COP,Target]=REFYR, refYr constrained emissions[COP,Target]  ,IF THEN ELSE(Sorted target type[COP,Target]=RS, RS constrained emissions[COP,Target]  ,IF THEN ELSE(Sorted target type[COP,Target]=INTENSITY REF,Intensity ref constrained emissions[COP,Target]  ,IF THEN ELSE(Sorted target type[COP,Target]=INTENSITY RS,Intensity RS constrained emissions[COP,Target]  ,IF THEN ELSE(Sorted target type[COP,Target]=PER CAPITA REF,Per capita ref constrained emissions[COP,Target]  ,IF THEN ELSE(Sorted target type[COP,Target]=PER CAPITA RS,Per capita RS constrained emissions[COP,Target]  , RS emissions[COP]))))))) | GtonsCO2/year |
| **Max RS emissions[COP,Target]** | The greater of RS emissions and those adjusted for GDP and/or population changes from their RS.  MAX(RS emissions[COP],  MAX(RS emissions[COP]/RS GDP[COP]\*GDP[COP], RS emissions[COP]/RS population[COP]\*Population[COP])) | GtonsCO2/year |
| **Emissions with cumulative constraints[COP,target]** | The model allows emissions to exceed RS when testing global targets. Otherwise, the model forces the emissions to not exceed the greater of the RS and RS adjusted by the ratio of GDP and population to their RS. Brings emissions from one target to the next regardless of target types. | GtonsCO2/year |
| **Emissions with cumulative constraints[COP,t1]** | IF THEN ELSE(AGGREGATE SWITCH=2, Constrained emissions  [COP,t1], MIN(Max RS emissions[COP,t1], Constrained emissions[COP,t1])) |  |
| **Emissions with cumulative constraints[COP,tNext]** | At all subsequent targets, if allow resumed growth = 0, then forces the emissions to also not exceed the emissions from the previous target. Brings emissions from one target to the next regardless of target types.  IF THEN ELSE(Sorted target year[COP, tNext]=Inactive Target Year  , Emissions with cumulative constraints[COP,tPrev]  , IF THEN ELSE(Allow resumed growth, IF THEN ELSE(AGGREGATE SWITCH=2, Constrained emissions[COP,tNext], MIN(Max RS emissions[COP,tNext], Constrained emissions[COP,tNext]))  , MIN(Emissions with cumulative constraints[COP,tPrev], Constrained emissions[COP,tNext]))) |  |
| **Previous emissions vs RefYr[COP,target]** |  | Dmnl |
| **Previous emissions vs RefYr[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is the RS emissions divided by the reference emissions, capping at the first target year.  SAMPLE IF TRUE(Time<=previous target year[COP,t1], RS emissions[COP]/reference emissions[COP,t1],RS emissions[COP]/reference emissions[COP,t1]) |  |
| **Previous emissions vs RefYr[COP,tNext]** | At all subsequent targets, the emissions for the previous target year divided by the reference emissions, capping at the given target year.  SAMPLE IF TRUE(Time<=previous target year[COP,tNext],emissions with cumulative constraints[COP,tPrev]/reference emissions[COP,tNext],emissions with cumulative constraints[COP,tPrev]/reference emissions[COP,tNext]) |  |
| **Previous emissions vs RS[COP,target]** |  | Dmnl |
| **Previous emissions vs RS[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is RS emissions divided by RS emissions, i.e., 1.  1 |  |
| **Previous emissions vs RS[COP,tNext]** | At all subsequent targets, the emissions for the previous target year divided by the RS emissions, capping at the given target year.  SAMPLE IF TRUE(Time<=previous target year[COP,tNext]  ,emissions with cumulative constraints[COP,tPrev]/RS emissions[COP]  ,emissions with cumulative constraints[COP,tPrev]/RS emissions[COP]) |  |
| **Previous emissions intensity vs RefYr[COP,target]** |  | Dmnl |
| **Previous emissions intensity vs RefYr[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is the RS intensity divided by the reference intensity, capping at the first target year.  SAMPLE IF TRUE(Time<=previous target year[COP,t1], RS intensity[COP]/reference intensity[COP,t1], RS intensity[COP]/reference intensity[COP,t1]) |  |
| **Previous emissions intensity vs RefYr[COP,tnext]** | At all subsequent targets, the emissions for the previous target year divided by the RS emissions, capping at the given target year.  SAMPLE IF TRUE(Time<=previous target year[COP,tNext],emissions with cumulative constraints[COP,tPrev]/GDP[COP]/reference intensity[COP,tNext], emissions with cumulative constraints[COP,tPrev]/GDP[COP]/reference intensity[COP,tNext]) |  |
| **Previous emissions per capita vs RefYr[COP,target]** |  | Dmnl |
| **Previous emissions per capita vs RefYr[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is the RS per capita divided by the reference per capita, capping at the first target year.  SAMPLE IF TRUE(Time<=previous target year[COP,t1], RS per capita[COP]/Reference per capita[COP], RS per capita[COP]/Reference per capita[COP]) |  |
| **Previous emissions intensity vs RefYr[COP,tnext]** | At all subsequent targets, the emissions for the previous target year divided by the population, divided by the emissions per capita at the reference year, capping at the emissions per capita at the target year.  SAMPLE IF TRUE(Time<=previous target year[COP,tNext],emissions with cumulative constraints[COP,tPrev]/Population[COP]/Reference per capita[COP], emissions with cumulative constraints[COP,tPrev]/Population[COP]/Reference per capita[COP]) |  |
| **Previous intensity vs RS[COP,target]** |  | Dmnl |
| **Previous intensity vs RS[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is RS intensity divided by RS intensity, i.e., 1.  1 |  |
| **Previous intensity vs RS[COP,tNext]** | At all subsequent targets, the emissions for the previous target year divided by the GDP adjusted, as defined in Section 3.3.1, divided by the RS emissions intensity, capping at the emissions intensity at the target year.  SAMPLE IF TRUE( Time<=previous target year[COP,tNext],Emissions with cumulative constraints[COP,tPrev]/GDP[COP]/RS intensity[COP],Emissions with cumulative constraints[COP,tPrev]/GDP[COP]/RS intensity[COP])) |  |
| **Previous emissions per capita vs RS[COP,tareget]** |  |  |
| **Previous emissions per capita vs RS[COP,t1]** | At the first target, the previous target year is the start year, when emissions are still RS. As such, the value is RS per capita divided by RS per capita, i.e., 1.  1 |  |
| **Previous emissions per capita vs RS[COP,tNext]** | At all subsequent targets, the emissions for the previous target year divided by the population adjusted, as defined in Section 3.3.1, divided by the RS emissions per capita, capping at the emissions per capita at the target year.  Time<=previous target year[COP,tNext]  ,Emissions with cumulative constraints[COP,tPrev]/Population[COP]/RS per capita[COP]  ,Emissions with cumulative constraints[COP,tPrev]/Population[COP]/RS per capita[COP] |  |
| **Target Emissions[COP]** | Synthesizes the emissions trajectories from each active target year to the next.  Emissions with cumulative constraints[COP,t4] | GtonsCO2/year |
| **Target Emissions vs RS[COP]** | Ratio of target emissions to RS emissions.  MAX(0, ZIDZ(Target Emissions[COP],RS emissions[COP])) | Dmnl |
| **Target Emissions vs RS at last set target[COP]** | SAMPLE UNTIL(Last Active Target Year[COP], Target Emissions vs RS[COP] , 1)  See Macro detail for SAMPLE UNTIL (Table 3‑27) | Dmnl |
| **IM 2 FF CO2[COP]** | Multiplies the ratio of target emissions to RS emissions by the RS CO2 FF emissions.  Target Emissions vs RS[COP]\*RS CO2 FF emissions[COP] | GtonsCO2/year |
| **RS emissions[COP]** | If Apply to CO2eq = 1 (default), then the RS emissions includes all the nonforest CO2eq; otherwise, if Apply to CO2eq = 2 or 3, it includes only CO2 FF emissions. If the land use emissions are set to also follow the pledge, RS emissions also includes them.  IF THEN ELSE(Apply to CO2eq[COP]=1, IF THEN ELSE(Land use CO2 emissions follow GHGs[COP], RS CO2eq total[COP], RS CO2eq nonforest emissions[COP]), IF THEN ELSE(Land use CO2 emissions follow GHGs[COP], RS CO2 land use gross emissions[COP], 0)+RS CO2 FF emissions[COP]) | GtonsCO2/year |
| **RS intensity[COP]** | The intensity, i.e., emissions per unit of GDP, for the RS.  RS emissions[COP]/GDP[COP] | GtonsCO2/million dollars |
| **RS per capita[COP]** | The emissions per capita for the RS.  RS emissions[COP]/Population[COP] | GtonsCO2/year/person |
| **Reference emissions[COP]]** | The RS emissions until the reference year, at which point the emissions cap at the reference year level.  SAMPLE IF TRUE(Time<=effective reference year[COP],RS emissions[COP],RS emissions[COP]) | GtonsCO2/year |
| **Reference intensity[COP,Target]** | The RS emissions intensity until the reference year, at which point the emissions intensity caps at the reference year level.  SAMPLE IF TRUE(Time <= effective reference year[COP], RS intensity[COP], RS intensity[COP]) | GtonsCO2/million dollars |
| **Reference per capita[COP,Target]** | The RS emissions per capita until the reference year, at which point the emissions per capita caps at the reference year level.  SAMPLE IF TRUE(Time <= Effective reference year[COP], RS per capita[COP], RS per capita[COP]) | GtonsCO2/million dollars |
| **Target realization[COP,Target]** | The model applies the change from the target base linearly starting at 0 at the start year and rising to the full value of the percent change in the target year. The target base is RS, intensity, or emissions per capita for target types 2, 3, or 4, respectively.  MIN(1,MAX(0  ,XIDZ(Time-previous target year[COP,Target]  ,sorted target year[COP,Target]-previous target year[COP,Target]  ,STEP(1,sorted target year[COP,Target])))) | Dmnl |
| Ultimate target value from rate[COP] | For when ultimate target[COP]=1 or 3, this calculates the ultimate target according to a post target rate. If the ultimate target is 1, then the rate used is that required to get to the target value from the start (or previous interim target if applicable); otherwise the rate used is a user-specified value.  SAMPLE UNTIL(Last Active Target Year[COP]+TIME STEP, EXP(effective ultimate target rate[COP]\*time from target to ultimate target[COP])\*Target Emissions[COP]/reference emissions[COP],1)  See Macro detail for SAMPLE UNTIL (Table 3‑27) | Dmnl |
| Annual rate of emissions to target[COP] | The rate of change in emissions from the previous target before the final target to the final target. If there is no interim target, the previous target is the start year.  SAMPLE IF TRUE(Time=IF THEN ELSE(Last Active Target Year[COP]>FF change start year[COP], Last Active Target Year[COP], y2050), LN(MAX(min ln term, ZIDZ(Target Emissions[COP],Previous emissions for rate[COP])))/MAX(One year, IF THEN ELSE(Last Active Target Year[COP]>FF change start year[COP], Last Active Target Year[COP], y2050)-Last active previous target year[COP]), :NA:) | 1/year |
| Time from target to ultimate target[COP] | INITIAL(Target Year[COP,t4]-Last Active Target Year[COP]) | Year |
| Effective ultimate target rate[COP] | IF THEN ELSE(Test NDCs :AND: Percent of NDC by end of pledge period[Semi Agg]>0 :AND: Final target type[COP]=0 :AND: Annual post target rate[COP]=0, NDC post target rate, IF THEN ELSE(Effective ultimate target [COP] =ULT SAME  , Annual rate of emissions to target[COP],Annual post target rate[COP]/"100 percent")) | 1/year |
| Annual post target rate[COP] | IF THEN ELSE(Zero emissions year specified post target rate[COP]<0, Zero emissions year specified post target rate[COP],Specified annual post target rate[COP]) | 1/year |
| Target emissions for rate[COP] | SAMPLE UNTIL(Last Active Target Year[COP], Target Emissions[COP], Target Emissions[COP])  See Macro detail for SAMPLE UNTIL (Table 3‑27) | GtonsCO2/year |
| Last Set Target Year[COP] | The last year with a set target year.  INITIAL(VECTOR SELECT( Target is Active[COP,set targets!], Effective Target Year[COP,set targets!], :NA:, VSMAX, VSERRNONE)) | Year |
| Last Active Target Year[COP] | The last year with a set target year; if there are no set target years, then this equals the start year.  INITIAL(IF THEN ELSE( Last Set Target Year[COP]=:NA:, Start Year[COP], Last Set Target Year[COP])) | Year |
| Previous emissions for rate[COP] | SAMPLE UNTIL(SAMPLE UNTIL(Last active previous target year[COP], Target Emissions[COP], Target Emissions[COP])  See Macro detail for SAMPLE UNTIL (Table 3‑27) | GtonsCO2/year |
| **Target emissions for rate[COP]** | The emissions at the target value.  SAMPLE UNTIL(Last Active Target Year[COP], Target Emissions[COP], Target Emissions[COP]) | GtonsCO2/year |

|  |  |  |
| --- | --- | --- |
| Table ‑ Input 2 Supported Action Calculated Parameters | | |
| **Annual GtonsCO2e in target year from all supported action** | Total annual emissions reductions pledged by developed countries to be reduced in developing countries.  SUM(Annual GtonsCO2e in target year from Supported Actions[Semi Agg!]) | GtonsCO2/year |
| **Share of supported action** [**COP]** | Fraction of total supported action mitigation to be applied to each country, assuming zero for all developed countries. | Dmnl |
| **Developed** | 0 |  |
| **Developing** | ZIDZ(Cumulative CO2[COP Developing],SUM(Cumulative CO2[COP Developing!])) |  |
| **Annual GtonsCO2e in target year supported from conditional pledges[COP]** | Annual GtonsCO2e in target year from all supported action\*Share of supported action[COP] | GtonsCO2/year |
| **Annual GtonsCO2e supported from conditional pledges over time** | Annual GtonsCO2e in target year supported from conditional pledges[COP]\*MAX(0, (MIN(FF change target year[COP], Time)-FF change start year[COP])/(FF change target year[COP]-FF change start year[COP])) | GtonsCO2/year |
| **Annual GtonsCO2e in target year from Supported Actions over time** | Annual GtonsCO2e in target year from Supported Actions[Semi Agg]\*MAX(0, (MIN(FF change target year[COP], Time)-FF change start year[COP])/(FF change target year[COP]-FF change start year[COP])) | GtonsCO2/year |
| **Supported action not used for CO2 FF[COP]** | MAX(0, Annual GtonsCO2e supported from conditional pledges over time[COP]-CO2 FF emissions domestic[COP]) | GtonsCO2/year |
| **Total SA not used for CO2 FF[COP]** | SUM(Supported action not used for CO2 FF[COP!])\*ZIDZ(Annual GtonsCO2e in target year from Supported Actions over time[COP], SUM(Annual GtonsCO2e in target year from Supported Actions over time[COP!])) | GtonsCO2/year |
| **Effective CO2 FF emissions[COP]** | CO2 FF emissions domestic[COP]-Annual GtonsCO2e in target year from Supported Actions over time[COP]+Total SA not used for CO2 FF[COP] | GtonsCO2/year |

|  |  |  |
| --- | --- | --- |
| Table ‑ Input 2 NDC Calculated Parameters | | |
| **Emissions reference year[COP]** | IF THEN ELSE(Test NDCs, NDC reference year[COP], Emissions reference year Reg[COP]) | Year |
| **NDC and MCS ultimate target[COP]]** | IF THEN ELSE( Final target type if test NDCs[COP] = 0, IF THEN ELSE(Effective percent of NDC by end of pledge period[Semi Agg]=0, 0, Post NDC target[COP]), IF THEN ELSE(Zero emissions year specified post target rate[COP]<0 :OR: Emissions from MCS in MCS target year[COP]>Emissions from NDC in NDC target year[COP], 3, MCS Ultimate target)) | Dmnl |
| **Zero emissions year specified post target rate[COP]** | IF THEN ELSE(Test NDCs :AND: MCS C neutral target year[Semi Agg]<FINAL TIME+Hundred years :AND:C neutral year as final target[COP]=0:AND:Effective MCS target type[COP]>0,LN(1-Max percent reduction/"100 percent")/MAX(One year, MCS C neutral target year[Semi Agg]-MCS target year),0)\*"100 percent" | Percent/year |
| **Final target type if test NDCs[COP]** | Specifies that the nature of the target if test NDCs.  IF THEN ELSE(C neutral year as final target[COP] ,1, Effective MCS target type[COP]) | Dmnl |
| **C neutral year as final target[COP]** | IF THEN ELSE(MCS C neutral target year[Semi Agg]<MCS target year:OR: (Effective MCS target type[COP]=0 :AND:MCS C neutral target year[Semi Agg]<FINAL TIME+Hundred years) , 1, 0) | Year |
| **NDC and MCS ultimate target[COP]** | IF THEN ELSE( Final target type if test NDCs[COP] = 0, IF THEN ELSE(Effective percent of NDC by end of pledge period[Semi Agg]=0, 0, Post NDC target[COP]), IF THEN ELSE(Zero emissions year specified post target rate[COP]<0 :OR: Emissions from MCS in MCS target year[COP]>Emissions from NDC in NDC target year[COP], 3, MCS Ultimate target)) | Dmnl |
| **MCS pct change from NDC ref year[COP]** | MCS is percent reduction (given in absolute value) from reference year.  IF THEN ELSE(C neutral year as final target[COP], -Max percent reduction, (Emissions from MCS in MCS target year[COP]/RS emissions in NDC Ref year[COP]-1\*"100 percent")) | Percent |
| **MCS pct change from MCS target year[COP]e** | MCS is percent reduction (given in absolute value) from value in NDC trajectory at MCS target year.  (Emissions from MCS in MCS target year[COP]/RS emissions in MCS target year[COP]-1)\*"100 percent" | Percent |
| **Pct change in FF emissions if MCS[COP]** | Mid-century strategy (MCS) percent change by the target year (defaulted to 2050) from the reference year.  IF THEN ELSE(MCS target year<MCS C neutral target year[Semi Agg] :AND: MCS pct change from reference year [COP]>0, Pct change in FF emissions if Test NDCs[COP], IF THEN ELSE(MCS C neutral target year[Semi Agg]<FINAL TIME+Hundred years , Pct change for zero emissions,0)) | Percent |

Table 3‑25 presents the macro for the RAMP FROM TO function, which yields an emissions trajectory between two times to reach a specified value. The path of the trajectory is specified to be either linear or exponential, but is forced to be linear if either the starting or ending emissions value is not positive. A linear path assumes a constant slope, whereas an exponential path assumes a constant annual rate.

Table 3‑25 Macro Detail for RAMP FROM TO

|  |
| --- |
| :MACRO: RAMP FROM TO( xfrom, xto, tstart, tend, islinear)  RAMP FROM TO = IF THEN ELSE( linear,linear ramp,exp ramp)  ~ xfrom  ~ Ramp function with different syntax (specifying from-to rather than slope) \  and selectable linear or exponential profile.  |  linear = IF THEN ELSE( xfrom > 0 :AND: xto > 0, islinear, 1)  ~ dmnl  ~ Force linear behavior if endpoints are nonpositive  |  linear ramp = xfrom + RAMP(slope,tstart,tend)  ~ xfrom  ~ |  exp ramp = IF THEN ELSE(Time$ <= tstart, xfrom  ,IF THEN ELSE( Time$ > tend, xto, xfrom\*EXP( rate\*(Time$-tstart)) ))  ~ xfrom  ~ |  slope = (xto-xfrom)/interval  ~ xfrom/tstart  ~ |  rate = IF THEN ELSE( xfrom > 0 :AND: xto > 0, LN(xto/xfrom)/interval, :NA: )  ~ 1/tstart  ~ |  interval = MAX(tend-tstart,TIME STEP$)  ~ tstart  ~ |  :END OF MACRO: |

Table 3‑26 presents the macro for the SSHAPE function, which yields a curve 0 to 1 with a rate that is consecutively slow, fast, and slow. It may be used to create an s-shape emissions trajectory for Input Mode 2.

Table 3‑26 Macro Detail for SSHAPE

|  |
| --- |
| :MACRO: SSHAPE(xin,profile)  SSHAPE = IF THEN ELSE( input>0.5, 1-(1-input)^profile\*0.5/0.5^profile, input^profile\*\  0.5/0.5^profile)  ~ dmnl  ~ S-shaped response, from 0-1 for input from 0-1. Profile should normally be >=1 \  (1=linear; 2=quadratic)  Always passes through (0.5, 0.5)  |  input = MIN(1,MAX(0,xin))  ~ xin  ~ |    :END OF MACRO: |

Table 3‑27 presents the macro for the SAMPLE UNTIL function. The value of the input remains constant after it reaches the specified time. This behavior is similar to Vensim’s “Sample If True” function but delayed by one time step so as to behave as a true level to avoid the potential for simultaneity.

Table 3‑27 Macro Detail for SAMPLE UNTIL

|  |
| --- |
| MACRO: SAMPLE UNTIL(lastTime,input,initval)  SAMPLE UNTIL = INTEG( (1-STEP(1,lastTime))\*(input-SAMPLE UNTIL)/TIME STEP$, initval)  ~ input  ~ |  :END OF MACRO: |

### Input mode 4: Emissions Specified by Excel Inputs

Input mode 4 (IM 4) allows the user to specify the CO2 FF emissions curve for each country or country grouping as a set of points in an Excel spreadsheet. Targets are applied to CO2 FF regardless of the Apply to CO2eq setting, such that if Apply to CO2eq=1 or 2, the other GHGs change by the same ratio as that of CO2 FF to RS CO2 FF. When the Input mode for a country or country grouping is set to 4, the C-ROADS-CP model will use the data from the “CO2 Emissions for CP.xls” file as input for that country or country grouping. Alterations to the spreadsheet must be saved to the file, and then the model run orSyntheSim restarted. Figure 3.16 illustrates the structure of IM 4.

Figure . Structure of Input Mode 4



| Table 3‑28 Input mode 4 CO2 FF Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| Regional CO2 FF emissions from table[Economic Regions] | Data variable generated from Input Data Model where it retrieves data from Excel specified spreadsheet.  GET XLS DATA('?Emissions for C-ROADS-CP', 'User 15 Region Inputs' , 'a' , 'b3' ) | Gtons.CO2year |
| Semi Agg CO2 FF emissions from table[Semi Agg] | Data variable generated from Input Data Model where it retrieves data from Excel specified spreadsheet.  GET XLS DATA('?Emissions for C-ROADS-CP', 'User 6 Region Inputs' , 'a' , 'b3' ) |
| Global CO2 FF emissions from table | Data variable generated from Input Data Model where it retrieves data from Excel specified spreadsheet.  GET XLS DATA('?User Data', 'User Global CO2 Target' , 'a' , 'b3' ) |
| IM 4 Regional CO2[Economic Regions] | Synthesizes historical MEF CO2 FF data with MEF projections from xls sheet.  IF THEN ELSE(Time<=CO2 last historical year, Regional Historical CO2 FF emissions[Economic Regions], Regional CO2 FF emissions from table[Economic Regions]) | TonsCO2/year |
| IM 4 Semi Agg CO2[Semi Agg] | Synthesizes historical semi agg CO2 FF data with semi agg projections from xls sheet.  IF THEN ELSE(Time<=CO2 last historical year, Semi Agg Historical CO2 FF emissions[Semi Agg], Semi Agg CO2 FF emissions from table[Semi Agg]) |
| IM 4 Global FF CO2 | Synthesizes historical global CO2 FF data with global projections from xls sheet.  IF THEN ELSE(Time<Year to start GHG projections, Global RS CO2 FF emissions, IF THEN ELSE(Use total CO2,Global CO2 emissions from table,Global CO2 FF emissions from table)) |  |
| Proportion of regional to COP[COP] | The proportion of each COP bloc to its respective regional group. Equal to 1 for all MEF regions and as follows non MEF.  RS CO2 FF emissions[Regional Other Eastern Europe]/RS Regional CO2 FF emissions[Developed non MEF]  RS CO2 FF emissions[OECD New Zealand]/RS Regional CO2 FF emissions[Developed non MEF]  RS CO2 FF emissions[G77 Other Large Asia]/RS Regional CO2 FF emissions[Developing non MEF]  RS CO2 FF emissions[G77 Other Latin America]/RS Regional CO2 FF emissions[Developing non MEF]  RS CO2 FF emissions[G77 Middle East]/RS Regional CO2 FF emissions[Developing non MEF]  RS CO2 FF emissions[G77 Other Africa]/RS Regional CO2 FF emissions[Developing non MEF]  RS CO2 FF emissions[G77 Small Asia]/RS Regional CO2 FF emissions[Developing non MEF] | Dmnl |
| Proportion of semi agg to COP[COP] | The proportion of each COP bloc to its respective regional group. Equal to 1 for all US, EU27, China, and India and as follows for others.  RS CO2 FF emissions[OECD Russia]/RS Semi Agg CO2 FF emissions[Other Developed 6R]  🡪Same for Other Eastern Europe, Canada, Japan, Australia, New Zealand, South Korea  RS CO2 FF emissions[OECD Mexico]/RS Semi Agg CO2 FF emissions[Other Developing 6R]  🡪 Same for Indonesia, Other Large Asia, Brazil, Other Latin America, Middle East, South Africa, Other Africa, and Small Asia | Dmnl |
| Proportion of global to COP[COP] | The proportion of each COP bloc to global values.  ZIDZ(RS CO2 FF emissions[COP],Global RS CO2 FF emissions) | Dmnl |
| IM 4 CO2[COP] | Translates CO2 FF emissions from 1, 6, or 15 regions from Excel inputs into 20 COP blocs. Allows the user to specify the emissions curve for each country or country grouping as a set of points in an Excel spreadsheet. Targets are applied to CO2 FF regardless of Apply to CO2eq setting, such that if Apply to CO2eq=1 or 2, the other GHGs change by the same ratio as that of CO2 FF to RS CO2 FF.  IF THEN ELSE(Time<Year to start GHG projections, RS CO2 FF emissions[COP], IF THEN ELSE(Input Mode for each group=4 :OR: AGGREGATE SWITCH =2, IM 4 Global FF CO2\*Proportion of global to COP[COP], IF THEN ELSE(AGGREGATE SWITCH=0, IM 4 Regional FF CO2[Economic Regions]\*Proportion of regional to COP[COP], IM 4 Semi Agg FF CO2[Semi Agg]\*Proportion of semi agg to COP[COP]))) | TonsCO2/year |

#### 

### Input mode 6: Emissions by Graphical Inputs of Global CO2eq Emissions

When Input Mode is set to 6, the model will use a “graphical input window” as its source of global or aggregated CO2 equivalent (CO2eq) emissions inputs. Targets are applied to CO2eq emissions (including forestry) regardless of the Apply to CO2eq setting, such that other GHGs change by the same ratio as that of CO2eq to the RS CO2eq. The default for the graphical input is the default RS setting. The user may redraw the graph and change the data by clicking and dragging with the mouse and choosing the close button. Figure 3.17 illustrates the structure of IM 6.

Figure . Structure of Input Mode 6

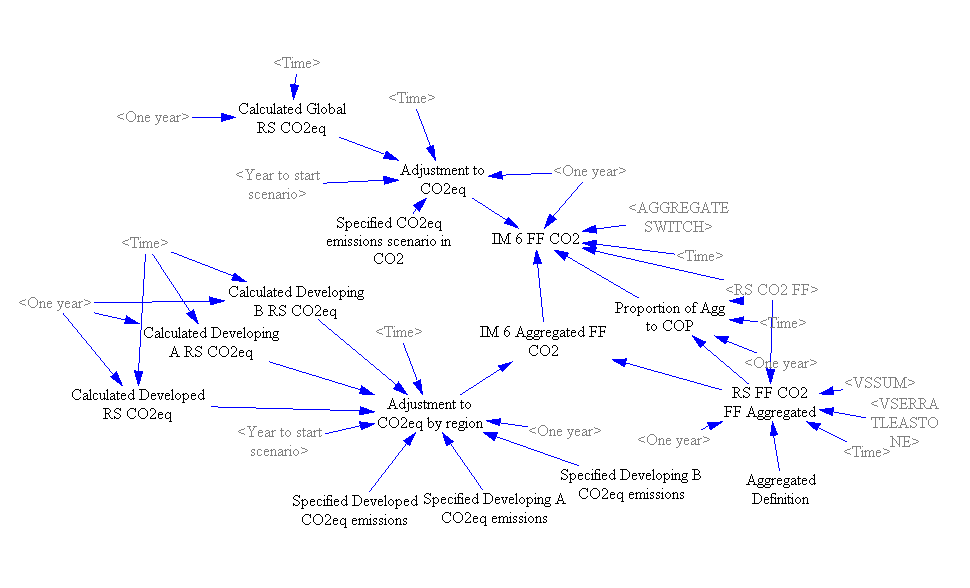


Table 3‑29 Input mode 6 CO2 FF Emissions Calculated Parameters

| **Parameter** | **Definition** | **Units** |
| --- | --- | --- |
| Calculated Global RS CO2eq | Sum of RS CO2 equivalent emissions from CO2 FF, CO2 net land use, CH4, N2O, and F-gases | GtonsCO2/year |
| Specified CO2eq emissions scenario in CO2 | Lookup value 2005-2100 for global CO2eq emissions | GtonsCO2/year |
| Adjustment to CO2eq | Ratio of CO2eq from specified scenario to that of the default RS  IF THEN ELSE(Time>=Year to start scenario, Specified CO2eq emissions scenario in CO2(Time/One year)/Calculated Global RS CO2eq, 1) | Dmnl |
| Specified Developed CO2eq emissions | Lookup value 2005-2100 for Developed CO2eq emissions | GtonsCO2/year |
| Specified Developing A CO2eq emissions | Lookup value 2005-2100 for Developing A CO2eq emissions | GtonsCO2/year |
| Specified Developing B CO2eq emissions | Lookup value 2005-2100 for Developing B CO2eq emissions | GtonsCO2/year |
| Adjustment to CO2eq by region[Aggregated regions]*ly* | Ratio of CO2eq from specified scenario to that of the default RS | Dmnl |
| [Developed Countries | IF THEN ELSE(Time>=Year to start scenario, Srpecified Developed CO2eq emissions(Time/One year)/Calculated Developed RS CO2eq, 1) |  |
| Developing A Countries | IF THEN ELSE(Time>=Year to start scenarrio, Specified Developing A CO2eq emissions(Time/One year)/Calculated Developing A RS CO2eq, 1) |  |
| Developing B Countries | IF THEN ELSE(Time>=Year to start scenario, Specified Developing B CO2eq emissions(Time/One year)/Calculated Developing B RS CO2eq, 1) |  |
| IM 6 Aggregated FF CO2[Aggregated Regions] | RS FF CO2 FF Aggregated [Aggregated Regions]\*Adjustment to CO2eq by region[Aggregated Regions] | GtonsCO2/year |
| IM 6 CO2[COP] | Adjusts CO2 FF emissions by same ratio as specified CO2eq is to that of RS. Targets are applied to CO2eq emissions (including forestry) regardless of Apply to CO2eq setting, such that other GHGs change by the same ratio as that of CO2eq to the RS CO2eq.  RS CO2 FF emissions[COP]\*Adjustment to CO2eq | GtonsCO2/year |

## Land Use Emissions

As shown in Figure 7.17, emissions from land use and land use change and forestry (LULUCF) are defined by the bounds of the specified Business as Usual (BAU) trajectory and the least probable trajectory based on a maximum likely reduction rate. The BAU of LULUCF assumes the gross land use emissions and sinks will remain at current levels throughout the century. Specifically, the default BAU of LULUCF uses historic gross emissions and removals data from Houghton (2017) through 2015. Beyond 2015, the *RS annual rate of change in land use emissions* and the *RS annual reduction in land use sinks* defaults to 0. This contrasts with assumptions from other modeling groups, including IPCCs SSP sceanrios, which assume a decrease in LULUCF emissions throughout the century. However, historic trends suggest otherwise; therefore, the model conservatively assumes no change. While the gross emissions and removals are both brought into the development version of the model as data variables, they are included as lookup tables in the model for general users.

The user may adjust the trajectories of CO2 land use emissions (defaults to net of gross LULUCF sources and sinks but may also be applied to just gross emissions) by specifying a percentage change to be achieved by a target year from emissions in a reference year. An interim target may be specified comparably.

Section 3.6 details the structure and values for carbon removals from afforeststation and other carbon dioxide removal (CDR) approaches.

Figure 3.18 Structure of Land Use Net Emissions



Figure 3.19 Structure of Land Use Net Emissions with AF



| Table 3‑30 Land Use Parameters | | |
| --- | --- | --- |
| Parameter | **Definition** | **Units** |
| COP region alloc CO2 land use emissions [COP] (data model) | Converts historical data through 2015 (Houghton and Nassikas, 2017) for each country as TgC/Year to GtonsCO2/year and aggregates those data to the 20 COP blocs. | GtonsCO2/year |
| COP region alloc CO2 land use sinks[COP] (data model) | Converts historical data through 2015 (Houghton and Nassikas, 2017) for each country as TgC/Year to GtonsCO2/year and aggregates those data to the 20 COP blocs | GtonsCO2/year |
| CO2 land use net emissions [COP] | This is the value included in the reporting of total GHG emissions, accounting for RS land use sinks but not accounting for removals from additional sequestration.  IF THEN ELSE(Input Mode for each group=4 :AND: Use total CO2 :AND:Time>=Year to start GHG projections, 0, CO2 Land use gross emissions[COP]- CO2 Land use sinks[COP]) | GtonsCO2/year |
| Global CO2 land use net emissions | Annual global net emissions of CO2 from land use as sum of that from each COP bloc. However, if *Choose RS* = 1 or *Test RCP for nonCO2FF GHGs* = 1, the global emissions for the selected RCP scenario overrides that sum for projections.  IF THEN ELSE((Choose RS=1 :OR: Test RCP for nonCO2FF GHGs) :AND: Time>Year to land use emissions forecast,Selected RCP CO2 land use emissions[World],SUM(CO2 land use net emissions[COP!])) | GtonsCO2/year |
| Rate of change of land use[COP] | Calculates the rate of change of the land use trajectory for each COP bloc:  FRAC TREND(CO2 land use emissions[COP],One year)  See Macro detail for FRAC TREND (Table 3‑7) | 1/year |
| CO2 land use net emissions with AF [COP] | Calculates the net land use emissions for CO2 reporting minus the net removals from afforestation, defined in Section 3.6. This is the value included in the reporting of total CO2eq emissions.  CO2 land use emissions[COP]-AF net removals[COP] | GtonsCO2/year |
| Global CO2 land use net emissions with AF | The sum of CO2 land use emissions minus AF net removals from all COP blocs. This is the value included in the reporting of total CO2eq emissions.  SUM(CO2 land use net emissions with AF[COP!]) | GtonsCO2/year |
| Rate of change of CO2 land use net emissions with AF[COP] | FRAC TREND(CO2 land use net emissions with AF[COP],One year) | 1/year |

| Table 3‑31 CO2 Land Use Gross Emissions and Sinks Parameters | | |
| --- | --- | --- |
| Parameter | **Definition** | **Units** |
| RS CO2 land use gross emissions [COP] | Historical values through 2015, after which projected values based on annual decrease from last historic value.  IF THEN ELSE(Time<=Year to land use emissions forecast, COP region alloc CO2 land use emissions[COP], Projected RS CO2 land use emissions[COP]) | GtonsCO2/year |
| Projected RS CO2 land use emissions[COP] | RS CO2 land use gross emissions projected from the last year of available data, defaulting to an annual rate of 0% per year.  Last CO2 land use emissions[COP]\*EXP(RS annual reduction in land use emissions\*(Time-Year to land use emissions forecast)) | GtonsCO2/year |
| Last CO2 land use emissions[COP] | Historic CO2 land use gross emissions at the last year of available data (2015).  Get data between times(COP region alloc CO2 land use emissions[COP] ,Year to land use emissions forecast , Interpolate ) | GtonsCO2/year |
| CO2 Land use gross emissions[COP] | CO2 land use gross emissions follow RS values until a given year, after which they change either according to the same proportion as CO2 or all GHGs relative to their RS or they change according to a specified reduction in land use emissions.  IF THEN ELSE(Time<=Year to land use emissions forecast , RS CO2 land use gross emissions[COP], IF THEN ELSE(Input Mode[COP]=6 :OR: Land use CO2 emissions follow GHGs[COP], CO2 FF emissions vs RS[COP]\*RS CO2 land use gross emissions[COP], IF THEN ELSE(CO2 Land use emissions target exists[COP], Projected CO2 land use gross emissions[COP], RS CO2 land use gross emissions[COP]))) | GtonsCO2/year |
| CO2 land use gross emissions at start year[COP] | INITIAL(Last CO2 land use emissions[COP]\*EXP( RS annual reduction in land use emissions\*(DF Start Year[COP]-Year to land use emissions forecast))) | GtonsCO2/year |
| Projected CO2 land use gross emissions[COP] | IF THEN ELSE(Time <= DF Start Year [COP],RS CO2 land use gross emissions[COP],CO2 land use gross emissions at start year[COP]\*Projected CO2 relative land use gross emissions[COP]) | GtonsCO2/year |
| Projected CO2 relative land use gross emissions | IF THEN ELSE( Land use CO2 interim exists[COP] :AND: Time < DF interim target year  [COP], Relative CO2 land use gross Emissions to Interim[COP], Relative CO2 land use gross emissions to target[COP]) | GtonsCO2/year |
| Land use emissions pct action[COP] | IF THEN ELSE(Land use net zero, (1-Target to land use net zero emissions[COP])\*"100 percent", MIN("100 percent", DF pct action Reg[COP])) | Percent |
| CO2 Land use emissions target exists[COP] | The target exists if the target year is greater than the start year.  IF THEN ELSE(Land use emissions pct action[COP]>0, 1, 0) | Dmnl |
| Land use CO2 interim exists [COP] | The interim target exists if the interim target year is greater than the start year but less than the target year.  IF THEN ELSE(DF interim target year[COP] > DF Start Year[COP]:AND: DF interim target year[COP] < DF target year[COP],1,0) | Dmnl |
| Relative CO2 land use gross Emissions to Target[COP] | RAMP FROM TO(Land use CO2 Target Startpoint[COP],1-Land use emissions pct action[COP]/"100 percent”, Land use CO2 Target Starttime[COP],DF target year[COP], CO2 Land use linear targets)  See Macro detail for RAMP FROM TO (Table 3‑25) | Dmnl |
| Relative CO2 land use gross Emissions to Interim [COP] | RAMP FROM TO(Max target DF,1-DF interim pct action[COP]/"100 percent",DF Start Year[COP], DF interim target year[COP],CO2 Land use linear targets)  See Macro detail for RAMP FROM TO (Table 3‑25) | Dmnl |
| Projected CO2 relative land use gross emissions [COP] | IF THEN ELSE( Land use CO2 interim exists[COP] :AND: Time < DF interim target year  [COP], Relative CO2 land use gross Emissions to Interim[COP], Relative CO2 land use gross emissions to target[COP]) | Dmnl |
| Projected CO2 land use gross emissions [COP] | The CO2 land use gross emissions according to the specified scenario. When Land use net zero = 1, forces the CO2 land use gross emissions in the target year and beyond to be equal to the lesser of its RS value and the CO2 land use sinks in the target year.  IF THEN ELSE(Time <= DF Start Year [COP],RS CO2 land use gross emissions[COP],IF THEN ELSE(Time<DF target year[COP], RS CO2 land use gross emissions at start year[COP]\*Projected CO2 relative land use gross emissions[COP],IF THEN ELSE(Land use net zero, MIN( RS CO2 land use gross emissions[COP], RS CO2 Land use sinks[COP]), RS CO2 land use gross emissions at start year[COP]\*Projected CO2 relative land use gross emissions[COP]))) | GtonsCO2/year |
| Land use emissions pct action[COP] | The percentage change in CO2 land use gross emissions compared to the start year emissions for each COP bloc.  INITIAL(IF THEN ELSE(Land use net zero, (1-Target to land use net zero emissions[COP])\*"100 percent", MIN("100 percent", DF pct action Reg[COP]))) | Percent |
| DF interim pct change[COP] | The percentage change in land use gross emissions compared to the start year emissions for each COP bloc.  INITIAL(IF THEN ELSE( Change land use globally=1, Global DF interim target year, DF interim target year EcR[Economic Regions])) | Percent |
| RS CO2 land use sinks[COP] | Historical values through 2015, after which projected values based on annual decrease from last historic value, defaulting to an annual rate of 0% per year.  IF THEN ELSE(Time<=Year to land use emissions forecast, COP region alloc CO2 land use sinks[COP], IF THEN ELSE(Choose RS=1 :OR: Test RCP for nonCO2FF GHGs, 0, Projected RS CO2 land use sinks[COP])) | GtonsCO2/year |
| CO2 land use sinks[COP] | IF THEN ELSE ( CO2 land sinks follow GHGs[COP] , CO2 FF emissions vs RS[COP] , IF THEN ELSE(CO2 land sinks follow sources, Projected CO2 relative land use emissions[COP], 1)) \* RS CO2 Land use sinks[COP] | GtonsCO2/year |

## Carbon Dioxide Removal (CDR)

Besides sequestration accomplished through afforestation, there are other technologies that could remove CO2 from the atmosphere. These other CDR technologies include soil carbon management, biochar, bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and enhanced weathering. A synthesis of literature (Table 3‑7) provides maximum removal potential and the timing to achieve these, for each CDR type. While afforestation is specified as a percent of the maximum area available for planting, as defined in 3.5.2, the other CDR types are specified as a percent of the maximum potential of each type.

A critical issue with CDR is energy and land demands for each type. Moreover, the potential reported in the literature for each CDR type does not consider the competing demands for energy and land. Moreover, there are storage losses over time, particularly for afforestation and soil carbon management, which decrease the continued removal of carbon.

|  |
| --- |
| Table ‑ Literature Sources of CDR Potential |
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| Lenton, T. M. (2010). The potential for land-based biological CO2 removal to lower future atmospheric CO2 concentration. *Carbon Management*, *1*(1), 145–160. https://doi.org/10.4155/cmt.10.12 |
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| Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870 |
| van Vuuren, D. P., Deetman, S., van Vliet, J., van den Berg, M., van Ruijven, B. J., & Koelbl, B. (2013). The role of negative CO2 emissions for reaching 2 °C--insights from integrated assessment modelling. *Climatic Change; Dordrecht*, *118*(1), 15–27. https://doi.org/http://dx.doi.org.libproxy.tulane.edu:2048/10.1007/s10584-012-0680-5 |
| Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 1. https://doi.org/10.1038/ncomms1053 |

Figure . Net Carbon Removal from Afforestation



Figure . Net Carbon Removal



| Table ‑ CDR Input Parameters | | | | | |
| --- | --- | --- | --- | --- | --- |
| Parameter | Definition | Range | Default Values | Units |
| Percent available land for afforestation | The percent of the Max available land for afforestation that is used for afforestation |  |  |  |
|  |  |  |  |  |
| Afforestation CDR start year | Year to start afforestation efforts. |  |  |  |
| Years to plant land committed to afforestation | Years it takes to plant the land that has been secured for afforestation | 1-50 | 30 | Years |
| Years to secure land for afforestation | Years it takes to plan and secure land for afforestation. | 1-10 | 10 | Years |
| Forest maturation time | Years for forests to reach maturity, approximately capturing net primary productivity growth curves.. | 10-100 | 80 | Years |
| Max C density on Afforested Land | Bastin et al. (2019) calculates to 0.6 if 2%/year lost from storage. | 0.2-1 | 0.6 | GtonsC/Mha |
| Percent loss per year of afforestation | Percent loss per year of afforestation | 0-2 | 2 | Percent/year |
| Max available land for afforestation[COP] | With default growing time of 80 years and 2%/year loss, a global total of 700 Mha achieves an annual max removal consistent with the mid point of Royal Society estimates,which has a range of 3-20 in CO2 GtonsCO2/year, giving an average of 11.5 GtonsCO2/year (3.1 GtonsC/year).  Bastin et al., Science 365, 76-79 (2019) 5 July 2019 indicates 900 MHa. |  |  | Mha |
| US |  |  | 50 |  |
| EU |  |  | 50 |  |
| Russia |  |  | 50 |  |
| Other Eastern Europe |  |  | 10 |  |
| Canada |  |  | 10 |  |
| Japan |  |  | 10 |  |
| Australia |  |  | 10 |  |
| New Zealand |  |  | 5 |  |
| South Korea |  |  | 5 |  |
| Mexico |  |  | 10 |  |
| China |  |  | 100 |  |
| India |  |  | 50 |  |
| Indonesia |  |  | 20 |  |
| Other Large Asia |  |  | 20 |  |
| Brazil |  |  | 50 |  |
| Other Latin America |  |  | 50 |  |
| Middle East |  |  | 0 |  |
| South Africa |  |  | 100 |  |
| Other Africa |  |  | 50 |  |
| Small Asia |  |  | 50 |  |
| Max CDR[nonAF CDR] | The maximum potentially removed per year, taken as the average of the range from the Royal Society Report (2018). |  |  | GtonsCO2/year |
| Agricultural soil carbon |  | 1-10 | 5.5 |  |
| Biochar |  | 2-5 | 3.5 |  |
| BECCS |  | 3-10 | 6 |  |
| Direct air capture |  | 0.5-5 | 2.75 |  |
| Mineralization |  | 0.5-4 | 2.25 |  |
| Choose CDR | Switch to control aggregation of sequestration settings.  0 = Inputs for total CDRs apply  1 = Inputs for non afforestation CDR and afforestation CDR apply  2 = Inputs for each type of CDR apply | 0-2 | 1 | Dmnl |
| Target CDR by type [Sequestration type] | The percent of the maximum achieved for each CDR type | 0-100 | 0 | Percent |
| Percent of total CDR achieved | Sets the percent of the maximum achieved for all CDR types | 0-100 | 0 | Percent |
| CDR Start Year by type [Sequestration type] |  | 2020-2100 |  | Year |
| Direct air capture, Mineralization |  |  | 2030 |  |
| All others |  |  | 2020 |  |
| CDR time to reach max  [nonAF CDR] |  |  |  | Years |
| Agricultural soil carbon |  |  | 30 |  |
| Biochar |  |  | 30 |  |
| BECCS |  |  | 20 |  |
| Direct air capture |  |  | 70 |  |
| Mineralization |  |  | 70 |  |
| Percent loss of carbon by CDR type [Sequestration type] | Percent loss from sequestered carbon pool per year. Based on IPCC’s WG1 AR5 Chapter 6. Table 6.15. 2013. | 0-2 |  | Percent/year |
| Afforestation | Also, based on typical biomass and soil release rates, through bacterial respiration (decay) and wildfire; determined through optimization of US forest data. |  | 2 |  |
| Agricultural soil carbon | Also based on typical soil release rates determined through optimization of US forest data. |  | 1 |  |
| Biochar | Also based on calculation from ~20% loss over long term (Caldecott et al, 2015) |  | 0.2 |  |
| BECCS | Based on IPCC assumption of permanence, storage loss is assumed to be zero |  | 0 |  |
| Direct air capture | Based on IPCC assumption of permanence, storage loss is assumed to be zero |  | 0 |  |
| Mineralization | Based on IPCC assumption of permanence, storage loss is assumed to be zero |  | 0 |  |

| Table ‑ CDR Calculated Parameters | | |
| --- | --- | --- |
| Parameter | **Definition** | **Units** |
| Target afforested land | Max available land for afforestation[COP]\*AF pct of max[COP]/"100 percent" | Mha |
| Land remaining for afforestation[COP] | Target afforested land[COP]-(Afforestable Land[COP]+Afforested Land[COP]) | Mha |
| Committing land to afforestation[COP] | IF THEN ELSE(Time<AF start year[COP], 0, MIN(Target afforested land[COP], Land remaining for afforestation[COP])/Years to secure land for afforestation) | Mha/year |
| Land afforestation rate[COP] | Afforestable Land[COP]/Years to plant land committed to afforestation[COP] | Mha/year |
| Afforestable Land[COP] | INTEG(CCommitting land to afforestation[COP]-Land afforestation rate[COP], 0) | Mha |
| Afforested Land[COP] | INTEG(Land afforestation rate[COP], 0) | Mha |
| Flux of C from Atm to Afforested Land[COP] | Max C density on Afforested Land[COP] \*DELAY3(Land afforestation rate[COP], Forest maturation time) | GtonsC/Year |
| Loss of C from Afforested Land to Atm[COP] | C on Afforested Land[COP]\*Percent loss per year of carbon by CDR type[Afforestation]/"100 percent" | GtonsC/Year |
| Net C Sequestered by Afforestation[COP] | Flux of C from Atm to Afforested Land[COP]-Loss of C from Afforested Land to Atm[COP] | GtonsC/Year |
| C on Afforested Land[COP] | INTEG(Flux of C from Atm to Afforested Land[COP]-Loss of C from Afforested Land to Atm[COP], 0) | GtonsC |
| Potential C from Atm to Afforested Land[COP] | (Max Afforestation Potential[COP] -C on Afforested Land[COP])/Forest maturation time | GtonsC/Year |
| C density on AF land[COP] | ZIDZ(C on Afforested Land[COP],Afforested Land[COP]) | GtonsC/Mha |
| Max Afforestation Potential[COP] | Max C density on Afforested Land[COP]\*Max available land for afforestation[COP] | GtonsC/Mha |
| Global AF net C removals | SUM(Net C Sequestered by Afforestation[COP!]) | GtonsC/year |
| Flux of CO2 from Atm to Afforested Land[COP] | Flux of C from Atm to Afforested Land[COP]\*CO2 per C | GtonsCO2/Year |
| Net CO2 Sequestered by Afforestation | Net C Sequestered by Afforestation\*CO2 per C | GtonsCO2/Year |
| Target CDR[Sequestration type] | Fraction of max CDR or max available land for afforestation. | Dmnl |
| NonAF CDR | IF THEN ELSE(Choose CDR by type=2, Target CDR by type[NonAF CDR], IF THEN ELSE(Choose CDR by type=1, Non afforestation Percent of max CDR achieved, Percent of total CDR achieved))/"100 percent" |  |
| Afforestation | IF THEN ELSE(Choose CDR by type>=1, Percent available land for afforestation, Percent of total CDR achieved)/"100 percent" |  |
| C removal rate effort nonAF CDR [nonAF CDR] | IF THEN ELSE(Time<CDR Start Year[NonAF CDR], 0, Max CDR[NonAF CDR]\*Target CDR[NonAF CDR])/CO2 per C | GtonsC/year |
| C removal rate in time for nonAF CDR [nonAF CDR] | SMOOTH3(C removal rate for nonAF CDR[NonAF CDR] , CDR Phase in Time by type[NonAF CDR]/Factor to approach full exponential change) | GtonsC/year |
| C removal by nonAF CDR[nonAF CDR) | MIN(C removal rate in time for nonAF CDR[NonAF CDR], C in Atmosphere/ELMCOUNT(NonAF CDR)/TIME STEP) | GtonsC/year |
| Emissions from storage by nonAF CDR[nonAF CDR] | Loss of CO2 from storage back into atmosphere.  Cumulative C removed by nonAF CDR[NonAF CDR]\*Percent loss of carbon [NonAF CDR]/"100 percent" | GtonsC/year |
| Net carbon removal by nonAF CDR[nonAF CDR] | C removal by nonAF CDR[NonAF CDR]-Emissions from storage by nonAF CDR[NonAF CDR] | GtonsC/year |
| Cumulative C removed by nonAF CDR | INTEG0C removal by nonAF CDR[NonAF CDR]-Emissions from storage by nonAF CDR[NonAF CDR], 0) | GtonsC |
| Cumulative C removed by type[Sequestration type] |  | GtonC |
| NonAF CDR | Cumulative C removed by nonAF CDR[NonAF CDR] |  |
| Afforestation | Cumulative C removed by AF |  |
| Cumulative C removed by AF | SUM(C on Afforested Land[COP!]) | GtonsC/year |
| Net carbon removal by type[Sequestration type] | Difference between carbon removed and carbon released from storage. | GtonsC/year |
| NonAF CDR | Net carbon removal by nonAF CDR[NonAF CDR] |  |
| Afforestation | Global AF net C removals |  |
| Net CDR by type[Sequestration type] | Net carbon removal by type[Sequestration type]\*CO2 per C | GtonsCO2/year |
| Total non afforestation C removal | SUM(C removal by nonAF CDR[NonAF CDR!]) | GtonsC/year |
| Total non afforestation CDR | Total non afforestation C removal\*CO2 per C | GtonsCO2/year |
| Net carbon removal | SUM(C removal by type[ Sequestration type!]) | GtonsC/year |
| Net CDR total | SUM(Net CDR by type[Sequestration type!]) | GtonsCO2/year |
| CDR by energy | CDR across all energy-based types, i.e., BECCS, DAC, and mineralization  SUM(CDR by type[Energy based CDR!]) | GtonsCO2/year |
| Net CDR by land | CDR across all land-based types, i.e., afforestation, agricultural soil carbon, and biochar  SUM(Net CDR by type[Land based CDR!]) | GtonsCO2/year |
| Net CDR by energy | SUM(Net CDR by type[Energy based CDR!]) | GtonsCO2/year |
| Net CDR by land | SUM(Net CDR by type[Land based CDR!]) | GtonsCO2/year |

## Carbon cycle

### Introduction

The carbon cycle sub-model is adapted from the FREE model (Fiddaman, 1997). While the original FREE structure is based on primary sources that are now somewhat dated, we find that they hold up well against recent data. Calibration experiments against recent data and other models do not provide compelling reasons to adjust the model structure or parameters, though in the future we will likely do so.

Other models in current use include simple carbon cycle representations. Nordhaus’ DICE models, for example, use simple first- and third-order linear models (Nordhaus, 1994, 2000). The first-order model is usefully simple, but does not capture nonlinearities (e.g., sink saturation) or explicitly conserve carbon. The third-order model conserves carbon but is still linear and thus not robust to high emissions scenarios. More importantly for education and decision support, neither model provides a recognizable carbon flow structure, particularly for biomass.

Socolow and Lam (2007) explore a set of simple linear carbon cycle models to characterize possible emissions trajectories, including the effect of procrastination. The spirit of their analysis is similar to ours, except that the models are linear (sensibly, for tractability) and the calibration approach differs. Socolow and Lam calibrate to Green’s function (convolution integral) approximations of the 2xCO2 response of larger models; this yields a calibration for lower-order variants that emphasizes long-term dynamics. Our calibration is weighted towards recent data, which is truncated, and thus likely emphasizes faster dynamics. Nonlinearities in the C-ROADS carbon uptake mechanisms mean that the 4xCO2 response will not be strictly double the 2xCO2 response.

### Structure

The adapted FREE carbon cycle (Figure 3.25) is an eddy diffusion model with stocks of carbon in the atmosphere, biosphere, mixed ocean layer, and three deep ocean layers. The model couples the atmosphere-mixed ocean layer interactions and net primary production of the Goudriaan and Kettner and IMAGE 1.0 models (Goudriaan and Ketner 1984; Rotmans 1990) with a 5-layer eddy diffusion ocean based on (Oeschger, Siegenthaler *et al.*, 1975) and a 2-box biosphere based on (Goudriaan and Ketner 1984).

In the FREE model, all emissions initially accumulate in the atmosphere. As the atmospheric concentration of C rises, the uptake of C by the ocean and biosphere increases, and carbon is gradually stored. The atmospheric flux to the biosphere consists of net primary production, which grows logarithmically as the atmospheric concentration of C increases (Wullschleger, Post *et al.*, 1995), according to:

Eq. 1



NPP = net primary production Ca = C in atmosphere

NPP0 = reference net primary production Ca,0 = reference C in atmosphere

βb = biostimulation coefficient

Because the relationship is logarithmic, the uptake of C by the biosphere is less than proportional to the increase in atmospheric C concentration. Effects of the current biomass stock, and human disturbance are neglected. The flux of C from the atmosphere to biomass decreases with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100. The sensitivity parameter, set by the user, governs the strength of the effect. The default sensitivity of 1 yields the average value found in Friedlingstein et al., 2006.

It is worth noting that this formulation, though commonly used, is not robust to large deviations in the atmospheric concentration of C. As the atmospheric concentration of C approaches zero, net primary production approaches minus infinity, which is not possible given the finite positive stock of biomass. As the concentration of C becomes very high, net primary production can grow arbitrarily large, which is also not possible in reality. The first of these constraints is not a problem for reasonable model trajectories. However, the model assumes a ratio of diminishing returns, defaulted to 2 times the intitial C in the atmosphere, at which point the NPP growth is reduced.

The Goudriaan and Ketner and IMAGE models (Goudriaan and Ketner, 1984; Rotmans, 1990) have detailed biospheres, partitioned into leaves, branches, stems, roots, litter, humus, and charcoal. To simplify the model, these categories are aggregated into stocks of biomass (leaves, branches, stems, roots) and humus (litter, humus). Aggregate first-order time constants were calculated for each category on the basis of their equilibrium stock-flow relationships. Charcoal is neglected due to its long lifetime. The results are reasonably consistent with other partitionings of the biosphere and with the one-box biosphere of the Oeschger model (Oeschger, Siegenthaler *et al.*, 1975; Bolin, 1986).

Eq. 2



*Cb* = *carbon in biomass* τb = biomass residence time

Eq. 3



*Ch = carbon in biomass* τ*h = humus residence time*

*φ = humidification fraction*

The interaction between the atmosphere and mixed ocean layer involves a shift in chemical equilibria (Goudriaan and Ketner, 1984). CO2 in the ocean reacts to produce HCO3– and CO3=. In equilibrium,

Eq. 4



Cm = C in mixed ocean layer Cm,0 = reference C in mixed ocean layer

Ca = C in atmosphere Ca,0 = reference C in atmosphere

*ζ = buffer factor*

The atmosphere and mixed ocean adjust to this equilibrium with a time constant of 1 year. The buffer or Revelle factor, ζ, is typically about 10. As a result, the partial pressure of CO2 in the ocean rises about 10 times faster than the total concentration of carbon (Fung, 1991). This means that 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 buffer factor itself rises with the atmospheric concentration of CO2 (Goudriaan and Ketner, 1984; Rotmans, 1990) and temperature (Fung, 1991). This means that the ocean’s capacity to absorb CO2 diminishes as the atmospheric concentration rises. This temperature effect is another of several possible feedback mechanisms between the climate and carbon cycle. The fractional reduction in the solubility of CO2 in ocean falls with rising temperatures. Likewise for the temperature feedback on C flux to biomass, we assume a linear relationship, likely a good approximation over the typical range for warming by 2100. The sensitivity parameter that governs the strength of the effect on the flux to the biomass also governs the strength of the effect on the flux to the ocean. For both effects, the default sensitivity of 1 yields the average values found in Friedlingstein et al., 2006.

Eq. 5



ζ = buffer factor Ca = CO2 in atmosphere

δb = buffer CO2 coefficient Ca,0 = reference CO2 in atmosphere

ζ0 = reference buffer factor

The deep ocean is represented by a simple eddy-diffusion structure similar to that in the Oeschger model, but with fewer layers (Oeschger, Siegenthaler *et al.*, 1975). Effects of ocean circulation and carbon precipitation, present in more complex models (Goudriaan and Ketner, 1984; Björkstrom, 1986; Rotmans, 1990; Keller and Goldstein, 1995), are neglected. Within the ocean, transport of carbon among ocean layers operates linearly. The flux of carbon between two layers of identical thickness is expressed by:

Eq. 6



*Fm,n = carbon flux from layer m to layer n e = eddy diffusion coefficient*

*Ck = carbon in layer k d = depth of layers*

The effective time constant for this interaction varies with d, the thickness of the ocean layers. To account for layer thicknesses that are not identical, the time constant uses the mean thickness of two adjacent layers. summarizes time constants for the interaction between the layers used in C-ROADS, which employs a 100 meter mixed layer, and four deep ocean layers that are 300, 300, 1300, and 1800 meters, sequentially deeper. 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.

Table 3‑37: Effective Time Constants for Ocean Carbon Transport

|  |  |
| --- | --- |
| **Layer Thickness** | **Time Constant** |
| 100 meters | 1 year |
| 300 meters | 14 years |
| 300 meters | 20 years |
| 1300 meters | 236 years |
| 1800 meters | 634 years |

Figure . Structure of Carbon Cycle



Table 3‑38 Carbon Cycle Parameter Inputs

| **Parameter** | **Definition** | **RS** | **Units** | **Source** |
| --- | --- | --- | --- | --- |
| Preindustrial C | Preindustrial CO2 content of atmosphere. | 590 | GtonsC |  |
| Biomass residence time | Average residence time of carbon in biomass. | 10.6 | Year | Adapted from Goudriaan, 1984 |
| Biostim coeff index | Index of coefficient for response of primary production to carbon concentration, as multiplying factor of the mean value. | 1 | Dmnl |  |
| Biostim coeff mean | Mean coefficient for response of primary production to CO2 concentration. Reflects the increase in NPP with doubling the CO2 level. | 0.42 | Dmnl | Goudriaan and Ketner, 1984; Rotmans, 1990 |
| Ratio of NPP diminishing returns | C/C0 at which point the growth in NPP from CO2 fertlization is reduced according to the strength in the effect, defaulted to a 5% decrease. | 0-4  Default = 2 | Dmnl |  |
| Humification Fraction | Fraction of carbon outflow from biomass that enters humus stock. | 0.428 | Dmnl | Adapted from Goudriaan, 1984 |
| Humus Res Time | Average carbon residence time in humus. | 27.8 | Year | Adapted from Goudriaan, 1984 |
| Buff C coeff | Coefficient of C concentration influence on buffer factor. | 3.92 | Dmnl | Goudriaan and Ketner, 1984 |
| Ref buffer factor. | Normal buffer factor. | 9.7 | Dmnl | Goudriaan and Ketner, 1984 |
| Mixing Time | Atmosphere - mixed ocean layer mixing time. | 1 | Year |  |
| Eddy diff mean | Rate of vertical transport and mixing in the ocean due to eddy diffusion motion | 4400 | Meter | Oeschger, Siegenthaler et al., 1975 |
| Eddy diff coeff index | Multiplier of eddy diffusion coefficient mean | 1 | Dmnl |  |
| Mixed depth | Mixed ocean layer depth. | 100 | Meters | Oeschger, Siegenthaler et al., 1975 |
| Preind Ocean C per meter | Corresponds with 767.8 GtC in a 75m layer. | 10.2373 | GtonsC/meter |  |
| Layer Depth[layers] | Deep ocean layer thicknesses.  1  2  3  4 | 300 300 1300 1800 | Meters Meters Meters Meters |  |
| Init NPP | Initial net primary production | 85.1771 | GtonsC/year | Adapted from Goudriaan, 1984 |
| Ppm CO2 per TonsC | 1 ppm by volume of atmosphere CO2 = 2.13 Gt C | 0.4695e | ppm/GtonsC | CDIAC (http://cdiac.ornl.gov/pns/convert.html) |
| Goal for CO2 in the atmosphere | Assumed threshold of CO2 in atmosphere above which irreversible climate changes may occur | 450 | Ppm |  |
| Sensitivity of C Uptake to Temperature | Allows users to control the strength of the feedback effect of temperature on uptake of C by land and oceans. 0 means no temperature-carbon uptake feedback and default of 1 yields the average values found in Friedlingstein et al., 2006. | 0-2.5  Default = 1 | Dmnl |  |
| Strength of temp effect on land C flux mean | Average effect of temperature on flux of carbon to land. Calibrated to be consistent with Friedlingstein et al., 2006. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested. | -0.01 | 1/DegreesC | Friedlingstein et al., 2006 |
| Strength of diminishing returns | Strength of reduction in growth CO2 fertilization of NPP as C/C0 exceeds the point of diminishing returns | 0-0.1  Default=0.05 | Dmnl |  |
| Sensitivity of pCO2 DIC to Temperature Mean | Sensitivity of equilibrium concentration of dissolved inorganic carbon to temperature. Calibrated to be consistent with Friedlingstein et al., 2006. Default Sensitivity of C Uptake to Temperature of 1 corresponds to mean value from the 11 models tested. | 0.003 | 1/DegreesC | Friedlingstein et al., 2006 |
| CH4 Generation Rate from Humus | The rate of the natural flux of methane from C in humus. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. | 1.5e-004 | 1/year |  |
| CH4 Generation Rate from Biomass | The rate of the natural flux of methane from C in biomass. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. | 1.0e-005 | 1/year |  |
| Fraction of anthro CH4 emissions included in indirect CO2 accounts | Accounts for CO2 emissions that are already included in the CH4 emissions. | 0.8 | Dmnl | Estimated from EPA 2011 http://www.epa.gov/climatechange/economics/international.html |
| CH4 per C | Molar mass ratio of CH4 to C, 16/12 | 1.33 | Mtons/MtonsC |  |
| Mtons per Gtons | Converts MtonsC to GtonsC. | 1000 | MtonsC/GtonsC |  |
| Sensitivity of Methane Emissions to Temperature | Allows users to control the strength of the feedback effect of temperature on release of C as CH4 from humus. Default of 0 means no temperature feedback and 1 is mean feedback. | 0-2.5  Default = 0 | Dmnl |  |
| Reference Temperature Change for Effect of Warming on CH4 from Respiration | Temperature change at which the C as CH4 release from humus doubles for the Sensitivity of Methane Emissions to Temperature=1. | 5 | DegreesC |  |

| Table 3‑39 Carbon Cycle Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| Atm conc CO2 | Converts weight of CO2 in atmosphere (GtonsC) to concentration (ppm CO2).  CO2 in Atmosphere\*ppm CO2 per GtonC | Ppm |
| Flux Atm to Ocean | Carbon flux from atmosphere to mixed ocean layer, including feedback from temperature change (where default is set for no feedback).  ((Equil C in Mixed Layer-C in Mixed Layer)/Mixing Time) | GtonsC/year |
| Flux Atm to Biomass | Carbon flux from atmosphere to biosphere (from primary production), including feedbacks from CO2 and temperature change.  Init NPP\*Fertilization effect | GtonsC/year |
| Biostim Coeff | Coefficient for response of primary production to carbon concentration, based on index and mean.  INITIAL(Biostim coeff index\*Biostim coeff mean) | Dmnl |
| Fertilization effect | Change in NPP due to feedbacks from CO2 and temperature change.    (1+Biostim coeff\*LN( C in Atmosphere/Preindustrial C))\*Effect of CO2 diminishing returns\*Effect of Warming on C flux to biomass | Dmnl |
| Effect of CO2 diminishing returns | 1-Strength of diminishing returns\*MAX(0, (C in Atmosphere/Preindustrial C-Ratio of NPP diminishing returns)/Ratio of NPP diminishing returns) | Dmnl |
| Effect of Warming on C flux to biomass | Feedback from temperature on carbon flux from atmosphere to the biomass.  1+Strength of Temp Effect on C Flux to Land\*Temperature change from preindustrial | GtonsC |
| Temperature change from preindustrial | Change in temperature relative to preindustrial times. See Section 3.10. | DegreesC |
| Flux Biomass to Atmosphere | Carbon flux from biomass to atmosphere.  CO2 in Biomass/Biomass Res Time\*(1-Humification Fraction) | GtonsC/year |
| Flux Biomass to Humus | Carbon flux from biomass to humus.  CO2 in Biomass/Biomass Res Time\*Humification Fraction | GtonsC/year |
| Flux Humus to Atmosphere | Carbon flux from humus to atmosphere.  CO2 in Humus/Humus Res Time | GtonsC/year |
| Global total CO2 emissions | CO2 emissions from FF (includes cement) and forestry, net of indirect CO2 in CH4 accounts, which will be emitted later via CH4 oxidation. If the Global FF emissions is less than 0, reflecting sequestration, then the forestry is assumed to be included and the lower limit of zero for (CO2 FF - CO2 from CH4 accounting) is removed.  IF THEN ELSE(Global CO2 FF emissions>=0, MAX(0, Global CO2 FF emissions-Indirect CO2 in CH4 accounting)+Global CO2 Forestry Emissions, Global CO2 FF emissions-Indirect CO2 in CH4 accounting) | GtonsCO2/year |
| Global total CO2 in C | Global total CO2 converted to GtonsC/year.  Global total CO2 emissions/CO2 per C | GtonsC/year |
| Init C in Atmosphere | Initial carbon in atmosphere calculated from 1850 Law Dome data.  INITIAL(Atmospheric CO2 Law Dome/ppm CO2 per GtonC) | GtonsC |
| Init C in Humus | Initial carbon in humus.  INITIAL(Flux Biomass to Humus\*Humus Res Time) | GtonsC |
| Init C in Biomass | Initial carbon in biomass.  INITIAL(Flux Atm to Biomass\*Biomass Res Time) | GtonsC |
| C in Atmosphere | Mass of carbon in the atmosphere.  INTEG(C from CH4 oxidation+Emissions from storage+Flux Biomass to Atmosphere+Flux C from permafrost release+Flux Humus to Atmosphere+Global C anthro emissions-Flux Atm to Biomass-Flux Atm to Ocean-Total C removal, Init C in Atmosphere) | GtonsC |
| C in Humus | Carbon in humus.  INTEG(Flux Biomass to Humus-Flux Humus to Atmosphere-Flux Humus to CH4, Init C in Humus) | GtonsC |
| C in Biomass | Carbon in the biomass.  INTEG(Flux Atm to Biomass-Flux Biomass to Atmosphere-Flux Biomass to CH4-Flux Biomass to Humus, Init C in Biomass) | GtonsC |
| C in Mixed Layer | Carbon in the mixed layer.  INTEG(Flux Atm to Ocean-Diffusion Flux [layer1], Init C in Mixed Ocean per meter\*Mixed Depth) | GtonsC |
| C in Deep Ocean[layers] | Carbon in deep ocean. | GtonsC |
| C in Deep Ocean[upper] | INTEG(Diffusion Flux[upper]-Diffusion Flux[lower], Init C in Deep Ocean per meter[upper]\*Layer Depth[upper]) |  |
| C in Deep Ocean[bottom] | INTEG(Diffusion Flux[bottom], Init C in Deep Ocean per meter[bottom]\*Layer Depth[bottom]) |  |
| Equil C in Mixed Layer | Equilibrium carbon content of mixed layer. Determined by the Revelle buffering factor, and by temperature. For simplicity, we assume a linear impact of warming on the equilibrium solubility of CO2 in the ocean. The user controls the strength of that effect.  Preind C in Mixed Layer\*Effect of Temp on DIC pCO2\*(C in Atmosphere/Preindustrial C)^(1/Buffer Factor) | GtonsC |
| Buffer Factor | Buffer factor for atmosphere/mixed ocean carbon equilibration.  ACTIVE INITIAL(Ref Buffer Factor\*(C in Mixed Layer/Preind C in Mixed Layer)^Buff C Coeff, Ref Buffer Factor) | Dmnl |
| Preind C in Mixed Layer | Initial carbon concentration of mixed ocean layer.  INITIAL(Preind Ocean C per meter\*Mixed Depth) | GtonsC |
| Mean Depth of Adjacent Layers[layers] | The mean depth of adjacent ocean layers. | Meters |
| Mean Depth of Adjacent Layers[layer1] | INITIAL((Mixed Depth+Layer Depth[layer1])/2) |  |
| Mean Depth of Adjacent Layers[lower] | INITIAL((Layer Depth[upper]+Layer Depth[lower])/2) |  |
| Diffusion Flux[layers] | Diffusion flux between 5 ocean layers. | GtonsC/year |
| Diffusion Flux[layer1] | (C in mixed layer per meter-C in deep ocean per meter[layer1])  \*Eddy diff coeff/Mean Depth of Adjacent Layers[layer1] |  |
| Diffusion Flux[lower] | (C in deep ocean per meter[upper]-C in deep ocean per meter[lower])  \*Eddy diff coeff/Mean Depth of Adjacent Layers[lower] |  |
| Eddy Diff Coeff | Rate at which carbon is mixed in the ocean due to eddy motion, based on index and mean.  INITIAL(Eddy diff coeff index\*Eddy diff mean) | meter\*meter/year |
| Layer Time Constant[layers] | Time constant of exchange between layers. | Year |
| Layer Time Constant[layer1] | INITIAL(Layer Depth[layer1]/(Eddy diff coeff/Mean Depth of Adjacent Layers[layer1])) |  |
| Layer Time Constant[lower] | INITIAL(Layer Depth[lower]/(Eddy diff coeff/Mean Depth of Adjacent Layers[lower])) |  |
| Effect of Temp on DIC pCO2 | The fractional reduction in the solubility of CO2 in ocean falls with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.  1-Sensitivity of pCO2 DIC to Temperature\*Temperature change from preindustrial | Dmnl |
| Sensitivity of pCO2 DIC to Temperature | Sensitivity of pCO2 of dissolved inorganic carbon in ocean to temperature.  INITIAL(Sensitivity of C Uptake to Temperature\*Sensitivity of pCO2 DIC to Temperature Mean) | 1/DegreesC |
| Strength of Temp Effect on C Flux to Land | Strength of temperature effect on C flux to the land.  INITIAL(Sensitivity of C Uptake to Temperature\*Strength of temp effect on land C flux mean) | 1/DegreesC |
| Effect of Warming on C flux to biomass | The fractional reduction in the flux of C from the atmosphere to biomass with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.  1+Strength of Temp Effect on C Flux to Land\*Temperature change from preindustrial | Dmnl |
| Flux Humus to CH4 | The natural flux of methane from C in humus. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback.  C in Humus\*CH4 Generation Rate from Humus\*Effect of Warming on CH4 Release from Biological Activity | GtonsC/year |
| Effect of Warming on CH4 Release from Biological Activity | The fractional increase in the flux of C as CH4 from humus with rising temperatures. We assume a linear relationship, likely a good approximation over the typical range for warming by 2100.  1+Sensitivity of Methane Emissions to Temperature\*(Temperature change from preindustrial)/(Reference Temperature Change for Effect of Warming on CH4 from Respiration) | Dmnl |
| Flux Biomass to CH4 | The natural flux of methane from C in biomass. The sum of the flux of methane from C in humus and the flux of methane from C in biomass yields the natural emissions of methane. Adjusted to account for temperature feedback.  C in Biomass\*CH4 Generation Rate from Biomass\*Effect of Warming on CH4 Release from Biological Activity | GtonsC/year |
| Flux Biosphere to CH4 | Carbon flux from biosphere as methane, in GtC/year, arising from anaerobic respiration.  Flux Biomass to CH4+Flux Humus to CH4 | GtonsC/year |
| C from CH4 oxidation | Flux of C into the atmosphere from the oxidation of CH4, the mode of removal of CH4 from atmosphere.  CH4 Uptake/CH4 per C/Mtons per Gtons | GtonsC/year |
| Indirect CO2 in CH4 accounting | Indirect CO2 emissions included in accounting data that occurs due to oxidation of CH4; in this model the indirect emissions are explicit from the methane cycle, and therefore are deducted from the CO2 accounting to correct the data. Also includes emissions for which CH4 represents recently-extracted biomass (e.g. enteric fermentation).  Global anthropogenic CH4 emissions/CH4 per C/Mtons per Gtons\*CO2 per C  \*Fraction of anthro CH4 emissions included in indirect CO2 accounts | GtonsCO2/year |
| C Sequestered | Accumulated net sequestered.  INTEG(Total C removal-Emissions from storage, Init C sequestered) | Gtons C |

### Behavior

Figure 3.26 and Figure 3.27 show simulation output for the four RCP scenarios.

Figure 3.26 Carbon Stocks under RCP Emissions Scenarios

1. *RCP8.5*



1. *RCP6.0*



1. *RCP4.5*



1. *RCP 2.6*



Figure 3.27 Carbon Cycle Fluxes under RCP Emissions Scenarios

1. *RCP8.5*



1. *RCP6.0*



1. *RCP4.5*



1. *RCP2.6*



### Calibration

The model reflects historic emissions well, though this is a weak test of validity (a rather wide variety of parameterizations and simple model structures perform equally well against the historic signal). Figure 3.28 shows this agreement between C-ROADS output and observed data by Law Dome and Mauna Loa.

Figure . Atmospheric CO2 - Model vs. History



Because the model lacks realistic ocean structure and employs a highly simplified portioning of the biosphere, there is potentially some concern that the atmospheric trajectory could be right for the wrong reasons, i.e. that errors in land and ocean fluxes would offset one another. However, land and ocean fluxes are consistent with decadal averages reported in IPCC reports (TAR, AR4, and AR5). It appears that there is not yet real consensus about future fluxes when temperature feedbacks are present, as evidenced by the large intermodel variation in C4MIP experiments (Friedlingstein *et al.*, 2006). Of greatest interest for our purposes is that the model reasonably reflects IPCC projections, as shown in Figure 3.29.

Figure . Atmospheric CO2 Projections vs. RCP Scenarios



Model fit is analyzed according to a series of statistical fit tests run in a separate statistics model, Comparison-Theil, known herein as the Statistics Model. Table 3‑40 presents the macro for the THEIL function in that model, which creates the variables to measure model fit. Of these measures, Theil’s inequality statistics decompose the mean square error (MSE) between simulated and actual data into 3 components: the fraction of the MSE due to (i) unequal means, UM; (ii) unequal variances, US; and (iii) unequal covariation, UC. Rounding may cause these fractions to not sum to one.

Comparisons against historical data and projections for CO2 concentrations are givens in Table 3‑41 and show that model fit is strong.

| Table 3‑40 Macro Detail for THEIL Function |
| --- |
| :MACRO: THEIL(historical,simulated:R2,MAPE,MAEM,RMSPE,RMSE,MSE,SSE,Dif Mea,Dif Var,Dif Cov,Um,Us,Uc,Count)  THEIL = residuals  ~ historical  ~ Note that first argument (historical) must be data;  second argument (simulation) can be data or a simulation,  but if it is data, it will not be checked for existence.  This could easily by changed by modifying the code below.  Arguments following the : are outputs. They generate model  variables that are visible in the listing on the Variable  tab of the control panel, and can be used in equations  and custom graphs/tables/reports. However, they cannot be  made visible on diagrams.  |  R2 = r\*r  ~ Dimensionless  ~ Correlation coefficient squared  |  MAPE = ZIDZ(Sum APE,Count)  ~ Dimensionless  ~ Mean Absolute Percent Error  |  MAEM = ZIDZ( Sum APE, Sum Yi )  ~ Dimensionless  ~ Mean Absolute Error divided by the mean of the data  |  RMSPE = SQRT(ZIDZ(Sum SPE,Count))  ~ Dimensionless  ~ Root Mean Square Percent Error  |  RMSE = SQRT(MSE)  ~ historical  ~ Root Mean Square Error  |  MSE = Dif Mea + Dif Var + Dif Cov  ~ historical\*historical  ~ Mean Square Error. The addition of the three components  |  SSE = Sum XmY2  ~ historical\*historical  ~ Sum of Square Errors (x-y)^2  |  Dif Mea = (M X-M Y)\*(M X-M Y)  ~ historical\*historical  ~ Difference of Means (bias)  |  Dif Var = (Sx-Sy)\*(Sx-Sy)  ~ historical\*historical  ~ Difference of variances  |  Dif Cov = 2\*Sx\*Sy\*(1-r)  ~ historical\*historical  ~ Difference of covariances  |  Um = ZIDZ(Dif Mea,MSE)  ~ Dimensionless  ~ Bias inequality proportion  |  Us = ZIDZ(Dif Var,MSE)  ~ Dimensionless  ~ Variance inequality proportion  |  Uc = ZIDZ(Dif Cov,MSE)  ~ Dimensionless  ~ Covariance inequality proportion  |  Count = INTEG(pick/dt,0)  ~ Dimensionless  ~ Counter for # of points  |  residuals = IF THEN ELSE(pick,Xi-Yi,:NA:)  ~ historical  ~ Errors  |  r=  MIN(1,ZIDZ(Mxy-(M X\*M Y),Sx\*Sy))  ~ Dimensionless [-1,1]  ~ Correlation coefficient. Calculated through the 'hand computation'.  Sterman (1984) pg. 63  MIN prevents numerical issues due to numerical precision; perhaps there is \  a better way to do this. -TF  |  Sum APE = INTEG(ABS(ZIDZ(Xi-Yi,Yi))/dt,0)  ~ Dimensionless  ~ Sum of Absolute Percent Errors  |  Sum Yi = INTEG(Yi/dt,0)  ~ historical  ~ Sum of y's (historical)  |  Sum SPE = INTEG((ZIDZ(Xi-Yi,Yi)\*ZIDZ(Xi-Yi,Yi))/dt,0)  ~ Dimensionless  ~ Sum of Square Percent Errors ((x-y)/y)^2  |  Sum XmY2 = INTEG((Xi-Yi)\*(Xi-Yi)/dt,0)  ~ historical\*historical  ~ Sum of Square Errors (x-y)^2  |  M X = ZIDZ(Sum Xi,Count)  ~ historical  ~ Mean of x (sum x)/n  |  M Y = ZIDZ(Sum Yi,Count)  ~ historical  ~ Mean of y (sum y)/n  |  Sx = SQRT(MAX(0,MX2-(M X\*M X)))  ~ historical  ~ Standard Deviation of x. Calculated using the 'hand computation' formula  to calculate the standard deviation without prior knowledge of the mean.  Sterman (1984), pg. 64  MAX prevents spurious numerical problems from roundoff.  |  Sy = SQRT(MAX(0,MY2-(M Y\*M Y)))  ~ historical  ~ Standard Deviation of y. Calculated using the 'hand computation' formula  to calculate the standard deviation without prior knowledge of the mean.  Sterman (1984), pg. 64  MAX prevents spurious numerical problems from roundoff.  |  pick = IF THEN ELSE(Y = :NA: :OR: X = :NA:, 0, 1)  ~ Dimensionless  ~ Flag to id historical value available.  Takes a value of one for every data point available  |  dt = TIME STEP$  ~ Time Units  ~ Note: if your Vensim is not the latest version, you may need to pass TIME \  STEP as a parameter.  |  Xi = pick\*X  ~ historical  ~ Simulated point entering calculations  |  Yi = pick\*Y  ~ historical  ~ Historical point entering calculations  |  Mxy = ZIDZ(SumXY,Count)  ~ historical\*historical  ~ Mean of x\*y (sum x\*y)/n  |  ErrVar = ZIDZ(SSE,(Count-1))  ~ historical\*historical  ~ Variance of the residuals  |  Sum Xi = INTEG(Xi/dt,0)  ~ historical  ~ Sum of x's (simulated)  |  MX2 = ZIDZ(SumX2,Count)  ~ historical\*historical  ~ Mean of x^2 (sum x^2)/n  |  MY2 = ZIDZ(SumY2,Count)  ~ historical\*historical  ~ Mean of y^2 (sum y^2)/n  |  Y :RAW: := historical  ~ historical  ~ |  X :RAW: :=  simulated  ~ historical  ~ |  SumXY = INTEG(Xi\*Yi/dt,0)  ~ historical\*historical  ~ Sum of x\*y  |  SumX2 = INTEG(Xi\*Xi/dt,0)  ~ historical\*historical  ~ Sum of x^2 (simulated)  |  SumY2 = INTEG(Yi\*Yi/dt,0)  ~ historical\*historical  ~ Sum of y^2 (historical)  |  :END OF MACRO: |

|  |  |
| --- | --- |
| Table 3‑41 CO2 Concentration Simulated Data Compared to Mauna Loa/Law Dome Historical Data (1850-2016) | |
|  | C-ROADS vs Historical CO2 Mauna Loa and Law Dome Data |
| Count | 167 |
| R2 | 0.9978 |
| MAPE | 0.0073 |
| MAEM | 0.0000 |
| RMSPE | 0.0084 |
| RMSE | 2.7770 |
| Theil Inequalities |  |
| UM | 0.5678 |
| US | 0.1651 |
| UC | 0.2671 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑42 CO2 Concentration Simulated Data Compared to RCP Projections (2000-2100) | | | | |
|  | RCP8.5 | RCP6.0 | RCP4.5 | RCP2.6 |
| Count | 11 | 11 | 11 | 11 |
| R2 | 1.0000 | 0.9998 | 0.9989 | 0.9936 |
| MAPE | 0.0133 | 0.0104 | 0.0148 | 0.0124 |
| MAEM | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| RMSPE | 0.0139 | 0.0112 | 0.0167 | 0.0135 |
| RMSE | 9.0431 | 5.9534 | 8.4597 | 5.7938 |
| Theil Inequalities |  | | | |
| UM | 0.7364 | 0.7615 | 0.7204 | 0.8194 |
| US | 0.2594 | 0.1982 | 0.2254 | 0.0620 |
| UC | 0.0042 | 0.0402 | 0.0541 | 0.1185 |

## Other greenhouse gases

### Other GHGs included in CO2equivalent emissions

C-ROADS explicitly models other well–mixed greenhouses gases, including methane (CH4), nitrous oxide (N2O), and the fluorinated gases (PFCs, SF6, and HFCs). PFCs are represented as CF4-equivalents due to the comparably long lifetimes of the various PFC types. HFCs, on the other hand, are represented as an array of the nine primary HFC types, each with its own parameters. The structure of each GHG’s cycle reflects first order dynamics, such that the gas is emitted at a given rate and is taken up from the atmosphere according to its concentration and its time constant. The remaining mass in the atmosphere is converted, according to its molecular weight, to the concentration of that gas. The multiplication of each gas concentration by the radiative coefficient of the gas yields its instantaneous radiative forcing (RF). This RF is included in the sum of all RFs to determine the total RF on the system.

For those explicitly modeled GHGs, the CO2 equivalent emissions of each gas are calculated by multiplying its emissions by its 100-year Global Warming Potential. Time constants, radiative forcing coefficients, and the GWP are taken from the IPCCs Fifth Assessment Report (AR5) Working Group 1 Chapter 8. (Table 8.A.1. Lifetimes, Radiative Efficiencies and Metric Values GWPs relative to CO2).

In addition to the anthropogenic emissions considered as part of the CO2 equivalent emissions, CH4, N2O, and PFCs also have a natural component. The carbon flux as CH4 from humus and biomass in the carbon cycle sector, converted to units of CH4, are the global natural CH4 emissions. These are consistent with those calculated from MAGICC output using the remaining emissions in the “zero emissions” scenario. The use of remaining emissions from MAGICC’s “zero emissions” scenario yields the global natural N2O emissions. The global natural PFC emissions are calculated by dividing Preindustrial mass of CF4 equivalents by the time constant for CF4. Such natural PFCs are from rocks. Figure 3.31 illustrates the general GHG cycle, while the unique aspects of the CH4 cycle warrant Figure 3.31

Figure . Structure of Other GHG cycle



Figure . Structure of CH4 cycle



Table 3‑43 provides the general equations for the other GHGs, with each gas modeled as its own structure. The units of each gas are: MtonsCH4, MtonsN2O-N, tonsCF4, tonsSF6, and tonsHFC for each of the primary HFC types. To calculate the CO2 equivalent emissions of N2O, the model first converts the emissions from MtonsN2O-N/year to Mtons N2O/year.

For CH4, temperature may affect the emissions rate by two mechanisms of feedback. The first feedback reflects the increased natural methane emissions from the biosphere with greater temperatures. This sensitivity parameter, Sensitivity of Methane Emissions to Temperature, affects the carbon fluxes from humus and from biomass in the carbon cycle sector, presented in Section 3.7.2. The model also accounts for release of CH4 from permafrost and clathrate stores, with an estimated 50 Mtons/year for each Degree C of temperature change per CH4 reference temperature change. The model currently defaults to the sensitivity reflecting no feedback.

| Table 3‑43 Inputted and Calculated Parameters of Other GHG Cycles | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **Global GHG Emissions** | The sum of the GHG emissions for each COP bloc. However, if Choose RS = 1 or Test RCP for nonCO2FF GHGs = 1, the global emissions for the selected RCP scenario overrides that sum for projections. For GHGs with anthropogenic and natural components (CH4, N2O, PFC), the sums the two components together to determine the total flux into the atmospheric:  IF THEN ELSE((Choose RS = 1 :OR: Test RCP for nonCO2FF GHGs ):AND: Time> Last year of GHG per GDP data, Selected RCP GHG emissions[World], SUM( GHG anthro emissions[COP!]))+Natural GHG emissions | CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: tonsCF4/year  SF6: tonsSF6/year  HFCs: tonsHFC/year |
| **GHG Uptake** | GHG/Time constant for GHG | CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: tonsCF4/year  SF6: tonsSF6/year  HFCs: tonsHFC/year |
| **Mass of GHG** | The mass of GHG in the atmosphere at each time:  INTEG(Global GHG Emissions-GHG Uptake, Initial GHG mass) | CH4: MtonsCH4  N2O: MtonsN2O-N  PFCs: tonsCF4  SF6: tonsSF6  HFCs: tonsHFC/year |
| **Preindustrial GHG mass** | The mass of GHG in the atmosphere at the start of the simulation (1850) based on the initial concentration and the conversion to concentration.  Preindustrial GHG conc/conversion mass to concentrations | CH4: MtonsCH4  N2O: MtonsN2O-N  PFCs: tonsCF4  SF6: tonsSF6  HFCs: tonsHFC/year |
| **ppt per mol** | 5.68e-009 | ppt/mole |
| **ppt GHG per ton GHG** | ppt per mol/molar mass GHG\*g per ton | Ppt/ton |
| **ppb GHG per Mton GHG (CH4 and N2O)** | ppt per mol/GHG molar mass\*g per ton\*ton per Mton/ppt per ppb | Ppb/Mton |
| **GHG atm conc** | Mass of GHG\*conversion mass to concentration | CH4 and N2O: ppb  All other GHGs: ppt |
| **GHG RF** | (GHG atm conc-Preindustrial GHG conc)\*GHG radiative efficiency/ppt per ppb | Watt/(meter\*meter) |
| **CH4 Only** | | |
| **Sensitivity of Methane Emissions to Permafrost and Clathrate** | Allows users to control the strength of the feedback effect of temperature on CH4 emissions from permafrost and clathrate. The default of 0 means no temperature feedback.  0 | Dmnl |
| **CH4 Emissions from Permafrost and Clathrate** | Methane emissions from melting permafrost and clathrate outgassing are assumed to be nonlinear. Emissions are assumed to be zero if warming over preindustrial levels is less than a threshold and linear in temperature above the threshold. The default sensitivity is zero, but the strength of the effect and threshold can be set by the user.  Sensitivity of Methane Emissions to Permafrost and Clathrate\*Reference Sensitivity of CH4 from Permafrost and Clathrate to Temperature\*  MAX(0,Temperature change from preindustrial-Temperature Threshold for Methane Emissions from Permafrost and Clathrate) | Mton/year |
| **Reference Sensitivity of CH4 from Permafrost and Clathrate to Temperature** | The reference emissions of methane from melting permafrost and outgassing from clathrates per degree C of warming above the threshold.  50 | Mtons/year/DegreeC |
| **Temperature Threshold for Methane Emissions from Permafrost and Clathrate** | 1  The threshold rise in global mean surface temperature above preindustrial levels that triggers the release of methane from permafrost and clathrates. Below this threshold, emissions from these sources are assumed to be zero. Above the threshold, emissions are assumed to rise linearly with temperature. | DegreesC |
| **Natural CH4 emissions** | Flux of methane from anaerobic respiration in the biosphere, in Mtons CH4/year. Rates of release in the carbon sector are calibrated to fit history and RCP projections. A54 Table 7.6 reports a range of 145-260, with a mean of 199.  Flux Biosphere to CH4\*CH4 per C\*Mtons per Gtons | Mton/year |

\*HFCs are modeled with the HFC type subscript, such that each HFC type moves through its own cycle independent of the other HFC types. The HFC RF is the sum of RFs from each HFC type.

### Other GHG Historical Data and Reference Scenarios

PRIMAP-hist (Gütschow *et al*, 2018) provides the historical emissions from 1850-2015 of CH4 and N2O, as well as for the fluorinated-gases (F-gases) SF6, PFCs, and HFCs. We aggregate the PRIMAP data to import into our data model of 180 countries, which then aggregates those data into the 20 COP blocs. Because PRIMAP-hist gives the HFC data as total CO2 equivalents, the emissions for each of the nine predominant HFC types uses the allocation of each type as determined by the data provided by the European Commission Joint Research Centre (JRC)/PBL Netherlands Environmental Assessment Agency. Emission Database for Global Atmospheric Research (EDGAR), release version 4.2. (2014).

Likewise to RS options for CO2 FF emissions, *Choose RS* also changes the RS for each of the non-CO2 gases. The structure is the same as for calculating CO2 FF emissions, described in Section 3.3. However, there are lower limits to the potential reduction of these gases, assumed to globally be the SSP2-26 values for CH4, N2O, SF6, and PFCs (from the SSP Scenarios Database). The regional allocation of the global floor is according to the same proportion of the regional to global RS emissions of that GHG. SF6 and PFCs, for which the SSP are given in F-gas aggregate, require the extra step of multpying the result by the ratio of current emissions of thegiven GHG to the current F-gas emissions. Once the limit of a given gas is reached, its emissions remain constant. If that happens when reductions apply to all GHGs, the CO2 emissions will decrease even more than that specified in order to achieve the specified GHG reductions.

The model does not assume the Kigali Amendment to the Montreal Protocol for reductions in HFC emissions is implemented. However, the structure allows for testing of Kigali starting in 2020, when HFC per GDP reductions increase to achieve near zero intensity over 10 years.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Table 3‑44 Starting GHG per GDP rate (Annual %) | | | | | | |
|  | **CO2** | **CH4** | **N2O** | **SF6** | **PFCs** | **HFCs** |
| US | -1 | -2 | -3 | -2 | -4 | -3 |
| EU | -1 | -2 | -3 | -2 | -4 | -3 |
| Russia | -1 | -2 | -3 | -2 | -4 | -3 |
| Other Eastern Europe | -1 | -2 | -3 | -2 | -4 | -3 |
| Canada | -1 | -2 | -3 | -2 | -4 | -3 |
| Japan | -1 | -2 | -3 | -2 | -4 | -3 |
| Australia | -1 | -2 | -3 | -2 | -4 | -3 |
| New Zealand | -1 | -2 | -3 | -2 | -4 | -3 |
| South Korea | -1 | -3 | -3 | -2 | -4 | -3 |
| Mexico | -1.5 | -2 | -3 | -2 | -4 | -3 |
| China | -2.5 | -5 | -6 | -2 | -4 | -3 |
| India | -2 | -5 | -6 | -2 | -4 | -3 |
| Indonesia | -1.5 | -5 | -6 | -2 | -4 | -3 |
| Other Large Asia | -1.5 | -3 | -4 | -2 | -4 | -3 |
| Brazil | -1.5 | -2 | -3 | -2 | -4 | -3 |
| Other Latin America | -1.5 | -3 | -3 | -2 | -4 | -3 |
| Middle East | -1.5 | -2 | -4 | -2 | -4 | -3 |
| South Africa | -1.5 | -2.5 | -4 | -2 | -4 | -3 |
| Other Africa | -1.5 | -2 | -2 | -2 | -4 | -3 |
| Small Asia | -1.5 | -2 | -2 | -2 | -4 | -3 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑45 GHG per GDP Long Term Rates and Time to Reach Them | | | | |
| **Parameter** | **Long Term Emissions per GDP Rate (% per year)** | **Time to Reach Long Term Emissions per GDP Rate (years)** | | |
|  |  | Developed | Developing A | Developing B |
| CH4 | -0.7 | 15 | 15 | 100 |
| N2O | -0.5 | 5 | 15 | 250 |
| SF6 | -0.2 | 20 | 20 | 20 |
| PFCs | -1.5 | 25 | 10 | 75 |
| HFCs | -0.7 | 10 | 10 | 5 |

Figure 3.32 illustrates the structure within C-ROADS of the *RS CO2eq total* of each region as the sum of RS emissions of CO2 FF, CO2 land use gross emissions, and each nonCO2 GHG multiplied by its GWP. In contrast, *CO2Equivalent Emissions* for each region are comparably calculated but use the CO2 land use net emissions with AF instead of the gross emissions. *RS CO2eq nonforest emissions* and *CO2eq nonforest emissions* are the same but without the the CO2 land use emissions.

The default defines *Apply to CO2eq* to be 1, such that the changes specified for the given input mode apply to the trajectory of *CO2eq nonforest emissions* if *Land use CO2 emissions follow GHGs* equals 0 (default), in which case CO2 land use gross emissions are controlled independently from CO2 FF, CH4, N2O, and F-gases. Otherwise, it applies to the *CO2eq nonforest emissions* plus *CO2 land use gross emissions* and independent inputs for land use gross emissions are ignored. The resulting CO2eq emissions relative to the RS CO2eq emissions are then multiplied by the RS emissions for each GHG included in the CO2eq emissions. For CH4, N2O, and PFCs only the anthropogenic portion is subject to change.

Figure . Structure of RS CO2eq Emissions



The user has two other options for the emissions of the other GHGs such that the targets apply only to CO2 (CO2 FF only if *Land use CO2 emissions follow GHGs* equals 0 and CO2 FF plus CO2 land use gross emissions if *Land use CO2 emissions follow GHGs* equals 1). When Apply to CO2eq is set to 2, the other GHG's change by the same proportion as CO2 FF to its RS. When Apply to CO2eq equals 3, each of the other GHGs follows a percentage of its RS as specified by a LOOKUP table with time. The structure for this is shown in Figure 3.33 and the inputs are given in Table 3‑46.

*Emissions for evaluating pledges* are calculated comparably to the *RS emissions* but use the actual projected emissions instead of the reference scenario values.

Figure . Structure of NonCO2 Emissions when Independent of CO2 FF Emissions



| Table 3‑46 Calculated Parameters of Other GHG (except MP) Emissions Trajectories | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **RS CO2eq nonCO2 emissions[COP]** | SUM(RS CO2eq emissions[COP,Minor Gas!]) | GtonsCO2/year |
| RS CO2eq emissions[COP,minor gas] |  | GtonsCO2/year |
| RS CO2eq emissions[COP,gCH4] | RS CH4 emissions CO2eq[COP] |  |
| RS CO2eq emissions[COP,gN2O] | RS N2O emissions CO2eq[COP] |  |
| RS CO2eq emissions[COP,gPFC] | RS PFC emissions CO2eq[COP] |  |
| RS CO2eq emissions[COP,gSF6] | RS SF6 emissions CO2eq[COP] |  |
| RS CO2eq emissions[COP,gHFCs] | RS total HFC emissions CO2eq[COP] |  |
| RS CO2eq emissions[COP,gCO2] | RS CO2 FF emissions[COP] |  |
| Global NonCO2 Target vs RS | Lookup tables for global inputs as functions of year, from 2010 to 2100, defaulting to 100% of RS at all times; for when Apply to CO2eq=3. | Percent |
| **Semi Agg NonCO2 Target vs RS[Semi Agg]** | Lookup tables for 6 Semi Agg inputs as functions of year, from 2010 to 2100, defaulting to 100% of RS at all times; for when Apply to CO2eq=3. | Percent |
| **Regional NonCO2 Target vs RS[Economic Regions]** | Lookup tables for 15 Economic Regional inputs as functions of year, from 2010 to 2100, defaulting to 100% of RS at all times; for when Apply to CO2eq=3. | Percent |
| **NonCO2 Target vs RS[COP]** | Maps the Semi Agg or Economic Region inputs, depending on the aggregation level, onto the 20 COP; for when Apply to CO2eq=3.  IF THEN ELSE(Apply to CO2eq[COP]<3 :OR: Time < NonCO2 Start Year, "100 percent", IF THEN ELSE(AGGREGATE SWITCH=0, VECTOR SELECT(Economic Region Definition[COP, Economic Regions!],Regional NonCO2 Target vs RS[Economic Regions!](Time/One year), 0, VSSUM,VSERRONEONLY), IF THEN ELSE(AGGREGATE SWITCH=1, VECTOR SELECT(Semi Agg Definition[COP, Semi Agg!],Semi Agg NonCO2 Target vs RS[Semi Agg!](Time/One year),0,VSSUM,VSERRONEONLY), Global NonCO2 Target vs RS(Time/One year)))) | Percent |
| **NonCO2 Target Emissions[COP]** | For when Apply to CO2eq=3, determines the emissions of the GHGs other than CO2, constraining the emissions to not exceed RS.  RS CO2eq nonCO2 emissions[COP]\*MAX(0,MIN(1,NonCO2 Target vs RS[COP]/"100 percent")) | GtonsCO2/year |
| **Independent NonCO2 Target Emissions vs RS[COP]** | For when Apply to CO2eq=3, sets the ratio of emissions to RS for GHGs other than RS independent of CO2 FF emissions.  ZIDZ(NonCO2 Target Emissions[COP],RS CO2eq nonCO2 emissions[COP]) | Dmnl |
| **CO2 FF emissions vs RS[COP]** | Calculates the ratio of actual CO2 FF emissions to RS so that the emissions of other GHGs may be proportionally changed for when Apply to CO2eq=1 or 2.  ZIDZ(CO2 FF emissions[COP],RS CO2 FF emissions[COP]) | Dmnl |
| **NonCO2 emissions vs RS[COP]** | Ratio of emissions of GHGs to their RS emissions. If Apply to CO2eq = 1 and/or 2 or Input mode= 6, then GHG emissions change by the same proportion as the target emissions to the RS emissions. The targets are applied to nonforest CO2eq for Apply to CO2eq=1 and to CO2 FF for Apply to CO2eq=2. Regardless, if Land use CO2 emissions follow GHGs =1, then CO2 land use gross emissions are also included. Otherwise, emissions follow the GHG independent emissions trajectory, defined by the RS and the user specified ratio to RS.  IF THEN ELSE(Choose RS=0 :AND: (Apply to CO2eq[COP]=1 :OR: Apply to CO2eq[COP]=2 :OR:Input Mode[COP]=6) :OR: Test inertia,CO2 FF emissions vs RS[COP],Independent NonCO2 Target Emissions vs RS[COP]) | Dmnl |
| **Final nonCO2 GHG emissions ratio[COP]** | EXP(Rate for nonCO2 GHG/"100 percent"\*(FINAL TIME-Last Active Target Year[COP])) | dmnl |
| **Ratio trajectory for nonCO2 GHGs[COP]** | RAMP FROM TO( 1, Final nonCO2 GHG emissions ratio[COP], Last Active Target Year[COP], FINAL TIME, profile) | Dmnl |
| **GHG emissions unadj [COP]** | Emissions of nonCO2 GHGs are determined by their ratio to their respective RS emissions but constrained to not fall below their lower limit.  IF THEN ELSE(Input Mode[COP]=4, IF THEN ELSE(Time<Year to start GHG projections, RS Global GHG, Global GHG emissions from table)\*Proportion of COP to global GHG[COP], IF THEN ELSE(Input Mode[COP]=5, IF THEN ELSE(Time<Year to start GHG projections, RS Global CH4, Specified Global CH4(Time/One year))\*Proportion of COP to global CH4[COP], MIN(RS CH4 emissions[COP], MAX(CH4 floor[COP], RS CH4 emissions[COP]\*NonCO2 emissions vs RS[COP])))) | CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: ktonsCF4/year  SF6: ktonsSF6/year  HFCs: tons[HFC type]/year |
| **GHG emissions[COP[** | Emissions of nonCO2 GHGs follow the determined GHG emissions unadj unless Choose nonCO2 rates>0. Then GHG emissions follow the unadjusted trajectory until the last specified target, after which the emissions follow the specified nonCO2 rate.  IF THEN ELSE(Choose nonCO2 rates=1 :OR: (Choose nonCO2 rates=2 :AND: Apply to CO2eq[COP] = 3), MAX(GHG floor[COP], IF THEN ELSE(NonCO2 Target vs RS[COP]="100 percent", Ratio trajectory for nonCO2 GHGs[COP], NonCO2 Target vs RS[COP]/ "100 percent")\* GHG emissions unadj at last active target year  [COP]), GHG anthro emissions unadj[COP]) | CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: ktonsCF4/year  SF6: ktonsSF6/year  HFCs: tons[HFC type]/year |
| **GHG emissions unadj at last active target year** | Time<=Last Active Target Year[COP], GHG emissions unadj[COP], GHG emissions unadj[COP] | CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: ktonsCF4/year  SF6: ktonsSF6/year  HFCs: tons[HFC type]/year |
| **Proportion of COP to global GHG** | ZIDZ(RS GHG emissions[COP], RS Global GHG) | dmnl |
| **GHG floor[COP]** | The lower limit of CH4, N2O, SF6 and PFCs. For SF6 and PFCs, the SSP database only provides F-gas aggregated projections. Under the Kigali amendment, HFCs decrease to zero. |  |
| **CH4** | Proportion of COP to global CH4[COP]\*SSP1 26 global CH4 emissions | CH4: MtonsCH4/year |
| **N2O** | Proportion of COP to global N2O[COP]\*SSP1 26 global N2O emissions/ktons per Mtons/N2O per N | N2O: MtonsN2O-N/year |
| **SF6** | SSP1 26 global F gas emissions\*Proportion of COP to global SF6[COP]\*RS SF6 current[COP]/F gas current[COP] | SF6: ktonsSF6/year |
| **PFCs** | SSP1 26 global F gas emissions\*Proportion of COP to global PFC[COP]\*RS PFC current[COP]/F gas current[COP] | PFCs: ktonsCF4/year |
| **CO2eq emissions from GHG[COP]** | What the emissions of a given nonCO2 GHG would be for each region if they had the same GWP as CO2.  GWP of GHG\* GHG anthro emissions[COP]/TonCO2 per GtonCO2 | GtonsCO2/year |
| **Global CO2eq emissions from GHG** | The sum of CO2 equivalent emissions of a given nonCO2 GHG from all regions.  SUM(CO2eq emissions from GHG[COP!]) | GtonsCO2/year |

\*HFCs are modeled with the HFC type subscript, such that each HFC type moves through its own cycle independent of the other HFC types. The CO2eq emissions from HFC is the sum of CO2eq emissions from each HFC type.

Table 3‑47 Time Constants, Radiative Forcing Coefficients, 100-year Global Warming Potential, and Molar Mass of other GHGs

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Gas** | **Preindustrial concentration** | **Natural Emissions** | **Time Constant (years)** **[[3]](#footnote-3)** | **Radiative Forcing Efficiency (watts/ppb/meter2)**3 | **100-year Global Warming Potential (tonsCO2/ton gas)** 3 | **Molar Mass (g/mole)** |
| **CH4** | 785.5 ppb[[4]](#footnote-4) | Flux Biosphere to CH4\*CH4 per C\*Mtons per Gtons | 12.4[[5]](#footnote-5) | 3.63e-4 | 28 (includes indirect effects from enhancements of ozone and stratospheric water vapour) | 16 |
| **N2O** | 275 ppb[[6]](#footnote-6) | 11.2 Mtons/year[[7]](#footnote-7) | 1215 | 3.00e-3 | 265 | 28 (N2O-N) |
|  | | | | | | |
| **Fluorinated Gases** | | | | | | |
| **PFCs (assuming CF4 equivalents)** | 40 ppt | Preindustrial PFC/Time Const for PFC (tons/year) | 50000 | 0.09 | 6630 | 88 |
| **SF6** | 0 | 0 | 3200 | 0.57 | 23500 | 146 |
| **HFCs** |  | | | | | |
| **HFC 134a** | 0 | 0 | 13.4 | 0.19 | 1300 | 102 |
| **HFC23** | 0 | 0 | 222 | 0.18 | 12,400 | 70 |
| **HFC32** | 0 | 0 | 5.2 | 0.11 | 677 | 52 |
| **HFC125** | 0 | 0 | 28.2 | 0.23 | 3170 | 120 |
| **HFC143a** | 0 | 0 | 47.1 | 0.16 | 4800 | 84 |
| **HFC152a** | 0 | 0 | 1.5 | 0.1 | 138 | 66 |
| **HFC227ea** | 0 | 0 | 38.9 | 0.26 | 3350 | 170 |
| **HFC245ca** | 0 | 0 | 6.5 | 0.24 | 716 | 134 |
| **HFC4310mee** | 0 | 0 | 16.1 | 0.42 | 1650 | 252 |

Table 3‑48 Fractional Uptake of CH4

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Parameter | Definition | RS Values | Units | Source |
| **Reference CH4 time constant** | Lifetime at preindustrial shares of troposphere, soil and other (e.g. stratospheric)  sink components | 8.5 | Year | Calculated from AR5 WG1 Chapter 6 |
| **Tropospheric CH4 path share** | Fraction of total removal from tropospheric chemical reaction | 0.88 | Dmnl |
| **Stratospheric CH4 path share** | Fraction of total removal from stratospheric reaction | 0.08 | Dmnl |
| **Initial CH4** | Initial CH4 conc/ppb CH4 per Mton CH4 |  | Mtons |  |
| **Fractional Uptake** | MAX(1/Effective max CH4 lifetime, 1/Reference CH4 time constant\*( Tropospheric CH4 path share/(Stratospheric CH4 path share\*(CH4 in Atm/Initial CH4) + 1-Stratospheric CH4 path share) +(1-Tropospheric CH4 path share) )) |  | 1/year | Formulated from Meinshausen et al., 2011 |
| **Effective max CH4 lifetime** | Accounts for negative feedbacks of temperature and aerosols not explicitly modeled which reduce the lifetime. Set to be approximately a 10% increase over the Reference lifetime. | 9.3 | Years | John et al, 2012. |
| **Time Const for CH4** | 1/Fractional Uptake |  | Years |  |

Figure 3.34 Structure of RF of CH4 and N2O



| Table 3‑49 CH4 and N2O RF Inputted and Calculated Parameters | | | | |
| --- | --- | --- | --- | --- |
| Parameter | Definition | Value | Units | Source |
| CH4 reference conc | Assumes reference year of 1750 | 722 | Ppb | AR5 WG1 Chapter 8 Anthropogenic and Natural Radiative Forcing, including Supplement Table 8.SM.1 Supplementary for Table 8.3: RF formulae for CO2, CH4 and N2O. |
| N2O reference conc | Assumes reference year of 1750 | 270 | Ppb |
| CH4 radiative efficiency coefficient | Coefficient of CH4 simplified radiative efficiency | 0.036 | Watt/(meter2) |
| N2O radiative efficiency coefficient | Coefficient of N2O simplified radiative efficiency | 0.12 | Watt/(meter2) |
| CH4 N2O interaction coefficient | Coefficient of CH4 N2O interaction. | 0.47 | Watt/(meter2) |
| CH4 N2O inter coef 2 | Coefficient of CH4 N2O interaction. | 2.01e-005 | Dmnl |
| CH4 N2O inter coef 3 | Coefficient of CH4 N2O interaction. | 5.31e-015 | Dmnl |
| CH4 N20 inter exp | First exponent of CH4 N2O interaction. | 0.75 | Dmnl |
| CH4 N20 inter exp 2 | Second exponent of CH4 N2O interaction. | 1.52 | Dmnl |
| CH4 N2O unit adj | Normalizes units to avoid dimensioned variable in exponent | 1 | 1/ppb |
| CH4 and N2O Radiative Forcing | The sum of the unit radiative forcing due to CH4 and N2O, taking into account the adjustments for each due to the other.  CH4 Radiative Forcing + N2O Radiative Forcing |  | Watt/(meter2) |
| N2O Radiative Forcing | Adjusts total RF from CH4 and N2O to be less than the sum of RF from each individually to account for interactions between both gases.  N2O Radiative Efficiency\*(sqrt(N2O atm conc\*CH4 N2O unit adj)-sqrt(N2O reference conc\*CH4 N2O unit adj))  -(Adjustment for CH4ref and N2O-Adjustment for CH4ref and N2Oref) |  | Watt/(meter2) |
| CH4 Radiative Forcing | Adjusts total RF from CH4 and N2O to be less than the sum of RF from each individually to account for interactions between both gases.  CH4 Radiative Efficiency\*(sqrt(CH4 atm conc\*CH4 N2O unit adj)-sqrt(CH4 reference conc\*CH4 N2O unit adj))  -(Adjustment for CH4 and N2Oref-Adjustment for CH4ref and N2Oref) |  | Watt/(meter2) |
| Adjustment for CH4ref and N2O | CH4 N2O interaction coeff \* LN( 1  +CH4 N2O inter coef 2 \*(CH4 reference conc\*N2O atm conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp  +CH4 N2O inter coef 3 \*CH4 reference conc\*CH4 N2O unit adj  \*(CH4 reference conc\*N2O atm conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp 2) |  | Watt/(meter2) |
| Adjustment for CH4 and N2Oref | CH4 N2O interaction coeff \* LN( 1  +CH4 N2O inter coef 2 \*(CH4 atm conc\*N2O reference conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp  +CH4 N2O inter coef 3 \*CH4 atm conc\*CH4 N2O unit adj  \*(CH4 atm conc\*N2O reference conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp 2) |  | Watt/(meter2) |
| Adjustment for CH4ref and N2Oref | CH4 N2O interaction coeff \* LN( 1  +CH4 N2O inter coef 2 \*(CH4 reference conc\*N2O reference conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp  +CH4 N2O inter coef 3 \*CH4 reference conc\*CH4 N2O unit adj  \*(CH4 reference conc\*N2O reference conc  \*CH4 N2O unit adj\*CH4 N2O unit adj)^CH4 N20 inter exp 2) |  | watt/(meter2) |

### Montréal Protocol Gases

Rather than explicitly modeling the cycles of the Montreal Protocol (MP) gases, whose emissions are dictated by the MP, historical and projected concentrations from 1955-2100 are taken from Chapter 8 of the Scientific Assessment of Ozone Depletion: 2006 (Daniel *et al.*, 2007). Bullister (2009) and Hansen *et al.* (1998) provide concentrations from 1910-1925 and 1930-1950, respectively. Daniel *et al.* (2007) also provides the RF of MP gases. Comparable to multiplying the resulting concentrations of the other GHGs by their respective RF coefficients, so too are the MP gas concentrations multiplied by their respective RF coefficients, the sum of the products of which yields the total MP RF.

Table 3‑50 MP Gas RF Forcing Coefficients (Data model)

|  |  |
| --- | --- |
| **Gas** | **Radiative Forcing Coefficient (watts/ppb/meter2)** |
| **CFCs** |  |
| **CFC11** | 0.25 |
| **CFC12** | 0.32 |
| **CFC113** | 0.3 |
| **CFC114** | 0.31 |
| **CFC115** | 0.18 |
| **Halons and HCFCs** |  |
| **H1211** | 0.3 |
| **H1301** | 0.32 |
| **HCFC22** | 0.2 |
| **HCFC141b** | 0.14 |
| **HCFC142b** | 0.2 |
| **HCFC123** | 0.14 |
| **Other ODS** |  |
| **CCl4** | 0.13 |
| **CH3CCl3** | 0.06 |
| **CH3Br** | 0.01 |

### GHG Behavior and Calibration

#### Well-mixed GHG Concentrations

This section compares the concentrations of CH4, N2O, PFCs, SF6, and HFCs to historical data and RCP projections for each scenario. In all cases, C-ROADS emissions follow historical data and the RCP projections. As Figure 3.35 through Figure 3.38 illustrate, calibration agreement is strong. Comparisons against the more recent SSP scenarios, not shown here, also match strongly for all radiative forcing levels (Baseline, and 6.0, 4.5, 3.4, 2.6, and 1.9 ).

Figure . Historical CH4 Concentrations



Figure . Projected CH4 Concentrations



Figure . Historical N2O Concentrations



Comparisons against historical data and projections for CH4 and N2O concentrations are given in Table 3‑51 through Table 3‑54 . These statistics indicate strong calibration except for that against CH4 projections in the RCP4.5 scenario. However, the error in that is concentrated in covariance (UC), suggesting that the mean and variance compares acceptably well.

Figure . Projected N2O Concentrations



|  |  |  |
| --- | --- | --- |
| Table 3‑51 CH4 Simulated Data Compared to Law Dome and GISS Historical Data | | |
|  | C-ROADS vs Historical CH4 Law Dome Data  (1850-1980) | C-ROADS vs Historical CH4 GISS Data  (1850-2016) |
| Count | 41 | 167 |
| R2 | 0.9956 | 0.9879 |
| MAPE | 0.0518 | 0.0804 |
| MAEM | 0.0000 | 0.0001 |
| RMSPE | 0.0580 | 0.0859 |
| RMSE | 71.0253 | 116.7678 |
| Theil Inequalities |  |  |
| UM | 0.7278 | 0.7494 |
| US | 0.2393 | 0.1566 |
| UC | 0.0328 | 0.0940 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑52 CH4 Concentration Simulated Data Compared to RCP Projections (2000-2100) | | | | |
|  | RCP8.5 | RCP6.0 | RCP4.5 | RCP2.6 |
| Count | 11 | 11 | 11 | 11 |
| R2 | 0.9881 | 0.8787 | 0.0798 | 0.9424 |
| MAPE | 0.0324 | 0.0317 | 0.0517 | 0.0240 |
| MAEM | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| RMSPE | 0.0415 | 0.0416 | 0.0601 | 0.0385 |
| RMSE | 81.0722 | 73.8719 | 102.8904 | 67.3995 |
| Theil Inequalities |  | | | |
| UM | 0.0917 | 0.0332 | 0.0117 | 0.2551 |
| US | 0.0025 | 0.7247 | 0.0919 | 0.3631 |
| UC | 0.9058 | 0.2421 | 0.8964 | 0.3819 |

|  |  |
| --- | --- |
| Table 3‑53 N2O Simulated Data Compared to Law Dome Historical Data (1850-2011) | |
|  | C-ROADS vs Historical N2O GISS Data |
| Count | 162 |
| R2 | 0.9847 |
| MAPE | 0.0126 |
| MAEM | 0.0000 |
| RMSPE | 0.0141 |
| RMSE | 4.0399 |
| Theil Inequalities |  |
| UM | 0.7987 |
| US | 0.0267 |
| UC | 0.1746 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑54 N2O Concentration Simulated Data Compared to RCP Projections (2000-2100) | | | | |
|  | RCP8.5 | RCP6.0 | RCP4.5 | RCP2.6 |
| Count | 11 | 11 | 11 | 11 |
| R2 | 0.9999 | 0.9999 | 1.0000 | 0.9969 |
| MAPE | 0.0023 | 0.0031 | 0.0034 | 0.0041 |
| MAEM | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| RMSPE | 0.0028 | 0.0034 | 0.0038 | 0.0047 |
| RMSE | 0.9401 | 1.1832 | 1.3231 | 1.5915 |
| Theil Inequalities |  | | | |
| UM | 0.0061 | 0.0126 | 0.0246 | 0.0559 |
| US | 0.8789 | 0.9266 | 0.9666 | 0.7971 |
| UC | 0.1151 | 0.0608 | 0.0088 | 0.1470 |

#### Well-mixed GHG Radiative Forcing

This section compares the sum of radiative forcing of all the well-mixed GHGs, including CO2, CH4, N2O, PFCs, SF6, HFCs, and MP gases to historical data and RCP projections. Figure 3.39 and Figure 3.40 and Table 3‑55 and Table 3‑56 illustrate that calibration agreement is strong for all comparisons.

Figure . Historical Well-Mixed GHG Radiative Forcing



#### 

Figure . Projected Well-Mixed GHG Radiative Forcing Compared to RCP



|  |  |
| --- | --- |
| Table 3‑55 Well Mixed Radiative Forcing Simulated Data Compared to RCP Historical Simulated Output (1850-2012) | |
|  | C-ROADS vs RCP Historical Output for Radiative Forcing from Well Mixed GHGs |
| Count | 163 |
| R2 | 0.9980 |
| MAPE | 0.0851 |
| MAEM | 0.0839 |
| RMSPE | 0.0995 |
| RMSE | 0.0856 |
| Theil Inequalities |  |
| UM | 0.7678 |
| US | 0.0815 |
| UC | 0.1507 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑56 Well Mixed Radiative Forcing Simulated Data Compared to RCP Projections (2000-2100) | | | | |
|  | RCP8.5 | RCP6.0 | RCP4.5 | RCP2.6 |
| Count | 11 | 11 | 11 | 11 |
| R2 | 0.9997 | 0.9995 | 0.9994 | 0.9954 |
| MAPE | 0.0290 | 0.0268 | 0.0298 | 0.0300 |
| MAEM | 0.0061 | 0.0070 | 0.0081 | 0.0096 |
| RMSPE | 0.0309 | 0.0292 | 0.0315 | 0.0320 |
| RMSE | 0.1379 | 0.0984 | 0.1057 | 0.0946 |
| Theil Inequalities |  | | | |
| UM | 0.8842 | 0.9468 | 0.9687 | 0.9243 |
| US | 0.0702 | 0.0000 | 0.0001 | 0.0277 |
| UC | 0.0455 | 0.0531 | 0.0311 | 0.0480 |

## Cumulative Carbon Emissions and Budget

C-ROADS calculates the cumulative carbon emissions, accounting for that which is sequestered through CDR technologies. The regional cumulative emissions account for the net carbon sequestered from afforestation. The global cumulative emissions account for the net sequestered from all CDR types, as described in Section 3.6.

C-ROADS begins to calculate cumulative emissions starting in 1870 and in 2011 for comparisons to the AR5 thresholds. The model also allows for the user to choose another starting year. Table 3‑57 presents the equations for *Cumulative CO2*. These cumulative emissions may be compared to the IPCC’s AR5 thresholds for limiting temperature change to 1.5 Degrees C and 2 Degrees C through 2100.

Figure . Structure of Cumulative CO2 Emissions



| Table 3‑57 Cumulative CO2 Emissions Calculated Parameters |
| --- |

| Parameter | Definition | Default Values | Units |
| --- | --- | --- | --- |
| Budget of cumulative CO2 since 1870 (for 66%) | From the Synthesis Report IPCC AR5: Available from: https://www.researchgate.net/publication/272784739\_Synthesis\_Report\_IPCC\_AR5  “Cumulative CO2 emissions at the time the temperature threshold is exceeded that are required for 66%, 50% or 33% of the Coupled Model Intercomparison Project Phase 5 (CMIP5) complex models Earth System Model (ESM) and Earth System Models of Intermediate Complexity (EMIC) simulations, assuming non-CO2 forcing follows the RCP8.5 scenario. “. | 2900 | GtonsCO2 |
| Cumulative CO2 for 66 pct chance below 2 deg | 1000 | GtonsCO2 |
| Cumulative CO2 for 50 pct chance below 2 deg | 1300 | GtonsCO2 |
| Cumulative CO2 for 33 pct chance below 2 deg | 1500 | GtonsCO2 |
| Cumulative CO2 for 66 pct chance below 1point5 deg | 400 | GtonsCO2 |
| Cumulative CO2 for 50 pct chance below 1point5 deg | 550 | GtonsCO2 |
| Cumulative CO2 for 33 pct chance below 1point5 deg | 850 | GtonsCO2 |

| Table 3‑57 Cumulative CO2 Emissions Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **CO2 emissions accumulation[COP]** | The change in cumulative CO2 net emissions with each time step, starting at the accumulation start year, i.e., 1870: Includes CO2 land use net emissions with AF removals, but does not consider the net removals of CDR that is considered only globally.  STEP(Total CO2 emissions[COP],Year to accumulate CO2 ) | GtonsCO2/year |
| **Cumulative CO2[COP]** | INTEG(CO2 Emissions Accumulation[COP], Initial cum CO2) | GtonsCO2 |
| **Total CO2 emissions** | Includes CO2 accounting for net removals from afforestation.  CO2 FF emissions [COP]+CO2 land use net emissions with AF[COP] | GtonsCO2/year |
| **Global cumulative CO2 without nonAF CDR** | Global cumulative CO2 from 1870, accounting for net removals from afforestation but excluding all removals from other CDR  SUM(Cumulative CO2 from 1870[COP!]) | GtonsCO2 |
| **Global cumulative CO2** | Global cumulative CO2 from 1870, accounting for net removals from all CDR  Global cumulative CO2 without nonAF CDR-Total cumulative non afforestation CO2 removed | GtonsC |
| **Global cumulative C** | Global cumulative CO2 from 1870, accounting for net removals from all CDR  Global cumulative CO2/CO2 per C | GtonsC |
| **Budget of CO2 remaining** | Budget of cumulative CO2 since 1870-Global cumulative CO2 | GtonsCO2 |
| **Budget of C remaining** | Budget of CO2 remaining/CO2 per C | GtonsC |
| **Year budget spent** | Reports the year the carbon budget is depleted. If not by 2100, then the year reported is “NA”  SAMPLE IF TRUE(Budget of CO2 remaining>0, IF THEN ELSE(Time=FINAL TIME, :NA:, Time), IF THEN ELSE(Time=FINAL TIME, :NA:, Time)) | Year |
| **Cumulative CO2 from 2011** | Cumulative CO2 from 2011, accounting for net removals from afforestation but excluding all removals from other CDR  STEP(Total CO2 emissions[COP], y2011) | GtonsCO2 |
| **Global cumulative CO2 since 2011** | Cumulative CO2 from 2011, accounting for net removals from all CDR  SUM(Cumulative CO2 since 2011[COP!])-Total cumulative non afforestation CO2 removed | GtonsC |
| **Global cumulative C from 2011** | Cumulative C from 2011, accounting for net removals from all CDR  Global cumulative CO2 since 2011/CO2 per C | GtonsC |
| **Probability of not exceeding 2 Deg C** | IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 66 pct chance below 2 deg, "66 percent", IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 50 pct chance below 2 deg, "50 percent", IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 33 pct chance below 2 deg, "33 percent", 0))) | percent |
| **Probability of not exceeding 1point5 Deg C** | IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 66 pct chance below 1point5 deg, "66 percent", IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 50 pct chance below 1point5 deg, "50 percent", IF THEN ELSE(Global cumulative CO2 since 2011<Cumulative CO2 for 33 pct chance below 1point5 deg, "33 percent", 0))) | percent |
| **Cumulative CO2 from 2011 if exceed 2 DegC** | SAMPLE IF TRUE(Threshold 2 Deg exceeded=0,Global cumulative CO2 since 2011, Global cumulative CO2 since 2011) | GtonsCO2 |
| **Cumulative CO2 from 2011 if exceed 1point5 DegC** | SAMPLE IF TRUE(Threshold 1point5 Deg exceeded=0,Global cumulative CO2 since 2011, Global cumulative CO2 since 2011) | GtonsCO2 |

## Climate

### Introduction

Like the carbon cycle, the climate sector is adapted from the FREE model, which used the DICE climate sector without modification (Nordhaus 1994). The DICE structure in turn followed Schneider and Thompson (1981).

The model has been recast in terms of stocks and flows of heat, rather than temperature, to make the physical process of accumulation clearer to users. However, the current model is analytically equivalent to the FREE and DICE versions.

FREE and DICE used exogenous trajectories for all non-CO2 radiative forcings. This version adds explicit forcings from CH4 and N2O.

### Structure

The model climate is a fifth-order, linear system, with three negative feedback loops. Two loops govern the transport of heat from the atmosphere and surface ocean, while the third represents warming of the deep ocean. Deep ocean warming is a slow process, because the ocean has such a large heat capacity. If the deep ocean temperature is held constant, the response of the atmosphere and surface ocean to warming is first-order.

Temperature change is a function of radiative forcing (RF) from greenhouse gases and other factors, feedback cooling from outbound longwave radiation, and heat transfer from the atmosphere and surface ocean to the deep ocean layer (Figure 3.44 and Eq. 7 & 8).

Eq. 7

Tsurf = Qsurf/Rsurf

Tdeep = Qdeep/Rdeep

Qsurf = ∫ (RF(t) – Fout(t) – Fdeep(t) )dt + Qsurf(0)

Qdeep = ∫ Fdeep(t) dt + Qdeep(0)

T = Temperature of surface and deep ocean boxes Fdeep = heat flux to deep ocean Q = heat content of respective boxes RF = radiative forcing R = heat capacity of respective boxes Fout = outgoing radiative flux

Eq. 8

Fout(t) = λ Tsurf

Fdeep(t) = Rdeep\*(Tsurf-Tdeep)/τ

λ = climate feedback parameter τ = heat transfer time constant

Radiative forcing from CO2 is logarithmic of the atmospheric CO2 concentration (IPCC TAR WG1, 2001, Table 6.2). Forcing from CH4 and N2O is less than the sum of RF from each individually to account for interactions between both gases. Forcing from each F-gas is the product of its concentration and its radiative forcing coefficient; the total forcings of F-gases is the sum of these products, as are the forcings from MP gases derived. The sum of other forcings, which include those from aerosols (black carbon, organic carbon, sulfates), tropospheric ozone, defaults to an exogenous time-varying parameter. The values use a composite of GISS 1850-2012 and the chosen SSP scenario thereafter. While the default assumes the SSP5-60, the other forcings projections will follow the selected SSP scenario. *RCP chosen other RF* allows the user to select the other RCP scenarios for just other forcings projections without affecting the emissions trajectories.

The equilibrium temperature response to a change in radiative forcing is determined by the radiative forcing coefficient, κ, and the climate feedback parameter, λ. Equilibrium sensitivity to 2xCO2eq forcing is 3C in the base case.

|  |  |  |
| --- | --- | --- |
|  | | Eq. 9 |
| Tequil = equilibrium temperature  Ca = atmospheric CO2 concentration  Ca,o = preindustrial atmospheric CO2 concentration | κ = radiative forcing coefficient  λ = climate feedback parameter |  |

Figure 3.42 Equilibrium Temperature Response



Figure . Structure of Climate Sector



Table 3‑58 Temperature Parameter Inputs

Figure . Structure of Radiative Forcings



|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Definition** | **RS** | **Units** | **Source** |
| Climate Sensitivity to 2x CO2 | Equilibrium temperature change in response to a 2xCO2 equivalent change in radiative forcing. According to AR5, high confidence that value likely between 1.5 and 4.5, with high confidence that extremely unlikely less than 1 and medium confidence that extremely unlikely greater than 6. Changed from AR4, for which lower likely limit was 2. | 3 | Degrees C | AR5, 2013 |
| CO2 Rad Force Coeff | Coefficient of Radiative Forcing from CO2 | 5.35 | Watt/meter2 | IPCC |
| Preindustrial CO2 | Preindustrial CO2 content of atmosphere. | 590 | GtonsC |  |
| Last historical RF year | Last year of GISS historical data. | 2012 | Year | GISS, (Miller *et al*, 2014) |
| Init Atmos UOcean Temp | Initial Temperature of the Atmosphere and Upper Ocean | 0 | Degrees C |  |
| Heat Transfer Rate | Rate of heat transfer between the surface and deep ocean. | 1.23 | watt/meter2/DegreesC | Schneider & Thompson (1981), calibrated to more closely reflect MAGICC 5.3 results.. |
| Area | Global surface area. | 5.1e+014 | Meter2 |  |
| Land thickness | Effective land area heat capacity, expressed as equivalent water layer thickness | 8.4 | Meter | Schneider & Thompson (1981) |
| land area fraction | Fraction of global surface area that is land. | 0.292 | Dmnl | Schneider & Thompson (1981) |
| watt per J s | Converts watts to J/s. | 1 | watt/(J/s) |  |
| days per year | Converts years to days. | 365 | days/year |  |
| sec per day | Converts days to seconds. | 86,400 | S/day |  |
| mass heat cap | Specific heat of water, i.e., amount of heat in Joules per kg water required to raise the temperature by one degree Celsius. | 4186 | J/kg/DegreesC |  |
| Density | Density of water, i.e., mass per volume of water. | 1000 | kg/meter3 |  |
| Goal for Temperature | Assumed threshold of temperature change above which irreversible climate changes may occur | 2 | Degrees C |  |
| J per W Yr | 365\*24\*60\*60/1e+022; converts Joules\*1e22 to watts\*year | 3.1536e-015 | JoulesE22/watt/year |  |
| Offset 700m heat | Calibration offset. | -16 | JoulesE22 |  |
| Adjustment for RCP Other RF | Adjusts RCP projections for calibration to account for mineral dust and land albedo forcings | -0.3 | Watt/meter2 |  |

| Table 3‑59 RF and Temperature Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| Effective Radiative Forcing | Allows user to test specific RF from calibration datasets and to test the effect of holding RF constant at a given time.  SAMPLE IF TRUE(Time<=Time to Commit RF  ,Total Radiative Forcing,Total Radiative Forcing) | Watt/meter2 |
| Total Radiative Forcing | "Well-Mixed GHG Forcing"+ Other Forcings | Watt/meter2 |
| Effective RF excluding volcanic RF | SMOOTH(Effective Radiative Forcing, Other forcings smoothing time) | watt/(meter\*meter) |
| Time to Commit RF | Year to hold the effective RF constant. Default sets it to beyond the simulation time.  2200 | Year |
| "Well-Mixed GHG Forcing" | RF from well mixed GHGs, i.e., CO2, N2O, CH4, PFCs, SF6, HFCs, and MP gases.  CO2 Radiative Forcing+CH4 and N2O Radiative Forcing+Halocarbon RF | Watt/meter2 |
| CO2 Radiative Forcing | Radiative forcing from CO2 in the atmosphere  CO2 Rad Force Coeff\*LN(Effective C in Atmosphere/Preindustrial C) | Watt/meter2 |
| Effective C in Atmosphere | Allows user to test an exogenous C in atmosphere when Switch for exogenous CO2 for RF=1; otherwise, the effective C in atmosphere is that modeled through the carbon cycle.  Switch for exogenous CO2 for RF\*Atmospheric CO2 data composite  +(1-Switch for exogenous CO2 for RF)\*C in Atmosphere | GtonsC |
| Atmospheric CO2 data composite | C in atmosphere from composite of data from CO2 Law Dome and Mauna Loa and projections from AR5 RCP8.5.  IF THEN ELSE( Time<INIT(GET DATA FIRST TIME(Atmospheric CO2 Mauna Loa)),Atmospheric CO2 Law Dome,IF THEN ELSE( Time>INIT(GET DATA LAST TIME(Atmospheric CO2 Mauna Loa)) ,RCP CO2 concentration [RCP85] ,Atmospheric CO2 Mauna Loa))/ppm CO2 per GtonC | GtonsC |
| CH4 and N2O Radiative Forcing | Adjusts total RF from CH4 and N2O to be less than the sum of RF from each individually to account for interactions between both gases, defined in Table 3‑49. | Watt/meter2 |
| Halocarbon RF | RF from PFCs, SF6, HFCs, and MP gases.  RF from F gases+MP RF Total | Watt/meter2 |
| MP RF[MP Gases]  (Data Model) | RF from Montreol Protocol gases, determined in Data Model, which optimistically assume that emissions of these gases will follow the limits set by the Montreal Protocol, as amended, and use data and projections from Bullister (2009), Daniel *et al.* (2007), and Hansen *et al.* (1998).  MP Gas Concentrations[MP Gases]\*MP Gas RF Efficiency[MP Gases]/ppt per ppb | Watt/meter2 |
| MP RF Total  (Data Model) | Radiative forcing due to Montreal Protocol gases, based on the concentration of each gas multiplied by its radiative forcing coefficient.  SUM(MP RF[MP Gases!]) | Watt/meter2 |
| RF from F gases | Radiative forcing due to fluorinated gases, based on the concentration of each gas multiplied by its radiative forcinge coefficient. The RF of HFCs is the sum of the RFs of the individual HFC types.  PFC RF+SF6 RF+HFC RF total | Watt/meter2 |
| HFC RF total | The sum of the RFs of the individual HFC types.  SUM(HFC RF[HFC type!]) | Watt/meter2 |
| Percent of well mixed GHG RF[gas, scenario] | Percent of RF from well-mixed GHGs that are due to each of them. The percent from each of CH4 and N2O assumes an equal share in their combined RF. | Percent |
| Percent of well mixed GHG RF[gCO2, scenario] | CO2 Radiative Forcing/"Well-Mixed GHG Forcing"\*"100 percent" |  |
| Percent of well mixed GHG RF[gCH4, scenario] | CH4 and N2O Radiative Forcing/"Well-Mixed GHG Forcing"/2\*"100 percent" |  |
| Percent of well mixed GHG RF[gN2O, scenario] | CH4 and N2O Radiative Forcing/"Well-Mixed GHG Forcing"/2\*"100 percent" |  |
| Percent of well mixed GHG RF[gPFC, scenario] | PFC RF/"Well-Mixed GHG Forcing"\*"100 percent" |  |
| Percent of well mixed GHG RF[gSF6, scenario] | SF6 RF/"Well-Mixed GHG Forcing"\*"100 percent" |  |
| Other Forcings History  (Data Model) | GISS other forcings, 1850-2012. (Miller *et al*, 2014) | Watt/meter2 |
| RCP chosen other RF | 1-4 = RCP chosen other RF, defaults to 3 | Dmnl |
| SSP chosen other RF | 1-5 = SSP chosen other RF, defaults to 5 | Dmnl |
| RCP Selection for other RF | Uses RCP SelectedScenario if calibrating. Othefsrwise, uses specific SSP scenario.  IF THEN ELSE( Choose RS,IF THEN ELSE( RCP Scenario = RCP SelectedScenario ,1,0), IF THEN ELSE ( RCP Scenario = RCP chosen other RF, 1, 0)) | Dmnl |
| Selected SSP Other RF[RCP Scenario] | VECTOR SELECT(SSP Selection for other RF[SSP Scenario!],SSP Other Forcings[SSP Scenario!, RCP Scenario] , 0 , VSSUM, VSERRONEONLY) | Watt/meter2 |
| Selected SSP RCP Other RF | VECTOR SELECT(RCP Selection for other RF[RCP Scenario!],Selected SSP Other RF[RCP Scenario!] , 0 , VSSUM, VSERRONEONLY) | Watt/meter2 |
| Selected RCP Other RF | VECTOR SELECT(RCP Selection for other RF[RCP Scenario!],RCP Other RF[RCP Scenario!] , 0 , VSSUM, VSERRONEONLY) | Watt/meter2 |
| Other Forcings | Forcings for all components except well-mixed GHGs.  Switch over from historical data to projections in 2012.  Projections are based on selected SSP-driven scenario and reduced by SRM unless Choose RS is set to 1, in which case the RCP scenarios are used for calibration.  IF THEN ELSE(Time<=Last historical RF year, Other Forcings History, IF THEN ELSE(Choose RS,Selected RCP Other RF+Adjustment for RCP Other RF, Selected SSP RCP Other RF  ))-SRM reduction in RF | Watt/meter2 |
| Heat in Atmosphere and Upper Ocean | Temperature of the Atmosphere and Upper Ocean  Effective Radiative Forcing-Feedback Cooling-Heat Transfer[layer1] | Year\*watt/meter2 |
| Heat in Deep Ocean[layers] | Heat content of each layer of the deep ocean.  INTEG(Heat Transfer, Init Deep Ocean Temp\*Deep Ocean Heat Cap) | Year\*watt/meter2 |
| Heat in Deep Ocean[upper] | Heat in each layer except for the bottom.  INTEG(Heat Transfer[upper]-Heat Transfer[lower], Init Deep Ocean Temp\*Deep Ocean Heat Cap[upper]) |  |
| Heat in Deep Ocean[bottom] | Heat in the bottom layer.  INTEG(Heat Transfer[bottom], Init Deep Ocean Temp\*Deep Ocean Heat Cap[bottom]) |  |
| Relative Deep Ocean Temp[layers] | Temperature of each layer of the deep ocean.  Heat in Deep Ocean[layers]/Deep Ocean Heat Cap[layers] | Degrees C |
| 2x CO2 Forcing | Radiative forcing at 2x CO2 equivalent  CO2 Rad Force Coeff\*LN(2) | Watt/meter2 |
| Equilibrium Temperature | Ratio of Radiative Forcing to the Climate Feedback Parameter  Radiative Forcing/Climate Feedback Param | Degrees C |
| Feedback Cooling | Feedback cooling of atmosphere/upper ocean system due to blackbody radiation.  Temperature change from preindustrial\*Climate Feedback Param | Watt/meter2 |
| Climate Feedback Param | Climate Feedback Parameter - determines feedback effect from temperature increase.  "2x CO2 Forcing"/Climate Sensitivity to 2x CO2 | Watt/meter2/Degrees C |
| Heat Transfer[layers] | Heat Transfer from the atmosphere & upper ocean to the first layer of the deep ocean and from each layer of the deep ocean to the layer below it.  Temp Diff\*Deep Ocean Heat Cap/Heat Transfer Time | Watt/meter2 |
| Heat Transfer[layer1] | (Temperature change from preindustrial-Relative Deep Ocean Temp[layer1])\*Heat Transfer Coeff/Mean Depth of Adjacent Layers[layer1] |  |
| Heat Transfer[lower] | (Relative Deep Ocean Temp[upper]-Relative Deep Ocean Temp[lower])\*Heat Transfer Coeff/Mean Depth of Adjacent Layers[lower] |  |
| Heat Transfer Coeff | The ratio of the actual to the mean of the heat transfer coefficient, which controls the movement of heat through the climate sector, is a function of the ratio of the actual to the mean of the eddy diffusion coefficient, which controls the movement of carbon through the deep ocean.  INITIAL((Heat Transfer Rate\*Mean Depth of Adjacent Layers[layer1])\*(Heat Diffusion Covar\*(Eddy diff coeff/Eddy diff mean)+(1-Heat Diffusion Covar))) | watt/meter2/(DegreesC/meter) |
| upper layer volume Vu | Water equivalent volume of the upper box, which is a weighted combination of land, atmosphere,and upper ocean volumes.  area\*(land area fraction\*land thickness+(1-land area fraction)\*Mixed Depth) | meter3 |
| lower layer volume Vu[layers] | Water equivalent volume of the deep ocean by layer.  area\*(1-land area fraction)\*Layer Depth[layers] | meter3 |
| volumetric heat capacity | Volumetric heat capacity of water, i.e., amount of heat in watt\*year required to raise 1 cubic meter of water by one degree C.  mass heat cap\*watt per J s/sec per yr\*density | watt\*year/meter3/DegreesC |
| Atm and Upper Ocean Heat Cap | Volumetric heat capacity for the land, atmosphere, and, upper ocean layer, i.e., upper layer heat capacity Ru; based on 70% 100m ocean layer and 30% 8.4m equiv land layer.  INITIAL(upper layer volume Vu\*volumetric heat capacity/area) | watt\*year/DegreesC/meter2 |
| Deep Ocean Heat Cap[layers] | Volumetric heat capacity for the deep ocean by layer, i.e., lower layer heat capacity Ru.  INITIAL(lower layer volume Vu[layers]\*volumetric heat capacity/area) | watt\*year/DegreesC/meter2 |
| Temperature change from preindustrial | Heat in Atmosphere and Upper Ocean/Atm and Upper Ocean Heat Cap | Degrees C |
| Temperature change from preindustrial Deg F | Temperature change from preindustrial\*temp conversion | Degrees F |
| Temp conversion | 1.8 | Degrees F/Degrees C |
| Equivalent CO2 | EXP(Effective RF excluding volcanic RF/CO2 Rad Force Coeff)  \*(Preindustrial C\*ppm CO2 per GtonC) | Ppm |
| "Mean temperature change 1980-1999" | Mean of actual data from the two historical temperature datasets (HADCRUT4 and GISTEMP) for the period of 1980-1999.  ("Mean GISTEMP temperature change 1980 - 1999"+"Mean HADCRUT4 temperature change 1980 - 1999")/number of historical temp datasets | Degrees C |
| "Mean HADCRUT4 temperature change 1980 - 1999" | Mean of actual 1980-1999 HADCRUT4 temperature change from preindustrial levels, inputted in the Data Model.  GET DATA MEAN(HADCRUT4 anomaly vPreind, y1980 , y1999) | Degrees C |
| "Mean GISTEMP temperature change 1980 - 1999" | Mean of actual 1980-1999 GISTEMP temperature change from preindustrial levels, inputted in the Data Model.  GET DATA MEAN(GISTEMP anomaly vPreind, y1980 , y1999) | Degrees C |
| Temperature change from 1990 | Temperature change with respect to the mean data over 1980-1999, determined as the mean of GISTEMP and HADCRUT4 means over this period.  IF THEN ELSE( Time >= y1990, Temperature change from preindustrial-"Mean temperature change 1980-1999", :NA: ) | Degrees C |
| Heat to 700m | Sum of the heat in the atmosphere and upper ocean and that in the top two layers of the deep ocean. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean and 300 m each for layers 1 and 2.  Heat in Atmosphere and Upper Ocean\*(1-land share)  +Heat in Deep Ocean[layer1]+Heat in Deep Ocean[layer2] | watt\*year/meter2 |
| Heat to 2000m | Heat to 2000m in deep ocean. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean, 300 m each for layers 1 and 2, and 1300 m for layer 3.  Heat to 700m+Heat in Deep Ocean[layer3] | watt\*year/meter2 |
| Heat to 700m J | Heat to 700 m in Joules\*1e22 for the area covered by water. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean and 300 m each for layers 1 and 2.  Heat to 700m\*J per W Yr\*(area\*(1-land area fraction))+Offset 700m heat | JoulesE22 |
| Heat to 2000m J | Heat to 2000 m in Joules\*1e22 for the area covered by water. Assumes default layer thicknesses, i.e., 100 m for the mixed ocean, 300 m each for layers 1 and 2, and 1300 m for layer 3.  Heat to 2000m\*J per W Yr\*(area\*(1-land area fraction)) | JoulesE22 |

### Calibration and Behavior

Total RF matches historical data and projected values for scenarios tested, as shown in Figure 3.46 and Figure 3.47. Figure 3.48 compares the behavior of the model to historic temperatures. With this structure, the model replicates 19th and 20th century climate, as observed by GISTEMP and HADCRUT4, reasonably well.

Figure . Historical Total Radiative Forcing



Figure . Projected Total Radiative Forcing Compared to RCP



|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Table 3‑60 Total Radiative Forcing Simulated Data Compared to RCP Historical Simulated Output (1850-2012) | | | | | |
|  | | | C-ROADS vs RCP Historical Output for Total Radiative Forcing | | |
| Count | | | 163 | | |
| R2 | | | 0.9267 | | |
| MAPE | | | 2.1927 | | |
| MAEM | | | 4.0646 | | |
| RMSPE | | | 18.4725 | | |
| RMSE | | | 0.2474 | | |
| Theil Inequalities | | |  | | |
| UM | | | 0.0533 | | |
| US | | | 0.3409 | | |
| UC | | | 0.6058 | | |
| Table 3‑61 Total Radiative Forcing Simulated Data Compared to RCP Projections (2000-2100) | | | | | |
|  | RCP8.5 | RCP6.0 | | RCP4.5 | RCP2.6 |
| Count | 11 | 11 | | 11 | 11 |
| R2 | 0.9923 | 0.9729 | | 0.9693 | 0.8691 |
| MAPE | 0.0891 | 0.0962 | | 0.0963 | 0.1053 |
| MAEM | 0.0217 | 0.0309 | | 0.0318 | 0.0436 |
| RMSPE | 0.1158 | 0.1218 | | 0.1195 | 0.1248 |
| RMSE | 0.2843 | 0.2562 | | 0.2570 | 0.2472 |
| Theil Inequalities |  | | | | |
| UM | 0.1331 | 0.0630 | | 0.0883 | 0.0647 |
| US | 0.5068 | 0.4526 | | 0.5849 | 0.7151 |
| UC | 0.3601 | 0.4844 | | 0.3267 | 0.2201 |

Figure . Historical Temperature Change from Preindustrial (1850-2016)



Figure . Projected Temperature Change from 1990 Compared to RCP



|  |  |  |
| --- | --- | --- |
| Table 3‑62 Temperature Change from Preindustrial Levels Simulated Data Compared to Historical Data (1850-2016) | | |
|  | C-ROADS vs HADCRUT4 Temperature Data  (1850-2016) | C-ROADS vs GISTEMP Temperature Data  (1880-2016) |
| Count | 167 | 137 |
| R2 | 0.8380 | 0.8261 |
| MAPE | 1.9519 | 1.5128 |
| MAEM | 7.3270 | 6.1734 |
| RMSPE | 11.4094 | 2.9491 |
| RMSE | 0.1287 | 0.1474 |
| Theil Inequalities |  |  |
| UM | 0.0252 | 0.0878 |
| US | 0.0367 | 0.0011 |
| UC | 0.9382 | 0.9111 |

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Table 3‑63 Temperature Change from 1990 Simulated Data Compared to RCP/CMIP5 (1860-2100) | | | | |
|  | RCP8.5 | RCP6.0 | RCP4.5 | RCP2.6 |
| Count | 239 | 239 | 239 | 239 |
| R2 | 0.9980 | 0.9965 | 0.9953 | 0.9927 |
| MAPE | 0.2214 | 0.1804 | 0.2117 | 0.2144 |
| MAEM | 0.4423 | 0.7639 | 1.0258 | 4.5517 |
| RMSPE | 0.3168 | 0.2875 | 0.3154 | 0.3276 |
| RMSE | 0.1462 | 0.0951 | 0.1119 | 0.1161 |
| Theil Inequalities |  | | | |
| UM | 0.0169 | 0.3537 | 0.3684 | 0.5515 |
| US | 0.8104 | 0.3146 | 0.3363 | 0.2103 |
| UC | 0.1727 | 0.3316 | 0.2953 | 0.2382 |

These robust statistics indicate that C-ROADS output reasonably matches the historical and projected evolution of the climate well. Although comparisons of historical temperatures are less robust than those of projections, the error in the former is concentrated in UC and arises from the year-by- year variations in temperature in the data not captured by the model. Figure 3.50 compares C-ROADS to the temperature projections reported in AR5.

Figure . 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 AR5. Bars also show comparisons in 2100 to AR4.



## Sea Level Rise

SLR, the structure shown in Figure 3.51, is modeled using the Vermeer and Rahmstorf (2009) semi-empirical model in which the increase in SLR rises with mean global surface temperature and falls with faster rates of warming (to capture the delay in the response of ice sheet melt to temperature change). That model is estimated from historical data 1880-2000, a period with low levels of warming that therefore likely underestimates future sea level rise from the faster-than-historical rates of melt of the Greenland and Antarctic ice sheets, other glaciers, and in the mean size of winter snowpack now being experienced. The slider “Additional SLR from Ice Melt” allows users to capture these effects. Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. The sensitivity to ice sheet melting does not affect the historic period. Figure 3.51 depicts the historical sea level rise. Table 3‑66 compares the C-ROADS simulated SLR with the historical data concatenated from the tide gauge and satellite sources.

Figure . Structure of Sea Level Rise

****

Table 3‑64 Sea Level Rise Parameter Inputs

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Parameter** | **Definition** | **Range** | **Default** | **Units** |
| **Init Sea Level Rise** | Sea level rise in the initial simulation year, i.e., 1850 | -240 | -240 | mm |
| **Sensitivity of Sea Level Rise to Temperature** | Sensitivity of sea level rise to temperature anomaly. From V&R (2009) supplement, table S1. Rahmstorf (2007) uses 3.4 | 5.6 | 5.6 | (mm/year)/degrees C |
| **Additional SLR from Ice Melt** | Allows users to capture the effects of future sea level rise from of the melt of Greenland and Antarctic ice sheets and other glaciers, and in the mean size of winter snowpack now being experienced, all of which are likely underestimated by the semi-empirical Vermeer and Rhamstorf 2009 model.  Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. Does not affect the historic period. | 0-5 | 0 | (mm/year)/degrees C |
| **Temp Adjustment for SLR** | Adjustment to global surface temperature that is relative to pre-industrial levels from the average of the 1951-1980 data that Vermeer and Rahmstorf (2009) used based on GISTEMP. See V&R 2009 supplement. |  | 0.2418 | Degrees C |
| **Reference Temperature** | V&R (2009) temperature change at reference, to be subtracted from temperature change at each time. |  | -0.41 | Degrees C |
| **Sensitivity of SLR rate to temp rate** | Slope of instantaneous temperature change - sea level change relationship (Vermeer & Rahmstorf, 2009) From V&R (2009) supplement, table S1. Rahmstorf (2007) uses 0 (i.e. term is missing) |  | -49 | mm/DegreesC |

| Table 3‑65 Sea Level Rise Calculated Parameters | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **Sea Level Rise** | Estimated Sea Level Rise (from initial level) is the accumulation of the rate of sea level rise. Source: Vermeer, M. and S. Rahmstorf. 2009. Global sea level linked to global temperature. Proc of the Nat Acad of Sci. 106(51):21527-21532. [www.pnas.org/cgi/doi/10.1073/pnas.0907765106](http://www.pnas.org/cgi/doi/10.1073/pnas.0907765106).  INTEG(Change in Sea Level, Initial SLR) | mm |
| **SLR in 2000** | SLR until 2000, then caps at that level.  SAMPLE IF TRUE(Time<=y2000 0, Sea Level Rise, Sea Level Rise) | mm |
| **Sea Level Rise from 2000** | Sea Level Rise indexed to zero in the year 2000.  IF THEN ELSE(Time<y2000 0, :NA:, Sea Level Rise-SLR in 2000) | mm |
| **Change in Sea Level** | Proportional to the temperature difference (around a base year, defined here to be 1800).  Equilibrium Change in Sea Level+Instant Change in Sea Level | mm/year |
| **Adjusted Sensitivity of Sea Level Rise to Temperature** | SLR is modeled using the Vermeer and Rahmstorf (2009) semi-empirical model in which the increase in SLR rises with mean global surface temperature and falls with faster rates of warming (to capture the delay in the response of ice sheet melt to temperature change). That model is estimated from historical data 1880-2000, a period with low levels of warming that therefore likely underestimates future sea level rise from the faster-than-historical rates of melt of the Greenland and Antarctic ice sheets, other glaciers, and in the mean size of winter snowpack now being experienced. The slider Additional SLR from Ice Melt allows users to capture these effects. Positive values capture accelerated SLR from rates of ice sheet melt higher than those reflected in the data Rahmstorf used. Negative values would capture lower rates of melting. Does not affect the historic period.  Sensitivity of Sea Level Rise to Temperature+STEP(Additional SLR from Ice Melt,Year to start additional SLR from ice melt) | mm/(year\* DegreesC) |
| **Equilibrium Change in Sea Level** | Vermeer & Rahmstorf (2009) sea level rise rate (open loop approx to initial transient). Rahmstorf (2007) is recovered when Sensitivity of SLR rate to temp rate = 0.  Adjusted Sensitivity of Sea Level Rise to Temperature\*(Adjusted Temperature change from preindustrial-Reference Temperature) | mm/year |
| **Adjusted Temperature change from preindustrial** | Temperature change from preindustrial levels adjusted to the model generated average global surface temperature that is used in the calculation of sea level rise from the Vermeer and Rahmstorf (2009) model.  Temperature change from preindustrial-Temp Adjustment for SLR | DegreesC |
| **Change in Relative Temperature** | Approximates dT/dt  (Adjusted Temperature change from preindustrial-SMOOTH(Adjusted Temperature change from preindustrial,TIME STEP))/TIME STEP | DegreesC/ year |
| **Instant Change in Sea Level** | Vermeer & Rahmstorf (2009) instantaneous sea level rise rate on the time scales under consideration. Rahmstorf (2007) is recovered when Sensitivity of SLR rate to temp rate = 0.  Sensitivity of SLR rate to temp rate\*Change in Relative Temperature | mm/year |

Figure 3.51 Historical Sea Level Rise



|  |  |
| --- | --- |
| Table 3‑66 Sea Level Rise Simulated Data Compared to Tide and Satellite Historical Data. (1850-2008) | |
|  | C-ROADS vs Historical Sea Level Rise |
| Count | 159 |
| R2 | 0.9514 |
| MAPE | 0.4550 |
| MAEM | -0.0036 |
| RMSPE | 1.4893 |
| RMSE | 24.0222 |
| Theil Inequalities |  |
| UM | 0.1966 |
| US | 0.2156 |
| UC | 0.5878 |

## pH

Figure 3.52 shows the structure of the pH sector of C-ROADS, which reflects the empirical function presented by Bernie *et al.* (2010)*.* Variable definitions and equations are presented in Table 3‑67. As the atmospheric concentration in the atmosphere increases, the pH of the ocean decreases by a third order response. Figure 3.53depicts the historical pH and projected pH for the default RS and the four RCP scenarios.

Figure . Structure of pH

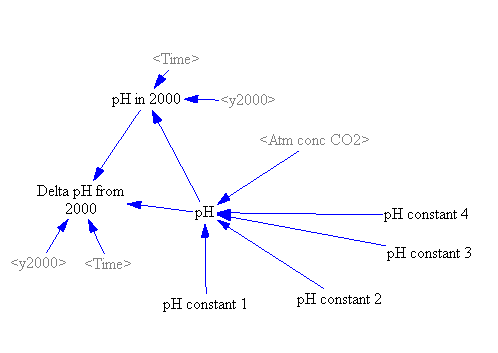
****

Table 3‑67 pH Parameters

|  |  |  |  |
| --- | --- | --- | --- |
| **Parameter** | **Definition** | **Units** | **Source** |
| **pH** | Estimated pH as a function of atmospheric CO2 concentration.  pH constant 1-pH constant 2\*Atm conc CO2+pH constant 3\*Atm conc CO2^2-pH constant 4\*Atm conc CO2^3 | pH units | Bernie *et al.,* 2010 |
| **pH constant 1** | 8.5541 | pH units |
| **pH constant 2** | 0.00173 | 1/(ppm) |
| **pH constant 3** | 1.3264e-006 | 1/(ppm\*ppm) |
| **pH constant 4** | 4.4943e-010 | 1/(ppm\*ppm\*ppm) |
| **pH in 2000** | SAMPLE IF TRUE(Time<=y2000, pH, pH) | pH units |  |
| **Delta pH from 2000** | IF THEN ELSE(Time<y2000, :NA:, pH-pH in 2000) | pH units |  |

Figure . Ocean pH



# Contributions to Climate Change

A post-processing model calculates regional contributions to GHG concentrations, temperature change, and SLR for a given scenario. It mirrors the physics of the main model, and calculates contributions by selectively omitting the emissions of one COP bloc at a time. This is the “residual method” of attribution (den Elzen et al. 2005).

The model and the real world are nonlinear, due to saturation of sink GHG uptake capacities, diminishing returns in CO2 radiative forcing, interactions between CH4 and N2O, and other phenomena. This means that the sum of the effects of individual country emissions (or other small perturbations) is not the same as the total effect of all emissions together. This is shown schematically below.

Figure . Effect of Nonlinearity on Attribution



The total response curve shows the effect of individual inputs (i.e. country emissions) on some climatic variable. The slope of the total response (blue dashed line) is different from the slope of the response evaluated at the system’s actual operating point (green dashed line). Due to the difference in slope (steeper in this case), the sum of a series of leave-one-out experiments will differ from the actual total response observed. To account for this interaction effect, the contributions assessed for individual regions are scaled so that the total contribution equals the actual observed change in the climate variables.

In principle, a drawback of the residual method is that analysis at different levels of aggregation may yield different results, due to nonlinearities. We experimented with other methods, and found differences to be slight.

One other caveat to observe is that the contributions assessed in C-ROADS reflect the warming from Kyoto gas emissions, and not the effects of ozone depleting substances, precursor gases or aerosols. Depending on how emissions of those non-Kyoto species are distributed relative to those of CO2 and the other Kyoto gases, total regional contributions may differ from those reported by C-ROADS.

Figure.4.2 illustrates the structure to determine contributions for CO2, but the structure is the same for the other well-mixed GHGs. Table 4‑1 defines the model parameters and equations. For each well-mixed GHG and scenario, the model runs the sum of emissions through the respective GHG cycle to determine the concentrations if each COP bloc were left out one at a time. Likewise, concentrations for each scenario determine the RF, and thus temperature and SLR, to determine these parameters if emissions from one COP bloc at a time were omitted.

Figure.. Structure to Analyze Contributions to CO2 FF Emissions

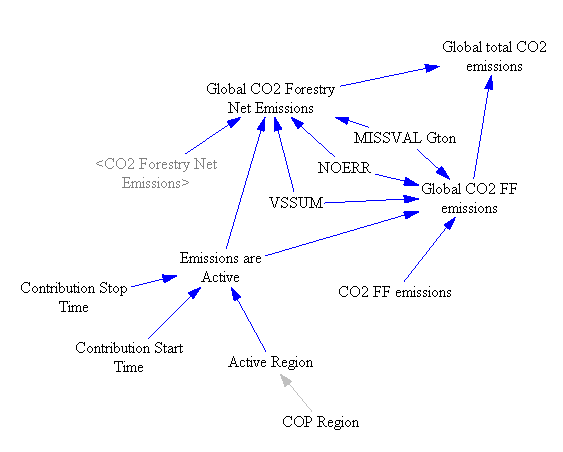


Table 4‑1 Leave-One-Out Structure for GHG Emissions

|  |  |  |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **COP Region[Leave one out]** | COP region corresponding with Leave One Out scenario  INITIAL(COP) | Dmnl |
| **Active Region[Leave one out,COP]** | Checks whether a given COP region matches a Leave One Out region  INITIAL(IF THEN ELSE(COP Region[Leave one out]=COP,1,0)) | Dmnl |
| **Contribution Start Time** | Year to start evaluating the contributions.  1850 | Year |
| **Contribution Stop Time** | Year to stop evaluating the contributions.  2100 | Year |
| **Emissions are Active[COP]** |  | Dmnl |
| **Emissions are Active[All in,COP]** | The emissions from all blocs are included.  1 |  |
| **Emissions are Active[All out,COP]** | Between the contribution start time and the contribution stop time, no emissions are included; otherwise all emissions are included.  1-STEP(1,Contribution Start Time)+STEP(1,Contribution Stop Time) |  |
| **Emissions are Active[Leave one out,COP]** | Between the contribution start time and the contribution stop time, emissions from all but one COP bloc at a time are included; otherwise all emissions are included.  1-STEP(Active Region[Leave one out,COP],Contribution Start Time)+STEP(Active Region[Leave one out,COP],Contribution Stop Time) |  |
| **Global GHG emissions** | Sum of GHG emissions from all regions except for from the one left out. Emissions from each scenario are carried through the respective GHG cycle yielding the GHG concentration if that one bloc were left out, i.e., **GHG concentration.**  VECTOR SELECT(Emissions are Active[COP!], GHG emissions[COP!], MISSVAL Gton , VSSUM , NOERR ) | CO2: GtonsCO2/Year  CH4: MtonsCH4/year  N2O: MtonsN2O-N/year  PFCs: tonsCF4/year  SF6: tonsSF6/year  HFCs: tonsHFC/year |

Figure 4.4 through Figure 4.3 show the structure to determine the contribution of each COP bloc to RF, temperature change, and CO2 concentration, respectively. Due to the nonlinearity of the system, scaling normalizes the sum of the individual contributions to the actual total effect, i.e., when no blocs are omitted. There is also a component of each of these parameters that is not due to contributions. For CO2 concentration, there is a baseline value to which the contributions are added. The RF and temperature variables have a component due to other forcings and MP gases, which are not attributed to individual contributions. For each of these variables, the sum of the contributions added to the component without contributions yields the value in C-ROADS.

Figure . Contributions to Radiative Forcing



Figure . Contributions to CO2 FF Emissions



Figure . Contributions to Temperature Change



| Table 4‑2 Scaled Contributions to CO2 concentrations, RF, and Temperature Change | | |
| --- | --- | --- |
| **Parameter** | **Definition** | **Units** |
| **CO2 Concentration** |  |  |
| **CO2 Total Contribution** | The atmospheric concentration of CO2 when emissions from all COP are included.  Atm conc CO2[All in]-Atm conc CO2[All out] | Ppm |
| **CO2 Individual Contribution[COP]** | The atmospheric concentration of CO2 when emissions from all COP are included, except for the given COP.  Atm conc CO2[All in]-Atm conc CO2[Leave one out] | Ppm |
| **CO2 Total Individual Contribution** | The total of the contribution of each COP bloc to atmospheric concentration.  SUM(CO2 Individual Contribution[COP!]) | Ppm |
| **CO2 Ratio of Total to Individual Contributions** | Ratio of the total contribution (all-in) to sum of marginal (individual, leave-one-out) contributions  ZIDZ(CO2 Total Contribution,CO2 Total Individual Contribution) | Dmnl |
| **CO2 Scaled Individual Contribution[COP]** | Adjusts the contribution of each COP bloc so that the sum of the contributions equals the total CO2 concentration when no emissions are left out.  CO2 Individual Contribution[COP]\*CO2 Ratio of Total to Individual Contributions | Ppm |
| **CO2 scaled total contributions[Source]** |  | Ppm |
| **CO2 scaled total contributions[Contributions]** | Atmospheric concentration of CO2 due to emissions from all COP blocs.  SUM(CO2 Scaled Individual Contribution[COP!]) |  |
| **CO2 scaled total contributions [Without contributions]** | Atmospheric concentration of CO2 other than that due to emissions from COP blocs.  Atm conc CO2[All out] |  |
| **Radiative Forcing** |  |  |
| **RF Total Contribution** | The RF when GHG emissions from all COP are included.  Radiative Forcing[All in]-Radiative Forcing[All out] | Watt/(meter2) |
| **RF Individual Contribution [COP]** | The RF when GHG emissions from all COP are included, except for the given COP.  Radiative Forcing[All in]-Radiative Forcing[Leave one out] | Watt/(meter2) |
| **RF Total Individual Contribution** | The total of the contribution of each COP bloc to RF.  SUM(RF change Individual Contribution[COP!]) | Watt/(meter2) |
| **RF Ratio of Total to Individual Contributions** | Ratio of the total contribution (all-in) to sum of marginal (individual, leave-one-out) contributions  ZIDZ(RF change Total Contribution,RF change Total Individual Contribution) | Dmnl |
| **RF Scaled Individual Contribution[COP]** | Adjusts the contribution of each COP bloc so that the sum of the contributions equals the total RF when no emissions are left out.  RF change Individual Contribution[COP]\*RF Ratio of Total to Individual Contributions | Watt/(meter2) |
| **RF scaled total contributions[Source]** |  | Watt/(meter2) |
| **RF scaled total contributions[Contributions]** | RF due to emissions from all COP blocs.  SUM(RF Scaled Individual Contribution[COP!]) |  |
| **RF scaled total contributions [Without contributions]** | RF other than that due to emissions from COP blocs.  Radiative Forcing[All out] |  |
| **Temperature Change** |  |  |
| **Temp change Total Contribution** | The temperature change when GHG emissions from all COP are included.  Temperature change from preindustrial[ All in]-Temperature change from preindustrial[ All out] | DegreesC |
| **Temp change Individual Contribution [COP]** | The temperature change when GHG emissions from all COP are included except for the given COP.  Temperature change from preindustrial[ All in]-Temperature change from preindustrial[ Leave one out] | DegreesC |
| **Temp change Total Individual Contribution** | The total of the contribution of each COP bloc to temperature change.  SUM(Temp change Individual Contribution[COP!]) | DegreesC |
| **Temp Ratio of Total to Individual Contributions** | Ratio of the total contribution (all-in) to sum of marginal (individual, leave-one-out) contributions  ZIDZ(Temp change Total Contribution,Temp change Total Individual Contribution) | Dmnl |
| **Temp Scaled Individual Contribution[COP]** | Adjusts the contribution of each COP bloc so that the sum of the contributions equals the temperature change when no emissions are left out.  Temp change Individual Contribution[COP]\*Temp Ratio of Total to Individual Contributions | DegreesC |
| **Temp scaled total contributions[Source]** |  | DegreesC |
| **Temp scaled total contributions[Contributions]** | Temperature change due to emissions from all COP blocs.  SUM(Temp Scaled Individual Contribution[COP!]) |  |
| **Temp scaled total contributions [Without contributions]** | Temperature change due to forcings other than those from emissions from COP blocs.  Temperature change from preindustrial[ All out] |  |

# Future Directions

In its current version, C-ROADS is a useful tool that allows decision-makers and other leaders to quickly assess some of the likely long-term climate impacts of particular national, regional or global emissions scenarios. As national and international leaders work to craft effective climate and energy policy capable of stabilizing greenhouse gas levels in a range that prevents the most dangerous consequences of climate change, this is a very important capability.

The modeling philosophy we follow is to ensure that the structure and assumptions of C- ROADS represent accepted, peer-reviewed science. Thus, as this Reference Guide describes, we include a variety of climate-carbon cycle feedbacks, but set many 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.

In addition, C-ROADS does not address the feedbacks between climate impacts and human dynamics of the system – anthropogenic GHG emissions, population growth, or GDP growth. Especially for scenarios with high greenhouse gas levels and high global mean temperature changes, this is unlikely to be realistic for the world system. C-ROADS also lacks other physical limits (water, other resources) that might slow the growth of human economies and thus the growth of emissions during the time-scale of the simulation.

Climate change is expected to have a range of impacts – on water availability, agriculture, human health, biodiversity and more. The current version of C-ROADS offers decision-makers information on only a small subset of possible climate impacts. Another future expansion of the model would include more impacts, and more spatially resolved information on particular impacts. Such output would help decision-makers better understand the ecological and human costs of different emissions scenarios, as well as help prepare them for the adaptation to climate change that cannot be avoided.

Finally, as national and international debate and implementation of climate and energy policy moves forward, the most important policy questions seem increasingly likely to be about the most effective approaches for reducing greenhouse gas emissions rather than about the need to reduce them. To address these issues, we have developed a new model, En-ROADS, that endogenously generates energy use, fuel mix, and GHG 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.

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1. See the World Climate Exercise <https://www.climateinteractive.org/programs/world-climate/> [↑](#footnote-ref-1)
2. In this section **sectors or sub-models** are written in bold, and model *variables* are written in italic. [↑](#footnote-ref-2)
3. AR5 WG1 Chapter 8. Table 8.A.1. Lifetimes, Radiative Efficiencies and Metric Values [↑](#footnote-ref-3)
4. Law Dome ice core [↑](#footnote-ref-4)
5. Value of CH4 and N2O time constants reported in AR5 WG1 Chapter 8 Table 8.A.1 noted to be for calculation of GWP, not for cycle. (“Perturbation lifetime is used in the calculation of metrics”) See Table 3-45 for CH4. Value of 117 years for N2O atmospheric time constant determined through optimization. [↑](#footnote-ref-5)
6. MAGICC output [↑](#footnote-ref-6)
7. AR5 WG1 Chapter 6 Table 6.9 [↑](#footnote-ref-7)