GEOCARB_NET (Help)

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1. Introduction

GEOCARB_NET provides a user-friendly GUI for GEOCARB -- a geologic carbon and sulfur cycle model -- originally developed by Berner (1990, 1991) and updated several times (GEOCARB II: Berner 1994; GEOCARB III: Berner & Kothavala 2001: GEOCARBSULF: Berner, 2006a; GEOCARBSULFvolc (Berner, 2006b, 2008).

GEOCARB_NET *interacts and modifies* during run-time the the most recent version of the model GEOCARBSULFvolc, and specifically, the R code written by Dana Royer (published in Royer et al. 2014). A separate paper introducing GEOCARB_NET will soon be available by Torsvik et al. (2023).

Some selected references:

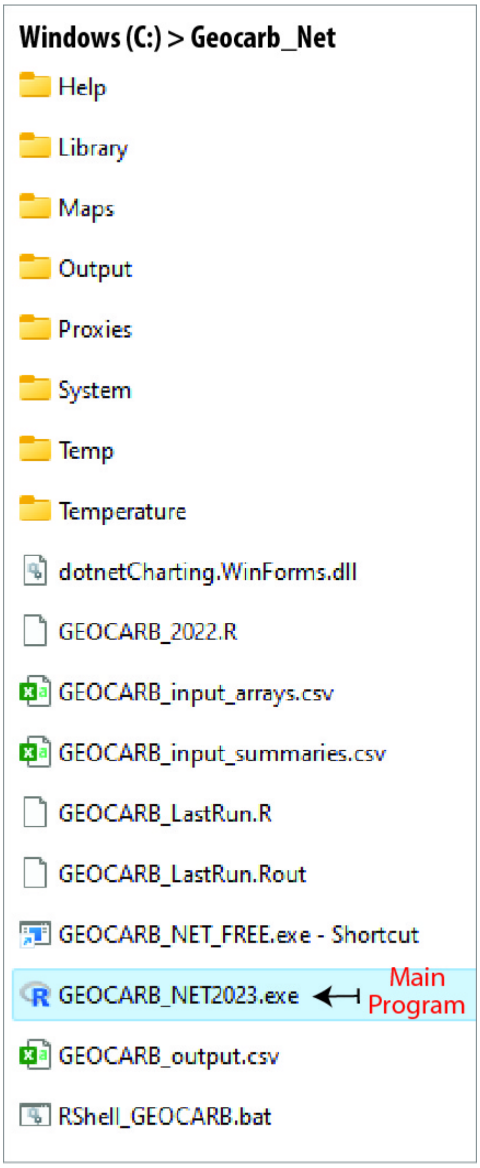
Berner, R. A., Lasaga, A. C. & Garrels, R. M. 1983. The carbonate-silicate geochemical cycle and its effect on atmospheric carbon dioxide over the past 100 million years: American Journal of Science 283, 7, 641–
Berner, R. A., 1990. Atmospheric carbon dioxide levels over Phanerozoic time: Science 249, 4975, 1382–1386
Berner, R. A., 1991. A model for atmospheric CO2 over Phanerozoic time: American Journal of Science 291, 4, 339–376
Berner, R. A., 1992. Weathering, plants, and the long-term carbon cycle: Geochimica et Cosmochimica Acta 56, 8, 3225–3231
Berner, R. A., 1994. GEOCARB II: A revised model of atmospheric CO2 over Phanerozoic time: American Journal of Science 294, 1, 56–91
Berner, R. A. & Maasch, K. A., 1996. Chemical weathering and controls on atmospheric O2 and CO2: Fundamental principles were enunciated by J.J. Ebelmen in 1845: Geochimica et Cosmochimica Acta, 60, 9, 1633–1637
Berner, R. A., 1997. The rise of plants and their effect on weathering and atmospheric CO2: Science 276, 544–546
Berner, R. A., Petsch, S. T., Lake, J. A., Beerling, D. J., Popp, B. N., Lane, R. S., Laws, E. A., Westley, M. B., Cassar, N., Woodward, F. I. & Quick, W. P., 2000. Isotope fractionation and atmospheric oxygen: Implications for Phanerozoic O2 evolution: Science, 287, 5458, 1630–1633
Berner, R. A., 2001. Modeling atmospheric O2 over Phanerozoic time: Geochimica et Cosmochimica Acta 65, 5, 685–694
Berner, R. A. & Kothavala, Z., 2001. GEOCARB III: A revised model of atmospheric CO2 over Phanerozoic time: American Journal of Science 301, 2, 182–204
Berner, R. A., Beerling, D. J., Dudley, R., Robinson, J. M. & Wildman, R. A., Jr. 2003. Phanerozoic atmospheric oxygen: Annual Review of Earth and Planetary Sciences 31, 105–134
Berner, R. A., 2004. The Phanerozoic Carbon Cycle: CO2 and O2: New York, Oxford University Press, 150 p.
Berner, R. A., 2006a. GEOCARBSULF: A combined model for Phanerozoic atmospheric O2 and CO2: Geochimica et Cosmochimica Acta 70, 23, 5653–5664
Berner, R. A., 2006b. Inclusion of the weathering of volcanic rocks in the GEOCARBSULF model: American Journal of Science 306, 5, 295–302
Berner, R. A., 2008. Addendum to "Inclusion of the weathering of volcanic rocks in the GEOCARBSULF model" (R. A. Berner, 2006, 306, 295-302): American Journal of Science 308, 1, 100–103,
Berner, R. A., 2009. Phanerozoic atmospheric oxygen: New results using the GEOCARBSULF model: American Journal of Science 309, 7, 603–606
Royer DL, Donnadieu Y, Park J, Kowalczyk J, Goddéris Y. 2014. Error analysis of CO2 and O2 estimates from the long-term geochemical model GEOCARBSULF. American Journal of Science, 314: 1259-1283

2. Software Installment

- *Make a sub-directory named c:\Geocarb_Net (unless existing already)*
- *Download "Geocarb_Net.ZIP" from the link below:*

http://www.planetaryhabitability.org/Software/Geocarb_Net.zip

The ZIP file is usually downloaded/stored on ‘Downloads’ and click on the ZIP file (or ‘Open file’), select all the files and sub-directories, and copy them to c:\Geocarb_Net’. When installed the sub-directory structure and files should look like the picture below.



The ZIP file is usually downloaded/stored on ‘Downloads’ and click on the ZIP file (or ‘Open file’), select all the files and sub-directories, and copy them to 'c:\Geocarb_Net’. When installed the sub-directory structure and files should look like the picture above.

- *Run the main program by clicking ‘GEOCARB_NET2023’*[right-click *'Pin to Start'* or *'Add to*

Favorites' to start later]

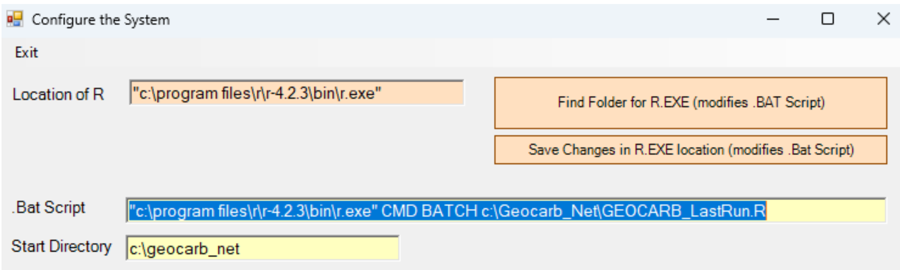
When starting the program (security reasons), the windows system may warn you not to 'Run File'. Click on 'Info' and a new message will appear and the click 'Run anyway'. This will only happen once.

CONFIGURE the system

Before you can operate the software you must install R on your computer.

- *In the program select 'Organize' and Configure' and type the 'Location of R' (i.e., location of R.exe) in the text box*.

'c:\program files\r\r-4.2.3\bin\r.exe' is the default location when downloading R but this may require administrative password, so you could put R somewhere else and the configure the system.



- *You can also locate R.exe by clicking 'Find Folder for R.EXE (modifies .BAT script)*'
- *When you have located R.exe then click 'Save Changes in R.EXE location'.*

This will modify and save a vital Windows Batch File (RShell_GEOCARB.Bat) that allows GEOCARB_NET to communicate with the R code where the actual carbon cycle modeling is undertaken. YOU ARE NOW READY TO OPERATE THE PROGRAM

3. System Requirements

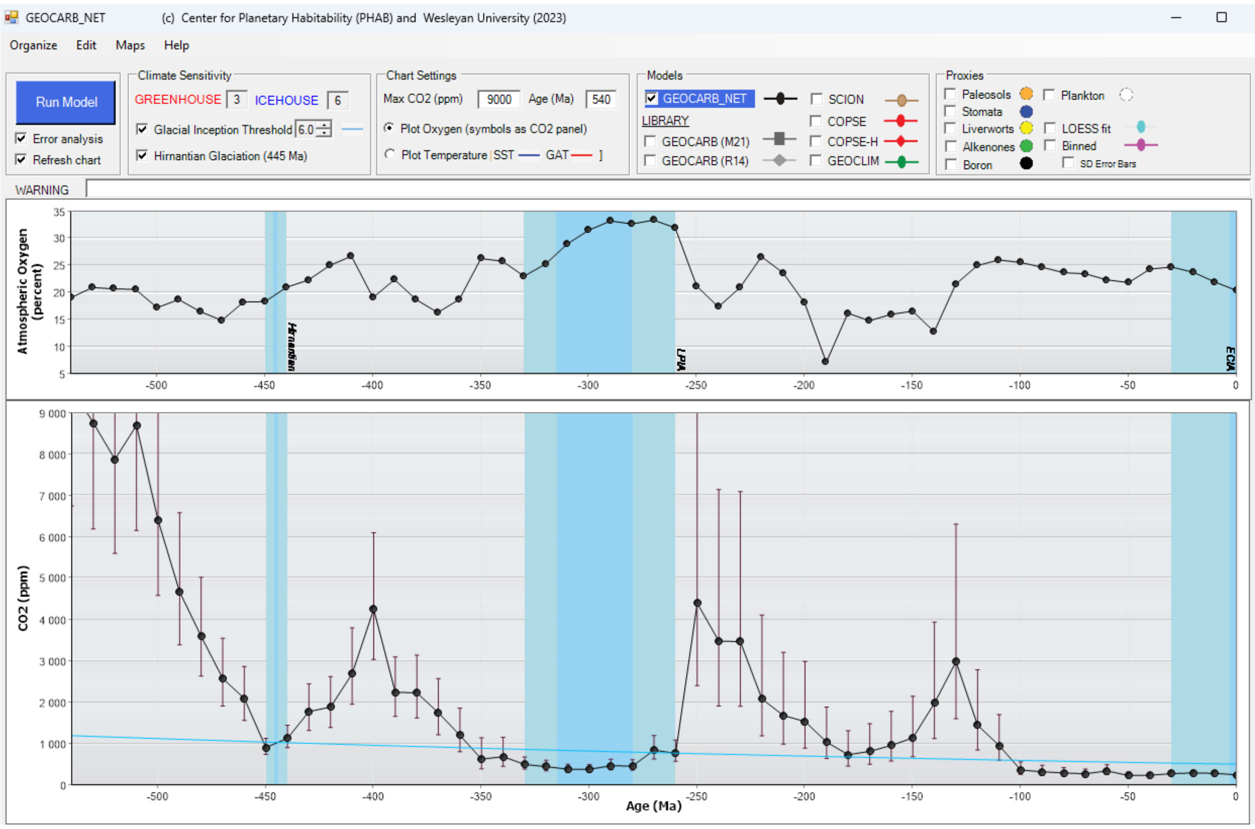
- Windows Operating System (developed under Windows 11)
- R (if not installed get it from http://www.r-project.org/
- The location of R.EXE must be specified in GEOCARB_NET (see 'Configure')

For modifying the raw code you also need:

- Visual Studio (2022 Version used here and code available on request)
- .netCharting (commercial visualization solution but the code can easily be rewritten to Visual Studio graph standards)

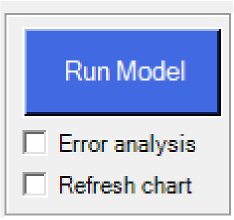
4. Main Screen

The main screen shown has two graphical panels, a lower graphic panel show atmospheric CO_2 estimates from models or proxies and the upper diagram show modeled O_2 - or alternatively - Sea Surface Temperatures (SST) and Global Average Temperatures (GATs). The SST curve is based on a blend of $\delta^{18}O$ data from phosphate and carbonate (less reliable in deep time) fossils. We have vetted the SST data-set of Song *et al.* 2019 (see Zhang & Torsvik 2022), which only include $\delta^{18}O$ from phosphate fossils before the Mesozoic, and we have extended the data-set to ~520 Ma with $\delta^{18}O$ data from phosphatic Siberian brachiopods (Wotte et al. 2019). The SST curve is based on $\delta^{18}O$ from fossils that once lived within 30º from the equator, we assume seawater composition as today, and the data have been averaged over 5 million year and shown with 95% confidence envelope (if N > 1) in 5 million years interval. The GAT curve (Scotese et al. 2021) is based on an area-scaled integration of all the climate belts but combines geological constraints (e.g., biome maps) and isotopic temperature data with some ad-hoc corrections . The GAT curve shows many similarities to SSTs, but its pre-Carboniferous estimates differ radically from high early Paleozoic SSTs, which they reject. As a consequence, the GAT curve exhibits minimum temperatures during the Hirnantian Icehouse and maximum temperatures near the Permo-Triassic boundary (Siberian Traps temperature anomaly).



Above the two graphic panels there are five panel-boxes that control the model and graphic settings:

PANEL BOX 1



RUN MODEL

The left-most button, when clicked, will run the original GEOBARB R code of Dana Royer. The program reads two input-files named *"GEOCARB_input_arrays.csv"* and *"GEOCARB_input_summaries.csv"*. These files are located in the *GEOCARB_NET directory*, they can be edited in EXCEL, but can also be changed directly by clicking '*Edit*' in the main menu. Estimating CO_2 and CO_2 for the past 570 million years is almost instantaneous, but a model run with Monte Carlo Error Analysis takes about 25 seconds whilst the much simpler % Error mode takes about 5 seconds but only reports errors in CO_2. If the 'Refresh' check-box is checked then the panels will be refreshed (cleared) automatically.

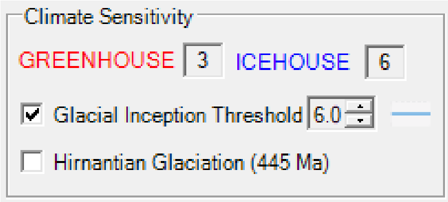
Error Analysis

By default no errors are shown for CO_2 estimates. The original GEOCARB R-code include a Monte Carlo error analysis but (by experience) it is hard to make the model errors converge and we therefore use a simplified CO_2 error analysis that can be viewed/edited by engaging 'Edit" and 'Error Setting'. This analysis essentially produce the same CO_2 error-confidences as the Monte Carlo error analysis ('inner band' in Royer et al. 2014).

Refresh chart

This tick-box controls whether models and proxies are plotting on top of each other or not.

PANEL BOX 2 (Climate Sensitivity)



Greenhouse vs. Icehouses

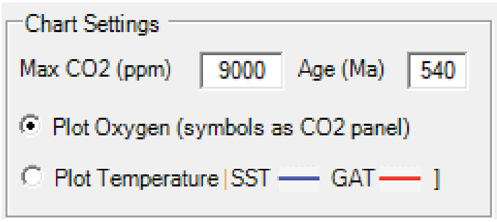
GEOCARB defaults to a prescribed climate sensitivity of 3ºC per doubling of CO_2 during Greenhouse climates and doubles this (defined by the GLAC parameter) to 6ºC during Icehouse climates. These constants are located in the file *"GEOCARB_input_summaries.csv"*. By default GEOCARB is set to Icehouse climates (6ºC climate sensitivity) between 330 and 260 Ma (the Late Paleozoic Ice Age) and for the past 30 million years. There was also a short-lived period (perhaps less than a millon year) of continental glaciations in Gondwana at 445 Ma (end-Ordovician Hirnantian glaciation). GEOCARB time-series parameters are binned in 10 Myr intervals but the short-lived Hirnantian glaciation can here be simulated by increasing the climate sensitivity at 450 and 440 Ma by clicking the 'Hirnantian Icehouse Model' box. The user can experiment with constant climate sensitivities by assigning the GLAC parameter a value of 1.

Plot Glacial Inception Threshold

Draws a blue solid line in the lower graphic panel, which is the theoretical threshold for glacial inception at a certain climate sensitivity level (6, 4.5 and 3 ^{o}C per doubling of CO_2). Assume a modern continental glacial threshold of 500 ppm and accounts for a dimmer Sun. The threshold values (back to 750 Ma) are read from an EXCEL file (*"Glacial_Threshold.csv"*) which is located in the *GEOCARB_NET/System* folder.

Hirnantian Glaciation (445 Ma)

PANEL BOX 3 (Chart Settings)



Max CO_2 (ppm)

Controls maximum CO_2 amplitude in the lower panel

Age (Ma)

Set maximum age range (defaults to 570 Ma).

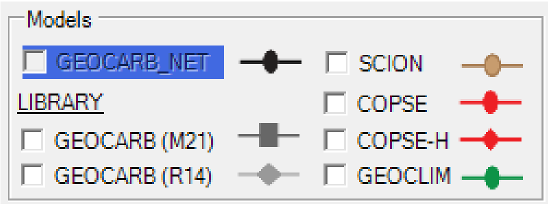
Plot Oxygen

Tick this box to display modelled O_2.

Plot Temperature (SST and GAT)

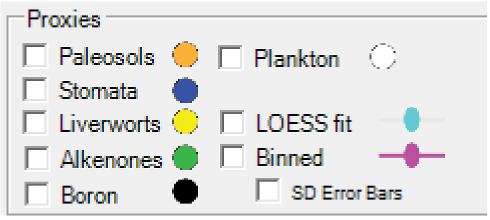
Tick this box to display temperatures insted of O_2.

PANEL BOX 4 (Models)



Some selected published models that can be compared with your own GEOCARB_NET model using the tick-boxes.

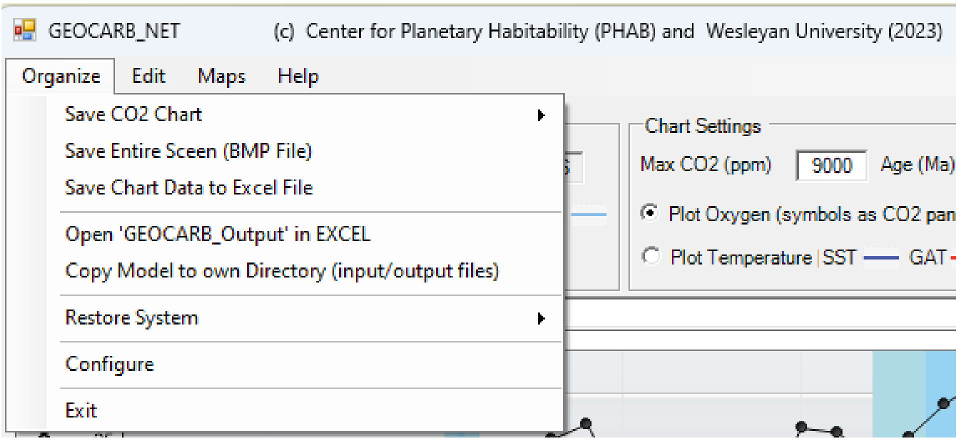
PANEL BOX 5 (Proxies)



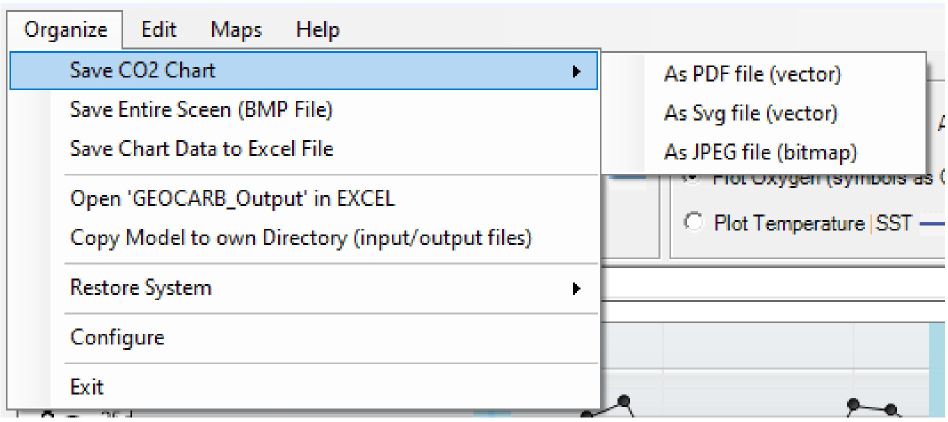
Tick-boxes to display individual proxies or binned/LOESS of of the five left-hand proxies. See section 6. Proxies for details.

4.1. Organize

'Organize' is one of the four options in the *'start-up menu'* and has several sub-options (see diagram below)



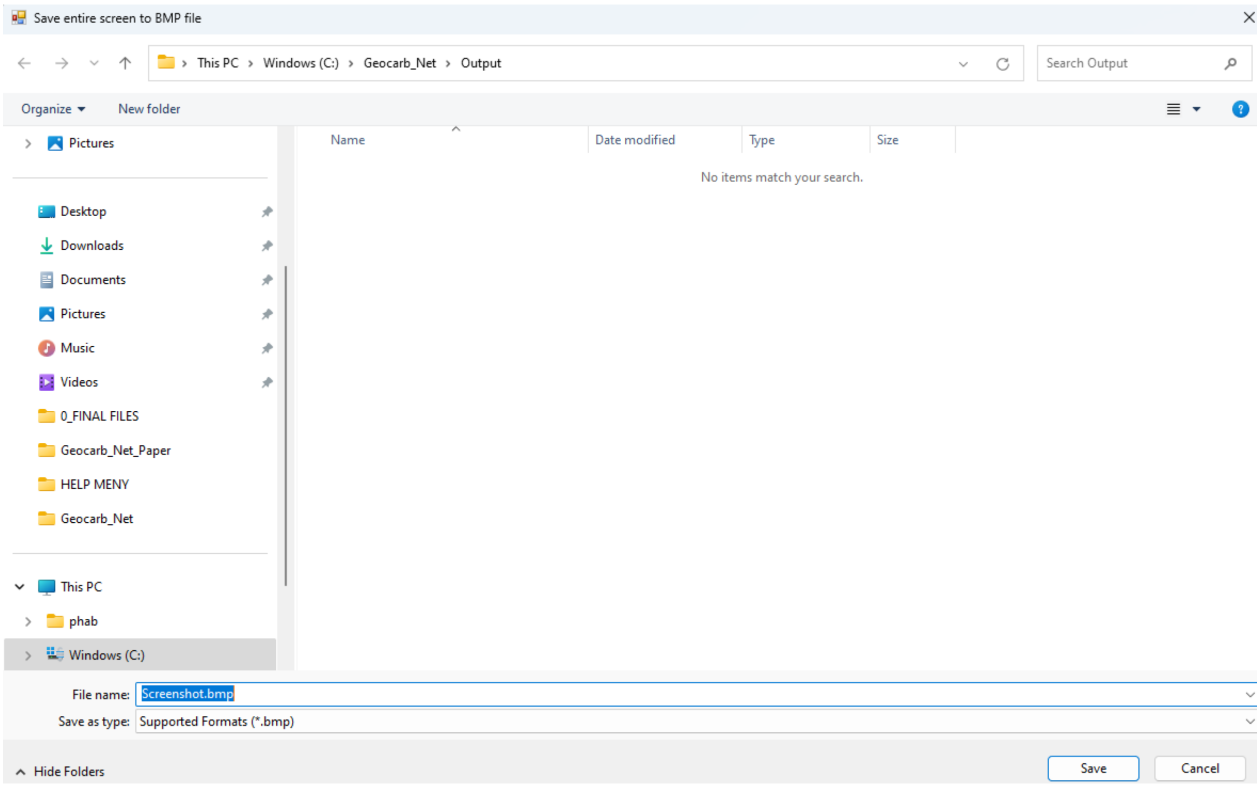
4.1.1. Save Graph



The lower graphic panel (CO2) can be saved to both vector (PDF, SVG) and image (JPEG) formats.

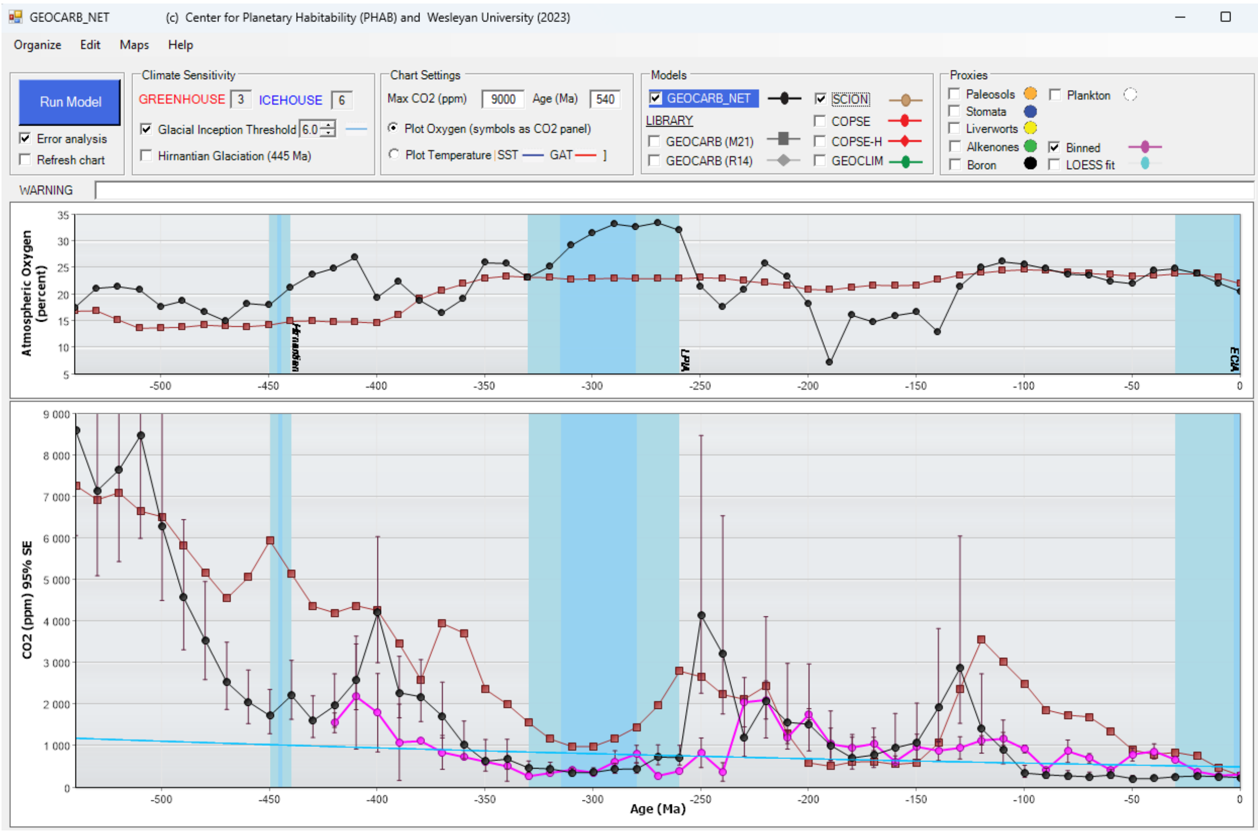
4.1.2. Save Entire Screen (BMP fil)e

Save a screenshot to a *.bmp file. Default output directory is /Geocab_Net/Output but the operator can save file to any directiry or file name.


Save entire screen to BMP file
This PC › Windows (C:) › Geocarb_Net › Output
Search Output
Organize
New folder
Pictures
Name
Date modified
Type
Size
No items match your search.
Desktop
Downloads
Documents
Pictures
Music
Videos
0_FINAL FILES
Geocarb_Net_Paper
HELP MENY
Geocarb_Net
This PC
phab
Windows (C:)
File name:
Screenshot.bmp
Save as type:
Supported Formats (*.bmp)
Hide Folders
Save
Cancel

4.1.3. Save Chart Data to EXCEL

This option saves all models & data displayed on the screen to an EXCEL file. In this example we have run a model with 'error analysis' and compared it with the 'SCION model' and 'binned proxy data'. If you open the saved EXCEL file (.csv format) you can then compare modeled CO_2 and O_2 in SCION (SCION CO2 and O2) and GEOCARB_NET (MODEL CO2, CO2-low, CO2-high, O2) in Table form, or make your own graphs in EXCEL. Running Mean (10 Myr bins) proxy values and one-sigma standard errors (starting from 420 Ma) are also listed in the file along with the estimated 'glacial inception threshold' (GIT) at each time-step (in this example based on a climate sensitivity of 6 °C during icehouse conditions and a 500 ppm threshold for recent times).



Age (Ma)	SCION CO2	O2	MODEL CO2	C02-Low	CO2-High	O2	GIT CO2 (2)	Binned Proxy CO2	St-Dev
570			8855.047	6328.268	12696.7	14.88095	1244.997		
560			9293.773	6562.41	13466.16	13.79043	1226.147		
550			8979.239	6365.108	12953.01	17.97579	1207.551		
540	7267.6	16.8	8587.34	6066.467	12431.21	17.5068	1189.207		
530	6925	16.9	7148.878	5098.012	10247.3	21.10896	1171.112		
520	7097.2	15.2	7642.791	5438.538	10988.26	21.43284	1153.262		
510	6650.1	13.6	8469.85	5998.283	12243.65	20.85065	1135.655		
500	6518.3	13.7	6292.123	4504.67	9001.178	17.71894	1118.288		
490	5830.6	13.8	4573.324	3319.406	6446.734	18.72478	1101.158		
480	5174	14.2	3548.14	2597.567	4957.226	16.69545	1084.263		
470	4549.5	14	2537.359	1881.251	3498.918	14.94358	1067.599		
460	5060.7	13.9	2064.606	1539.831	2828.418	18.25976	1051.163		
450	5940.7	14.2	1730.287	1296.959	2359.45	17.92856	1034.954		
440	5143.4	14.9	2219.2	1643.989	3062.772	21.32576	1018.968		
430	4364.6	15	1612.069	1204.064	2208.387	23.68851	1003.202		

420	4207.3	14.8	1970.782	1451.696	2738.844	24.88819	987.6542	1560	235.2
410	4378.3	14.8	2582.041	1873.083	3644.411	26.90349	972.3217	2192	1262.24
400	4260.6	14.6	4208.437	3005.33	6039.73	19.37046	957.2019	1800.75	942.27
390	3462.2	16.1	2282.326	1682.048	3159.095	22.38529	942.2922	1092	917.28

4.1.4. Open GEOCARB_Output in EXCEL

Model output is written to a file named 'GEOCARB_output.csv' in the '/GEOCARB_NET' directory, and if the model is run without 'error analysis', then 'GEOCARB_output.csv' will look like this:

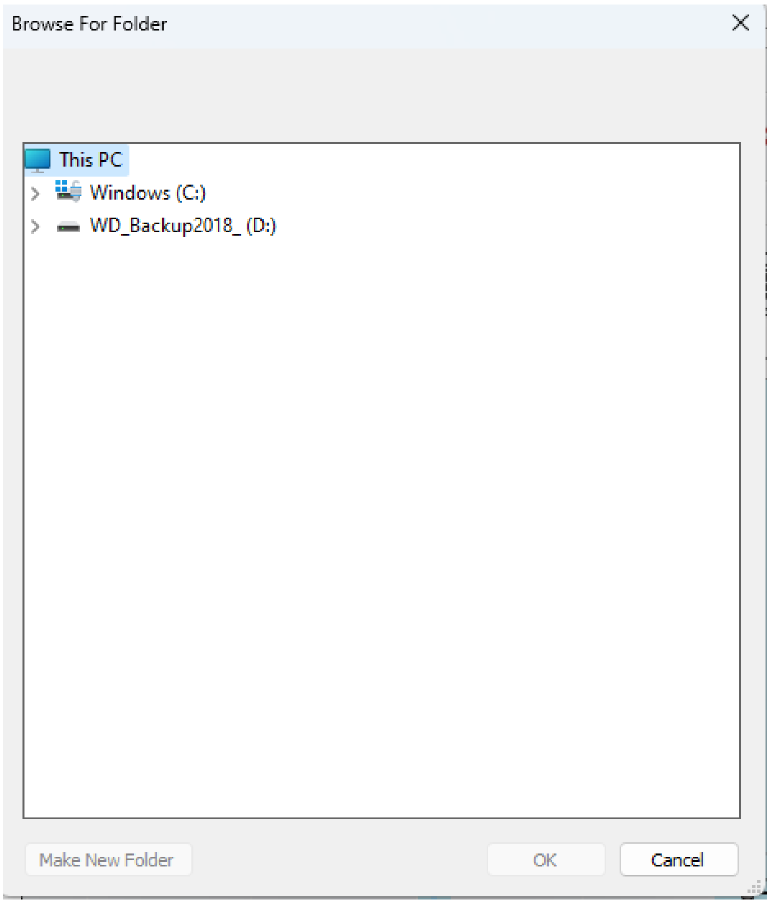
	age (Myrs ago)	failed runs (%)	CO2 (ppm)	O2 (%)
1	570	0	8855.047	14.88095
2	560	0	9293.773	13.79043
3	550	0	8979.239	17.97579
4	540	0	8587.34	17.5068
5	530	0	7148.878	21.10896
6	520	0	7642.791	21.43284
7	510	0	8469.85	20.85065
8	500	0	6292.123	17.71894
9	490	0	4573.324	18.72478
10	480	0	3548.14	16.69545

If the model is run with 'error analysis', then 'GEOCARB_output.csv' will change to the output shown below where we also include minimum (low) and maximum (high) estimates of CO_2. The total propogated errors are lised as ERROR(%).

Age (Ma)	CO2 (ppm)	LOW CO2	HIGH CO2	ERROR(%)	O2 (%)
570	8855.047	6328.268	12696.7	35.95931	14.88095
560	9293.773	6562.41	13466.16	37.14179	13.79043
550	8979.239	6365.108	12953.01	36.68408	17.97579
540	8587.34	6066.467	12431.21	37.05888	17.5068
530	7148.878	5098.012	10247.3	36.01469	21.10896
520	7642.791	5438.538	10988.26	36.30689	21.43284
510	8469.85	5998.283	12243.65	36.86821	20.85065
500	6292.123	4504.67	9001.178	35.73124	17.71894
490	4573.324	3319.406	6446.734	34.19097	18.72478
480	3548.14	2597.567	4957.226	33.25205	16.69545

4.1.5. Copy Model to own Directory (input/output files)

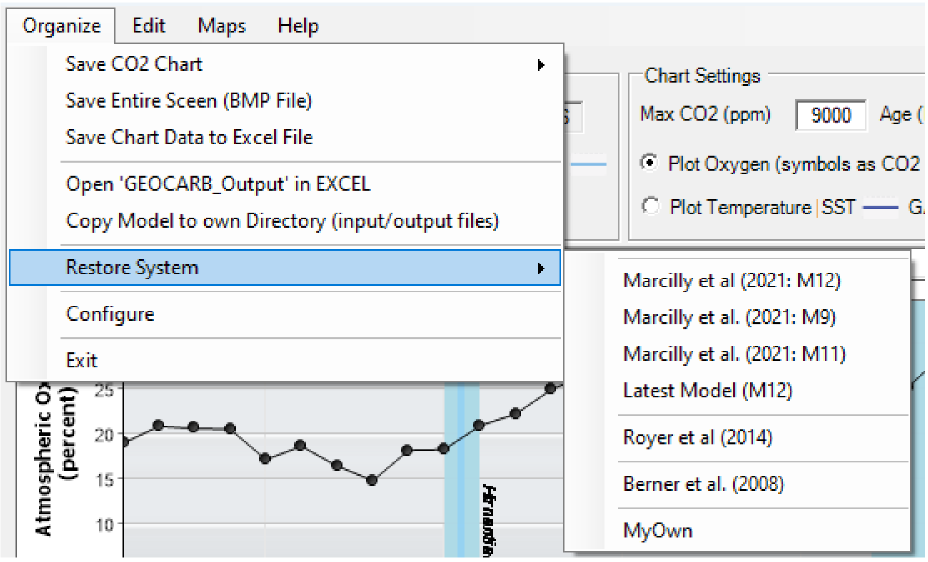
Copies all the input and output files to a specific directory.


Browse For Folder
This PC
Windows (C:)
WD_Backup2018_ (D:)
Make New Folder
OK
Cancel

4.1.6. Restore System: Run Model

*Input parameters from published models are copied from the **Geocarb_Net/Library** (files:*GEOCARB_input_arrays*.csv and *GEOCARB_input_summaries.csv*) to the **Geocarb_Net** directory and then the models are run automatically.

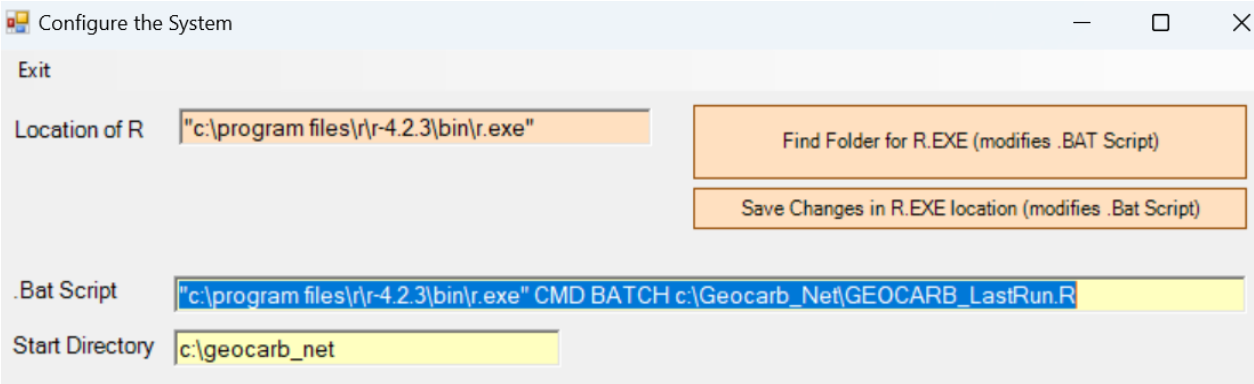
*Default models include Royer *et al*. (2014) and Marcilly *et al.* (2021: Models M9, M11 and M12), Berner (pre-2014) and a refined version of Model 12 in Marcilly *et al*. 2021 (dubbed 'Latest Model'). This model as refined weathering parameters for the past 540 Myrs.



4.1.7. Configure

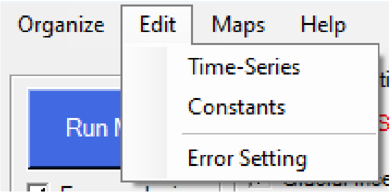
VERY IMPORTANT

Before you can operate this software you must install R on your computer and type the *'Location of R'* (i.e., location of r.exe) in the text box (e.g., c:\program files\r\r-4.2.3\bin\r.exe). Then click *'Save Changes in R.EXE location'* that will modify and save a vital Windows Batch File (RShell_GEOCARB.Bat) that allows GEOCARB_NET to communicate with the R code where the actual carbon cycle modeling is undertaken. Start directory defaults to c:\geocarb_net. If you have installed R but don't know the location of the r.exe file, click on 'Find Folder for R.EXE"



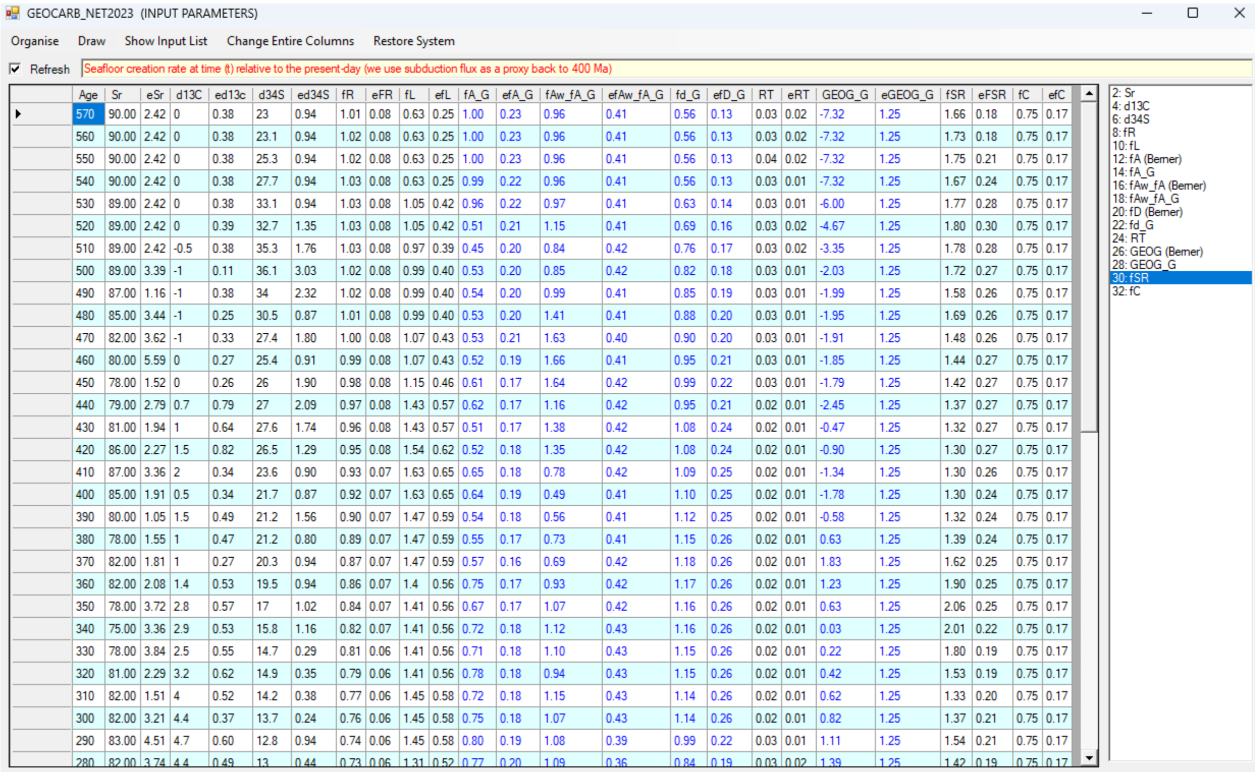
4.2. Edit

'Edit' is one of the four options in the *'start-up menu'* and has several sub-options (see diagram below)



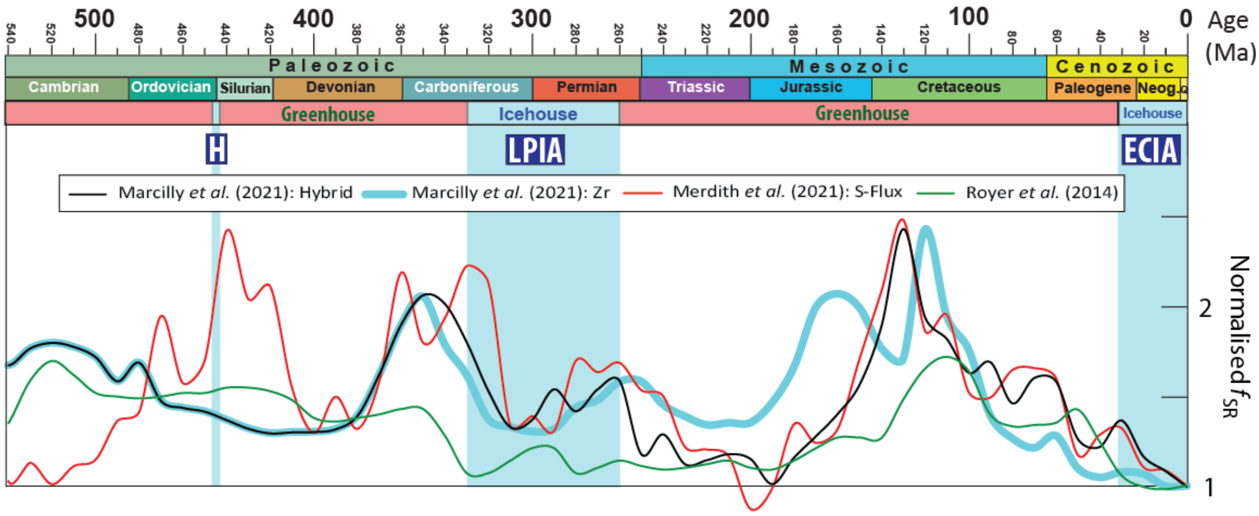
4.2.1. Time-Series

- Select 'Edit' ('Time-Series') in the main menu to make changes to the GEOCARB time-series. These are averaged in 10 Myr bins (0-570 Ma) and stored in *GEOCARB_input_arrays.cvs* that is located in the startup directory (c:\GEOCARB_Net).
- The input file (*GEOCARB_input_arrays.cvs)* consists of [33 columns] but in the program we only display those that will affect our model calculations, i.e. those columns/time-series that were replaced by 'Godderis' colums in Royer et al. (2014) are listed (here simplified by _G).
- By clicking *'Draw'* you can also select a time-series to display by clicking the time-series of interest in the right-hand box. You can also compare time-series with pre-2014 Berner models. You can revert to the input listing by clicking *'Show Input List'.*

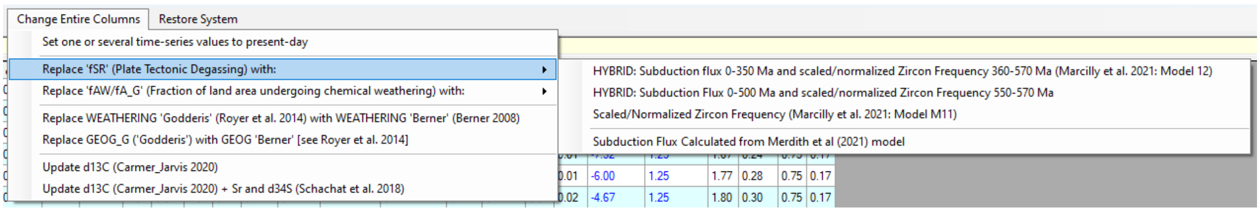


Age	Sr	eSr	d13C	ed13c	d34S	ed34S	fR	eFR	fL	efL	fA_G	efA_G	fAw_fA_G	efAw_fA_G	fd_G	efD_G	RT	eRT	GEOG_G	eGEOG_G	fSR	eFSR	fC	efC
570	90.00	2.42	0	0.38	23	0.94	1.01	0.08	0.63	0.25	1.00	0.23	0.96	0.41	0.56	0.13	0.03	0.02	-7.32	1.25	1.66	0.18	0.75	0.17
560	90.00	2.42	0	0.38	23.1	0.94	1.02	0.08	0.63	0.25	1.00	0.23	0.96	0.41	0.56	0.13	0.03	0.02	-7.32	1.25	1.73	0.18	0.75	0.17
550	90.00	2.42	0	0.38	25.3	0.94	1.02	0.08	0.63	0.25	1.00	0.23	0.96	0.41	0.56	0.13	0.04	0.02	-7.32	1.25	1.75	0.21	0.75	0.17
540	90.00	2.42	0	0.38	27.7	0.94	1.03	0.08	0.63	0.25	0.99	0.22	0.96	0.41	0.56	0.13	0.03	0.01	-7.32	1.25	1.67	0.24	0.75	0.17
530	89.00	2.42	0	0.38	33.1	0.94	1.03	0.08	1.05	0.42	0.96	0.22	0.97	0.41	0.63	0.14	0.03	0.01	-6.00	1.25	1.77	0.28	0.75	0.17
520	89.00	2.42	0	0.39	32.7	1.35	1.03	0.08	1.05	0.42	0.51	0.21	1.15	0.41	0.69	0.16	0.03	0.02	-4.67	1.25	1.80	0.30	0.75	0.17
510	89.00	2.42	-0.5	0.38	35.3	1.76	1.03	0.08	0.97	0.39	0.45	0.20	0.84	0.42	0.76	0.17	0.03	0.02	-3.35	1.25	1.78	0.28	0.75	0.17
500	89.00	3.39	-1	0.11	36.1	3.03	1.02	0.08	0.99	0.40	0.53	0.20	0.85	0.42	0.82	0.18	0.03	0.01	-2.03	1.25	1.72	0.27	0.75	0.17
490	87.00	1.16	-1	0.38	34	2.32	1.02	0.08	0.99	0.40	0.54	0.20	0.99	0.41	0.85	0.19	0.03	0.01	-1.99	1.25	1.58	0.26	0.75	0.17
480	85.00	3.44	-1	0.25	30.5	0.87	1.01	0.08	0.99	0.40	0.53	0.20	1.41	0.41	0.88	0.20	0.03	0.01	-1.95	1.25	1.69	0.26	0.75	0.17
470	82.00	3.62	-1	0.33	27.4	1.80	1.00	0.08	1.07	0.43	0.53	0.21	1.63	0.40	0.90	0.20	0.03	0.01	-1.91	1.25	1.48	0.26	0.75	0.17
460	80.00	5.59	0	0.27	25.4	0.91	0.99	0.08	1.07	0.43	0.52	0.19	1.66	0.41	0.95	0.21	0.03	0.01	-1.85	1.25	1.44	0.27	0.75	0.17
450	78.00	1.52	0	0.26	26	1.90	0.98	0.08	1.15	0.46	0.61	0.17	1.64	0.42	0.99	0.22	0.03	0.01	-1.79	1.25	1.42	0.27	0.75	0.17
440	79.00	2.79	0.7	0.79	27	2.09	0.97	0.08	1.43	0.57	0.62	0.17	1.16	0.42	0.95	0.21	0.02	0.01	-2.45	1.25	1.37	0.27	0.75	0.17
430	81.00	1.94	1	0.64	27.6	1.74	0.96	0.08	1.43	0.57	0.51	0.17	1.38	0.42	1.08	0.24	0.02	0.01	-0.47	1.25	1.32	0.27	0.75	0.17
420	86.00	2.27	1.5	0.82	26.5	1.29	0.95	0.08	1.54	0.62	0.52	0.18	1.35	0.42	1.08	0.24	0.02	0.01	-0.90	1.25	1.30	0.27	0.75	0.17
410	87.00	3.36	2	0.34	23.6	0.90	0.93	0.07	1.63	0.65	0.65	0.18	0.78	0.42	1.09	0.25	0.02	0.01	-1.34	1.25	1.30	0.26	0.75	0.17
400	85.00	1.91	0.5	0.34	21.7	0.87	0.92	0.07	1.63	0.65	0.64	0.19	0.49	0.41	1.10	0.25	0.02	0.01	-1.78	1.25	1.30	0.24	0.75	0.17
390	80.00	1.05	1.5	0.49	21.2	1.56	0.90	0.07	1.47	0.59	0.54	0.18	0.56	0.41	1.12	0.25	0.02	0.01	-0.58	1.25	1.32	0.24	0.75	0.17
380	78.00	1.55	1	0.47	21.2	0.80	0.89	0.07	1.47	0.59	0.55	0.17	0.73	0.41	1.15	0.26	0.02	0.01	0.63	1.25	1.39	0.24	0.75	0.17
370	82.00	1.81	1	0.27	20.3	0.94	0.87	0.07	1.47	0.59	0.57	0.16	0.69	0.42	1.18	0.26	0.02	0.01	1.83	1.25	1.62	0.25	0.75	0.17
360	82.00	2.08	1.4	0.53	19.5	0.94	0.86	0.07	1.4	0.56	0.75	0.17	0.93	0.42	1.17	0.26	0.02	0.01	1.23	1.25	1.90	0.25	0.75	0.17
350	78.00	3.72	2.8	0.57	17	1.02	0.84	0.07	1.41	0.56	0.67	0.17	1.07	0.42	1.16	0.26	0.02	0.01	0.63	1.25	2.06	0.25	0.75	0.17
340	75.00	3.36	2.9	0.53	15.8	1.16	0.82	0.07	1.41	0.56	0.72	0.18	1.12	0.43	1.16	0.26	0.02	0.01	0.03	1.25	2.01	0.22	0.75	0.17
330	78.00	3.84	2.5	0.55	14.7	0.29	0.81	0.06	1.41	0.56	0.71	0.18	1.10	0.43	1.15	0.26	0.02	0.01	0.22	1.25	1.80	0.19	0.75	0.17
320	81.00	2.29	3.2	0.62	14.9	0.35	0.79	0.06	1.41	0.56	0.78	0.18	0.94	0.43	1.15	0.26	0.02	0.01	0.42	1.25	1.53	0.19	0.75	0.17
310	82.00	1.51	4	0.52	14.2	0.38	0.77	0.06	1.45	0.58	0.72	0.18	1.15	0.43	1.14	0.26	0.02	0.01	0.62	1.25	1.33	0.20	0.75	0.17
300	82.00	3.21	4.4	0.37	13.7	0.24	0.76	0.06	1.45	0.58	0.75	0.18	1.07	0.43	1.14	0.26	0.02	0.01	0.82	1.25	1.37	0.21	0.75	0.17
290	83.00	4.51	4.7	0.60	12.8	0.94	0.74	0.06	1.45	0.58	0.80	0.19	1.08	0.39	0.99	0.22	0.03	0.01	1.11	1.25	1.54	0.21	0.75	0.17
280	82.00	3.74	4.4	0.49	13	0.44	0.73	0.06	1.31	0.52	0.77	0.20	1.09	0.36	0.84	0.19	0.03	0.02	1.39	1.25	1.42	0.19	0.75	0.17

- Data values can be directly edited in the input data grid, entire columns can also be replaced directly in EXCEL, but in the program you can (e.g.) change "Plate Tectonic" degassing (f_{SR}) to some pre-compiled data-sets, which here include two models published in Marcilly et al. (2021), namely a hybrid model based on subduction flux and scaled zircon-frequency (Model 12) and a purely scaled zircon frequency curve (M11). We also include a extension of our hybrid M12 model using subduction flux back to 500 Ma, which is also can be compared with estimated subduction flux from the Merdith et al. (2021) model. Select one of thesef_{SR} then 'save changes' and exit the 'Edit Input' mode. Subsequently 'Run Model' in the main menu to see the changes in estimated CO_2. Example of different values of f_{SR} that can be selected in GEOCARB_NET and compared with the curve used in Royer et al. (2014) is shown in the diagram below.

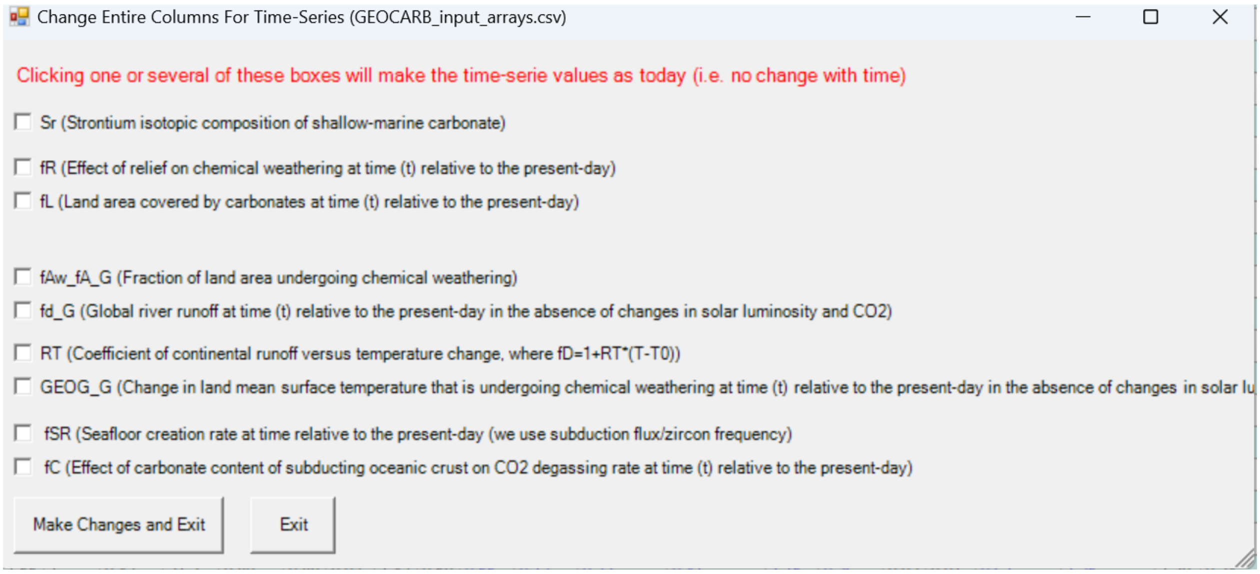


Example of different values of f_{SR} that can be selected in GEOCARB_NET and compared with the curve used in Royer et al. (2014).

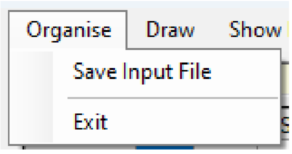


- Weathering parameters and GEOG ('Godderis') introduced in Royet et al. (2014) can be replaced by the earlier 'Berner' parameters.

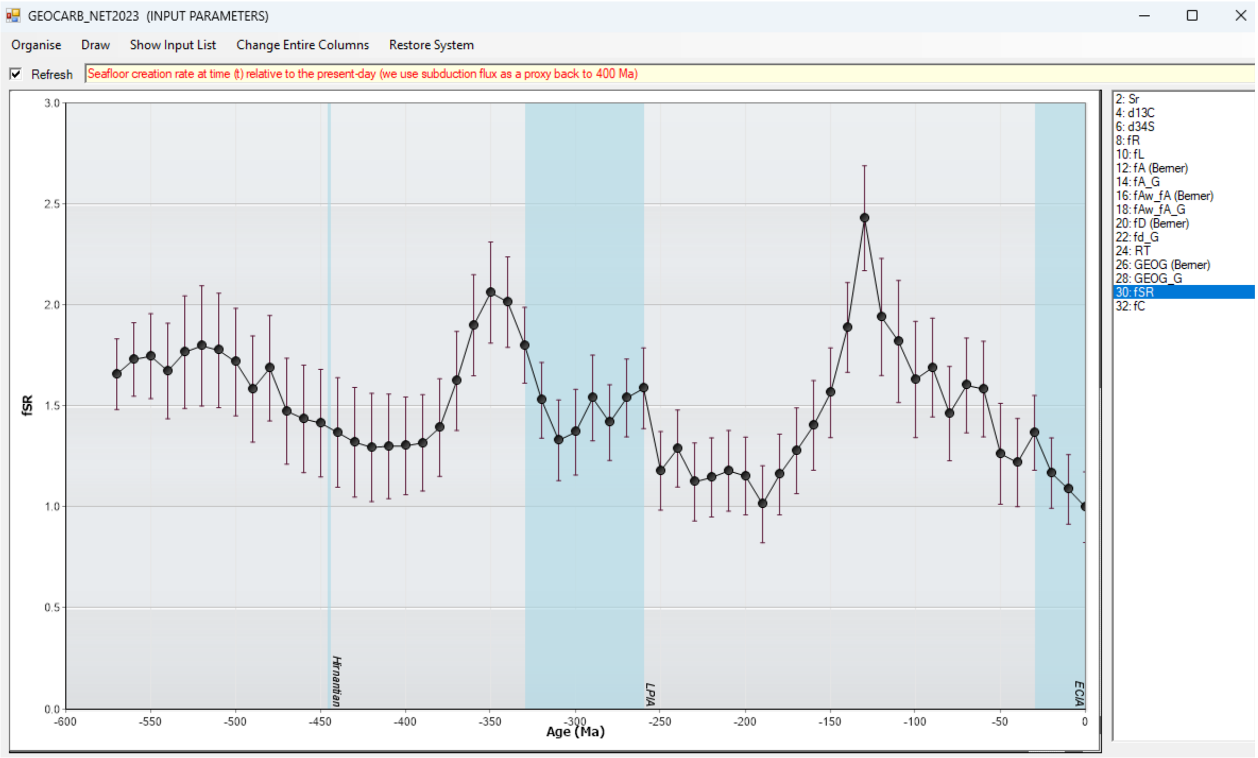
- In order to test the influence of various time-series parameters we have also implemented a simple procedure to set one or many time-series to present values (e.g. no variation back in time).


Change Entire Columns For Time-Series (GEOCARB_input_arrays.csv)
Clicking one or several of these boxes will make the time-serie values as today (i.e. no change with time)
Sr (Strontium isotopic composition of shallow-marine carbonate)
fR (Effect of relief on chemical weathering at time (t) relative to the present-day)
fL (Land area covered by carbonates at time (t) relative to the present-day)
fAw_fA_G (Fraction of land area undergoing chemical weathering)
fd_G (Global river runoff at time (t) relative to the present-day in the absence of changes in solar luminosity and CO2)
RT (Coefficient of continental runoff versus temperature change, where fD=1+RT*(T-T0))
GEOG_G (Change in land mean surface temperature that is undergoing chemical weathering at time (t) relative to the present-day in the absence of changes in solar lu
fSR (Seafloor creation rate at time relative to the present-day (we use subduction flux/zircon frequency)
fC (Effect of carbonate content of subducting oceanic crust on CO2 degassing rate at time (t) relative to the present-day)
Make Changes and Exit
Exit

4.2.1.1. Organize

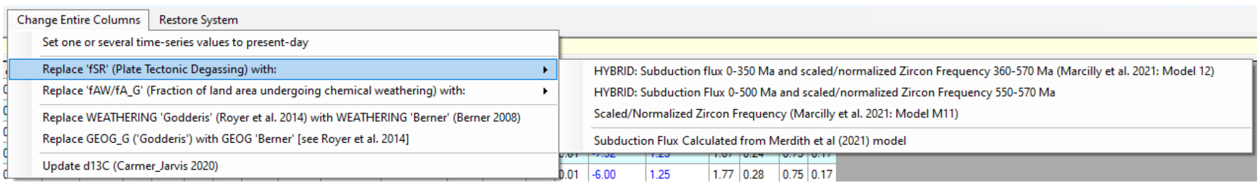


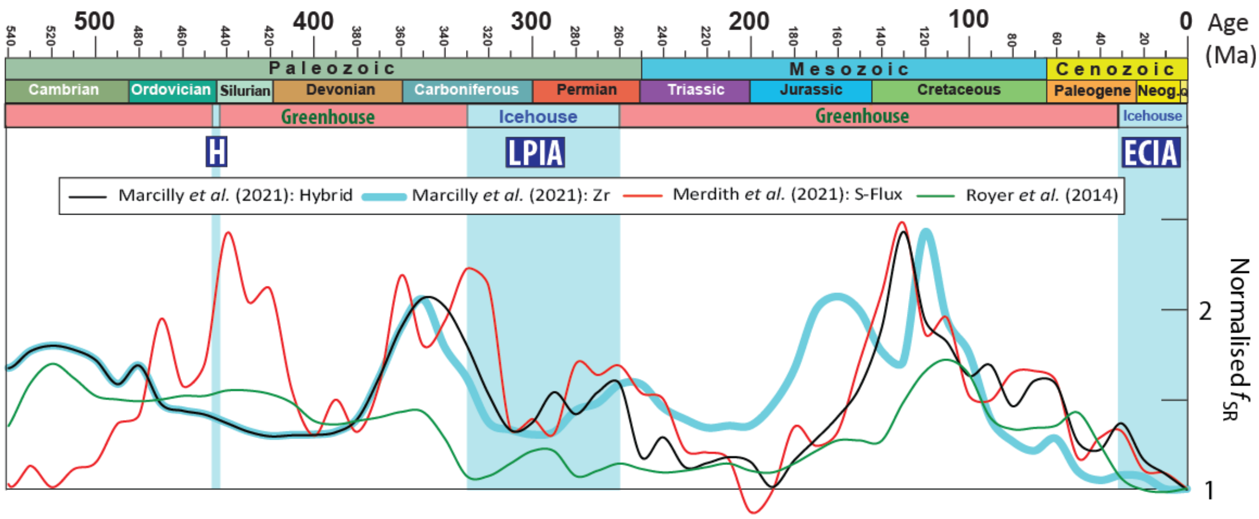
4.2.1.2. Draw

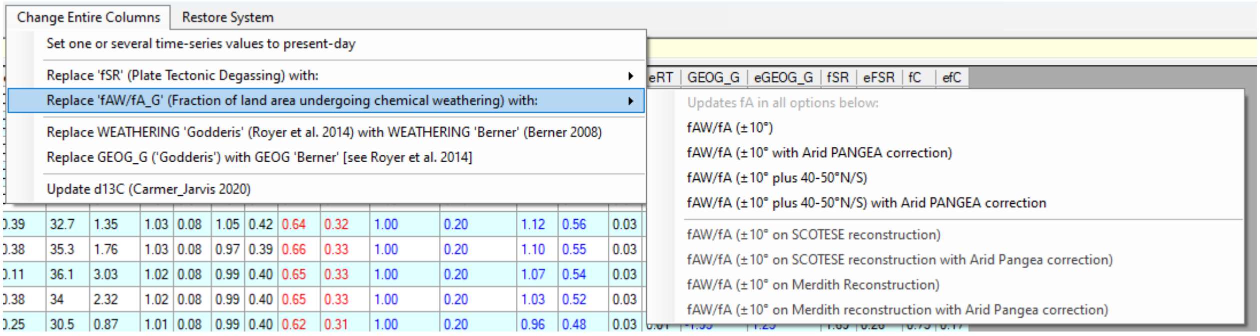


4.2.1.3. Show Input List

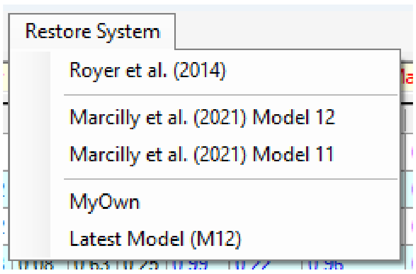
4.2.1.4. Change Entire Columns





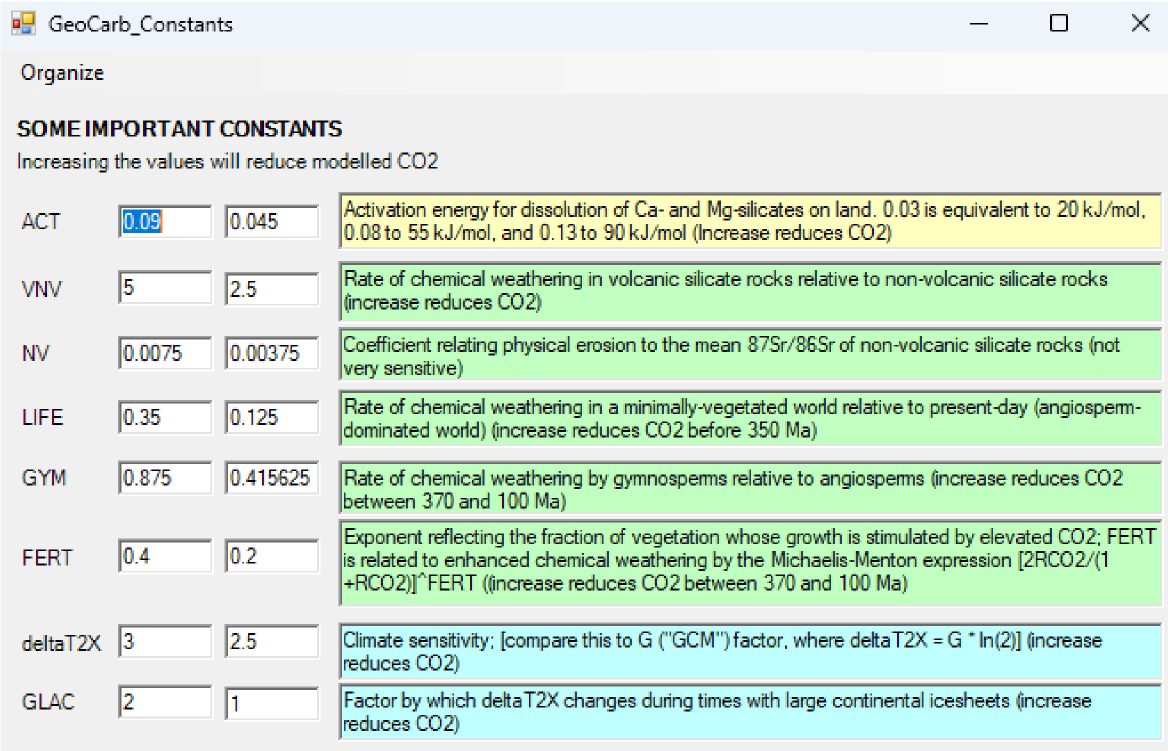


4.2.1.5. Restore System



4.2.2. Constants

- GEOCARB constants are stored in an EXCEL comma separated file *GEOCARB_input_summaries.cvs*.
- The input file consists of 56 constants but in the 'Edit constant' mode we only display 9 important parameters that can be edited directly in the program (remember to 'Save changes' before 'Exit' the form).



GeoCarb_Constants

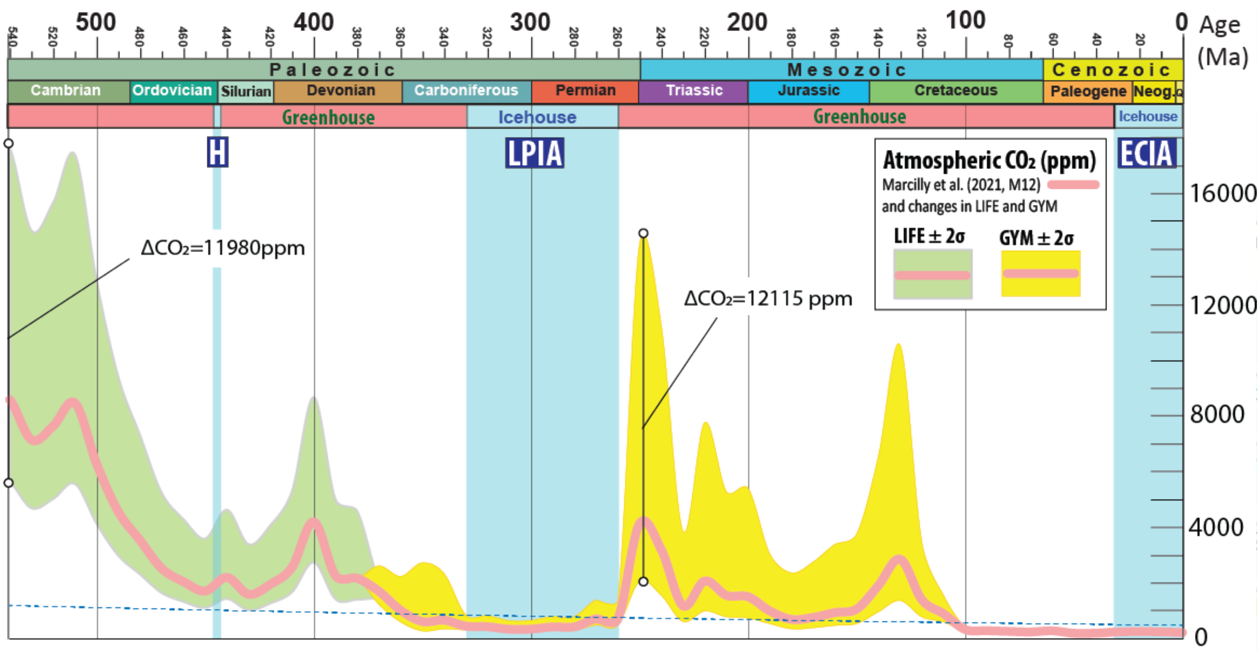
Organize

SOME IMPORTANT CONSTANTS

Increasing the values will reduce modelled CO2

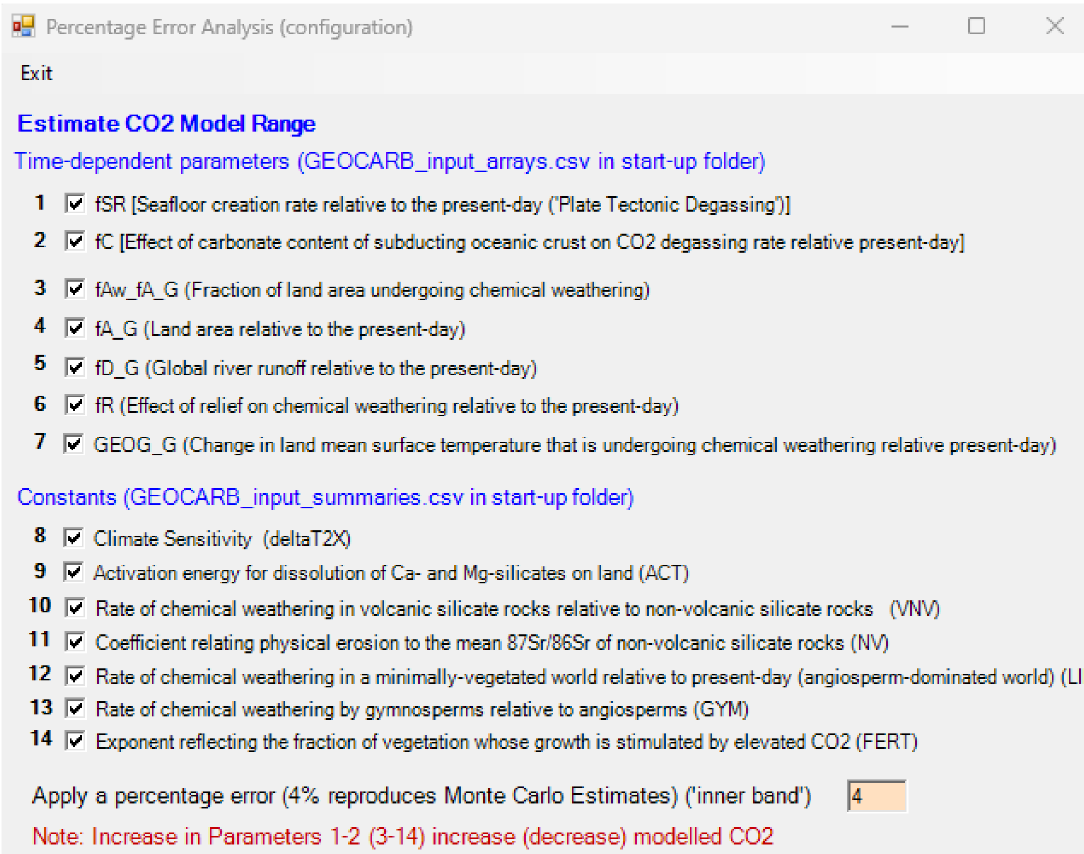
ACT	0.09	0.045	Activation energy for dissolution of Ca- and Mg-silicates on land. 0.03 is equivalent to 20 kJ/mol, 0.08 to 55 kJ/mol, and 0.13 to 90 kJ/mol (Increase reduces CO2)
VNV	5	2.5	Rate of chemical weathering in volcanic silicate rocks relative to non-volcanic silicate rocks (increase reduces CO2)
NV	0.0075	0.00375	Coefficient relating physical erosion to the mean 87Sr/86Sr of non-volcanic silicate rocks (not very sensitive)
LIFE	0.35	0.125	Rate of chemical weathering in a minimally-vegetated world relative to present-day (angiosperm-dominated world) (increase reduces CO2 before 350 Ma)
GYM	0.875	0.415625	Rate of chemical weathering by gymnosperms relative to angiosperms (increase reduces CO2 between 370 and 100 Ma)
FERT	0.4	0.2	Exponent reflecting the fraction of vegetation whose growth is stimulated by elevated CO2; FERT is related to enhanced chemical weathering by the Michaelis-Menton expression [2RCO2/(1+RCO2)]^FERT ((increase reduces CO2 between 370 and 100 Ma)
deltaT2X	3	2.5	Climate sensitivity; [compare this to G ("GCM") factor, where deltaT2X = G * ln(2)] (increase reduces CO2)
GLAC	2	1	Factor by which deltaT2X changes during times with large continental icesheets (increase reduces CO2)

Below we show predicted changes in CO_2 by varying two plant-assisted weathering parameters (LIFE, GYM). Changing these parameters within the quoted 2σ values can have dramatic effects on predicted CO_2 levels during the early Palaeozoic (LIFE) and the early-mid Mesozoic (GYM).



4.2.3. Error Setting

- Determining model uncertainties is complex and as a complement to the original Monte Carlo Error Analysis we have implemented a simple percentage error analysis where important time-series can be assigned a fixed error.
- We also apply the error-analysis to some important constants, e.g.. climate sentitivity, that defaults to 3ºC but is doubled to 6ºC in GEOCARB during icehouse conditions.
- GEOCARB_NET will first calcute the avererage modelled CO_2 and by adding/subtracting the selcted error percentage for the parameters shown below, the program will also calulate a lower and upper bound for the the modelled CO_2.
- Applying a percentage error of 4% closely reproduce Monte Carlo Estiamtes ('inner bands', Royer et al. 2014)



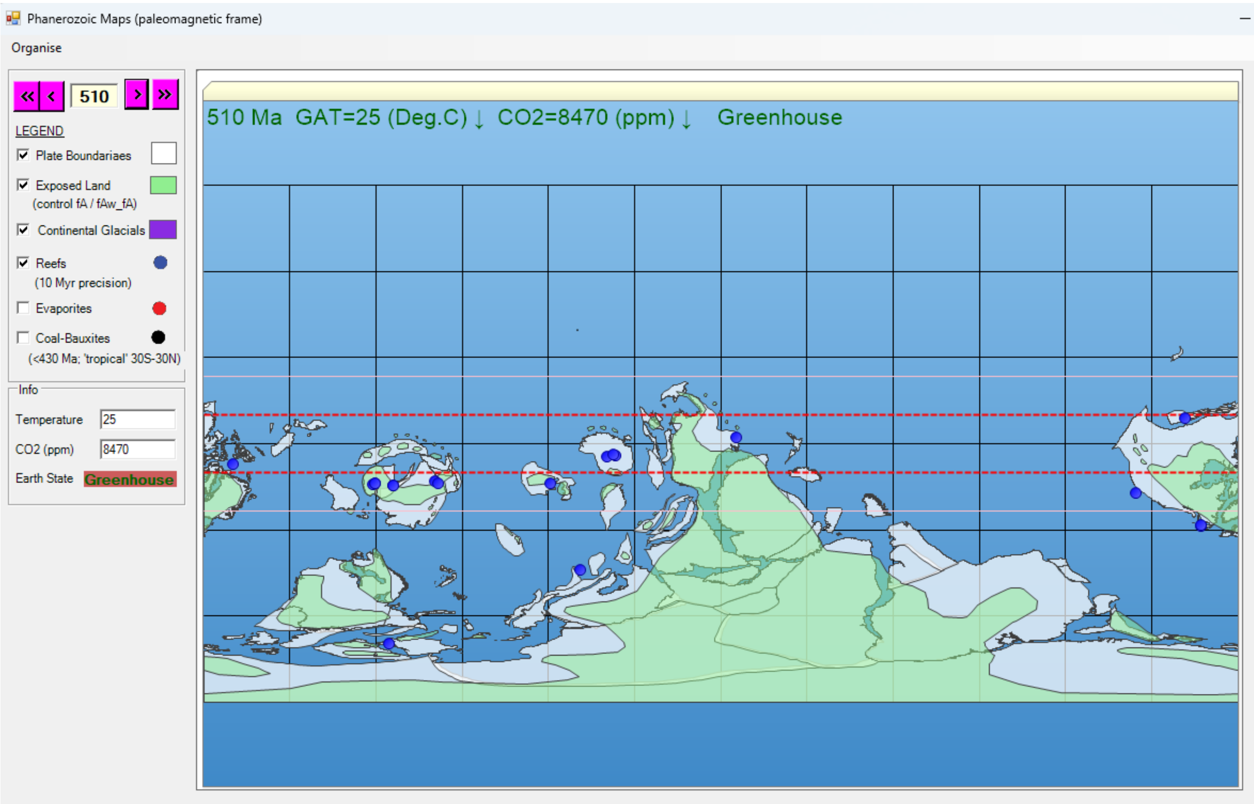
When modeling uncertainties in GEOCARB_NET with the '% Error option', the modeled output file "GEOCARB_output.cvs" will look like the table below. The first column is Age, then mean CO_2 (ppm), LOW CO2 (lower bound), HIGH CO2 (upper bound), Error(%) [cumulative error in the modeled CO_2) and O_2(%) (no error analysis).

Age (Ma)	CO2 (ppm)	LOW CO2	HIGH CO2	ERROR(%)	O2 (%)
570	6328.92	4590.28	8931.85	34.30	14.88
560	6601.36	4719.56	9442.15	35.77	13.62
550	6422.43	4609.79	9145.94	35.31	18.07
540	6061.95	4335.99	8662.92	35.69	17.36
530	5049.69	3646.66	7144.28	34.63	21.14
520	5403.77	3894.32	7667.91	34.92	21.40
510	5983.44	4291.45	8536.81	35.48	20.74

500	4452.26	3228.06	6286.31	34.34	17.42
490	3224.85	2371.20	4485.23	32.78	18.74
480	2500.71	1854.60	3447.41	31.85	16.64

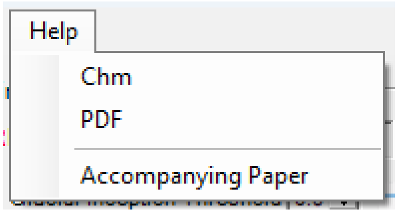
4.3. Maps

The 'Maps' mode is selected from the startup page and merely serve to illustrate how the f_A (exposed land relative present day) and $f_{AW}\_f_A$ (fraction of land area undergoing chemical weathering) parameters are estimated. The latter parameter can be constructed by scaling the area of most intensive silicate weathering (10S-10N, red stippled lines in map) and can also be adjusted for aridity in the tropics associated with super-continents (model M12 in Marcilly et al. 2021). You can inspect our palogeographic reconstructions in 10 Myr intervals and selectively display 'Exposed Land', 'Continental Glacials'.



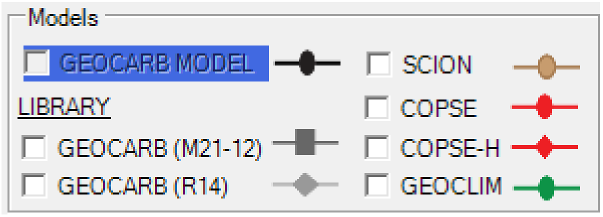
4.4. Help

Select Chm (interactive) or PDF documentation that describe all the functions the GEOCARB_NET. You can also download an aaacompaning paper thet describe GEOCAR_NET with many examples.



5. Models

The 'Model Library' consists of estimated Phanerozoic CO_2 and O_2 (only for GEOCARB and SCION) 'evels using different carbon-cycle models.
Model results are found in an Excel-file named *"LIBRARY_CO2_O2_Models"* located in **c:/Geocarb_Net/Library**



GEOCARB:
Royer et al (2014): Errors estimated by Monte Carlo simulations [GEOCARB (R14) in diagram above]
Marcilly et al.(2021): Model 12 with error-estimates from GEOCARB_NET [GEOCARB (M21-12) in diagram above]

Marcilly et al. (2021|): Model 12 with error-estimates from GEOCARB_NET + simulating the shortlived Hirnantian glaciation (ca. 445 Ma) with climate sensitivity 6º at 450 and 440 Ma.
Marcilly et al. (2021): Model 9 with error-estimates from GEOCARB_NET

Table 2 (Marcilly et al. 2021)

Overview of the 12 different models we have used to estimate atmospheric CO2 in the GEOCARBSULFvolc program. All parameters as in Royer et al. (2014) except time-dependent changes in f_{SR}, f_A and f_{AW_fA}. In the original GEOCARBSULF code these parameters are described as ‘‘Seafloor creation rate at time (t) relative to the present-day” (f_{SR}), ‘‘Land area at time (t) relative to the present-day” (f_A) and ‘‘Fraction of land area undergoing chemical weathering” (f_{AW_fA} & f_{AW10_fA}). For the latter two parameters we use those of Royer et al. (2014) before 520 Ma. Model Revised parameter descriptions (others as in Royer et al. 2014)

- M1: Revised f_A and f_{AW_fA} scaled by exposed land within ±10º and between 40 and 50ºN/S
- M2: As M1 but f_{AW_fA} adjusted for arid equatorial regions
- M3: Revised f_{SR} (arc-zircon model)
- M4: Revised f_{SR} (hybrid model: Subduction flux 0–350 Ma and arc-zircon model for older times)
- M5: M2 + M3
- M6: M2 + M4
- M7: Revised f_A and f_{AW10_fA}
- M8: M7 + M3
- M9: M7 + M4
- M10: As M7 but f_{AW10_fA} adjusted for arid equatorial regions
- M11: As M8 but f_{AW10_fA} adjusted for arid equatorial regions
- M12: As M9 but f_{AW10_fA} adjusted for arid equatorial regions

COPSE:

Lenton et al. (2018) [COPSE in diagram above]
Lenton et al. (2018) HYBRID: Uses degassing/weathering parameters as in Marcilly et al. (2021: Model 12) and climate sensitivity of 3^{o} (greenhouses) and 6^{o} (cold houses) as in GEOCARBSULF [COPSE-H in diagram above]

GEOCLIM:

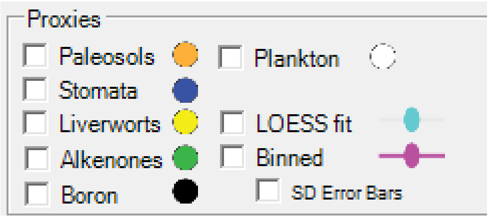
Godderis and Donnadieu (2019) [GEOCLIM in diagram above]

SCION:

Mills et al. (2021) [SCION in diagram above]

6. Proxies

All proxy data can be found in EXCEL-files located in c:/Geocarb_Net/Proxies. The proxy file is named *"Royer2018_VC_PP_Raw_CO2.csv"* and a global running mean curve (10 Myr bins) is dubbed *"Royer2018_VC_PP_Binned10_CO2.csv"*.



Proxies
Include $\delta^{13}C$ of paleosols, marine phytoplankton, long chained alkenones in haptophytic algae, liverworts, stomatal densities and indices in plants, and $\delta^{11}B$ of marine carbonate.

BINNED (10 Myr)
We have averaged proxy systems based on the most reliable Cenozoic proxies (The CenCO2PIP Consortium, 2023), which has been combined back in time with the most up-to date Paleozoic-Mesozoic compilation of Dana Royer [a refinement of the Foster et al. 2017) data compilation] and phytoplankton proxies (Witkowski *et al.* 2018). In total, our new binned CO_2 proxy curve back to 450 Ma is based on more than 2500 proxies from phytoplankton (N=832), boron (805), paleosols (555), stomata (286) and a subordinate number of alkenones (23) and liverworts (15).

The global running mean curve (10 Myr bins) contains mean values, 1σ standard deviation (SD) and the number of proxies for each mean value. The binned curve is by default shown with 95% confidence errors based on standard errors [SE = SD/sqrt(N)] but can be displayed with SD 95% confidence errors.

LOESS fit
Foster et al. 2017

Visit **paleo-CO2** for information about proxies

7. Key Input Files

Several files (all located and modified in the *c:\Geocarb_Net* directory) are crucial for the GEOCARB_Net software operation. These are:

(1) *GEOCARB_input_arrays.cvs*
(2) *GEOCARB_input_summaries.csv*

GEOCARB_input_arrays.cvs contains the values and estimated errors of the various time-series used in GEOCARB. The software always uses the version located in the c:\GEOCARB_Net directory, and the file consists of 33 columns listed below. Those columns with the time-series and errors marked in red are never used in this software and only kept for file compatibility with earlier GEOCARB version. Thus only the '_Godderis' columns should be modified in addition to other columns that are not background-color highligted. The file can be changed directly in EXCEL or selecting 'Edit' and 'Time-Series" in the program.

GEOCARB_input_arrays.cvs

Time Series	Notes	Dimension	References
Age		million years	
Sr	Strontium isotopic composition of shallow-marine carbonate	(87Sr/86Sr-0.7)*10^4	Berner (1994, 2004)
eSr	*Errors*		
d13C	Stable carbon isotopic composition of shallow-marine carbonate	per mil	Berner (2004, 2006a, 2009)
ed13C	*Errors*		
d34S	Stable sulfur isotopic composition of shallow-marine carbonate	per mil	Wu et al (2010)
ed34S	Errors		
fR	Effect of relief on chemical weathering at time (t) relative today	dimensionless	Berner (2004)
efR	*Errors*		
fL	Land area covered by carbonates at time (t) relative today	dimensionless	Berner (2004); Bluth and Kump (1991)
efL	*Errors*		
fA	**Land area at time (t) relative today**	dimensionless	Berner (2004); Otto-Bleisner (1995)
efA			
fA_Godderis			Godderis et al (2012); **Marcilly et al. (2021)**
efA_Godderis			
fAw_fA	**Fraction of land area undergoing chemical weathering**	dimensionless	Godderis et al (2012); **Marcilly et al. (2021)**

Time Series	Notes	Dimension	References
efAw_fA			
fAw_fA_Godderis			
efAw_fA_Godderis			
fD	**Global river runoff at time (t) relative today in the absence of changes in solar luminosity and CO2**	dimensionless	Berner (2004); Otto-Bleisner (1995)
efD			
fD_Godderis			Godderis et al (2012)
efD_Godderis			
RT	Coefficient of continental runoff versus temperature change, where fD=1+RT*(T-T0)	1/K	Godderis et al (2012)
eRT	*Errors*		
GEOG	**Change in land mean surface temperature that is undergoing chemical weathering at time (t) relative today in the absence of changes in solar luminosity and CO2 (see p. 35 in Berner 2004)**	K	Berner (2004); Otto-Bleisner (1995)
eGEOG			
GEOG_Godderis			Godderis et al. (2012)
eGEOG_Godderis			
fSR	Seafloor creation rate at time (t) relative today	dimensionless	Berner (2004); **Marcilly et al. (2021)**
eFSR	*Errors*		
fC	Effect of carbonate content of subducting oceanic crust on CO2 degassing rate at time (t) relative today; 0.75 for >150 Ma, then ramps up linearly to 1 at present-day	dimensionless	Berner (2004)
efC	*Errors*		

GEOCARB_input_summaries.csv" provides a summary of all input parameters (see also Appendices 1-3 in Royer et al, 2014), including all necessary information for the time-invariant constants. Here we only list all the parameters, type and what they are. The file can be edited in EXCEL but the program can make changes to some important parameters, e.g. climate sensitivity (deltaT2V) and factor (GLAC) by which it change during icehouses.

GEOCARB_input_summaries.csv *(only 3 selected columns shown)*

Parameter	Type	Notes
Sr	time array	Strontium isotopic composition of shallow-marine carbonate
d13C	time array	Stable carbon isotopic composition of shallow-marine carbonate
d34S	time array	Stable sulfur isotopic composition of shallow-marine carbonate
fR	time array	Effect of relief on chemical weathering at time (t) relative to the present-day

fL	time array	Land area covered by carbonates at time (t) relative to the present-day
fA	time array	Land area at time (t) relative to the present-day
fD	time array	Global river runoff at time (t) relative to the present-day in the absence of changes in solar luminosity and CO2
fAw_fA	time array	Fraction of land area undergoing chemical weathering
RT	time array	Coefficient of continental runoff versus temperature change, where fD=1+RT*(T-T0)
GEOG	time array	Change in land mean surface temperature that is undergoing chemical weathering at time (t) relative to the present-day in the absence of changes in solar luminosity and CO2 (see p. 35 in Berner 2004)
fSR	time array	Seafloor creation rate at time (t) relative to the present-day
fC	time array	Effect of carbonate content of subducting oceanic crust on CO2 degassing rate at time (t) relative to the present-day; 0.75 for >150 Ma, then ramps up linearly to 1 at present-day
ACT	constant	Activation energy for dissolution of Ca- and Mg-silicates on land. 0.03 is equivalent to 20 kJ/mol, 0.08 to 55 kJ/mol, and 0.13 to 90 kJ/mol (ACT = DE/RTTo; see p. 28 in Berner 2004).
ACTcarb	constant	Activation energy for dissolution of carbonates on land
VNV	constant	Rate of chemical weathering in volcanic silicate rocks relative to non-volcanic silicate rocks
NV	constant	Coefficient relating physical erosion to the mean 87Sr/86Sr of non-volcanic silicate rocks
exp_NV	constant	Exponent relating physical erosion to the mean 87Sr/86Sr of non-volcanic silicate rocks
LIFE	constant	Rate of chemical weathering in a minimally-vegetated world relative to present-day (angiosperm-dominated world)
GYM	constant	Rate of chemical weathering by gymnosperms relative to angiosperms
FERT	constant	Exponent reflecting the fraction of vegetation whose growth is stimulated by elevated CO2; FERT is related to enhanced chemical weathering by the Michaelis-Menton expression [2RCO2/(1+RCO2)]^FERT
exp_fnBb	constant	Exponent used to describe the effect of climate on silicate or carbonate weathering in the absence of vascular plants at time (t) relative to the present-day
deltaT2X	constant	Climate sensitivity [compare this to G (GCM) factor where deltaT2X = G * ln(2)]
GLAC	constant	Factor by which deltaT2X changes during times with large continental icesheets
J	constant	Coefficient used to calculate CAPd13C (called "alphac" in BASIC code), the stable carbon isotopic fractionation between shallow-marine carbonate and shallow-marine organic matter; CAPd13C = 27+J*(oxygen/38-1)
n	constant	Exponent used to calculate CAPd34S (called "alphas" in BASIC code), the stable sulfur isotopic fractionation between shallow-marine CaSO4 sulfur and pyrite sulfur; CAPd34S = 35((oxygen/38)^n)
Ws	constant	Effect on temperature from the linear increase in solar luminosity over time
exp_fD	constant	Exponent that scales the dilution of dissolved HCO3- with runoff (fD)
Fwpa_0	constant	Sulfate flux from oxidative weathering of old pyrite at present-day
Fwsa_0	constant	Sulfate flux from weathering of CaSO4 sulfur at present-day
Fwga_0	constant	Carbon flux from weathering of old sedimentary organic matter at present-day
Fwca_0	constant	Carbon flux from weathering of old Ca and Mg carbonates at present-day
Fmg_0	constant	Carbon degassing flux from volcanism, metamorphism, and diagenesis of organic matter at present-day
Fmc_0	constant	Carbon degassing flux from volcanism, metamorphism, and diagenesis of carbonates at present-day

Fmp_0	constant	Sulfur degassing flux from volcanism, metamorphism, and diagenesis of pyrite at present-day
Fms_0	constant	Sulfur degassing flux from volcanism, metamorphism, and diagenesis of CaSO4 sulfur at present-day
Fwsi_0	constant	Weathering flux for all Ca and Mg silicates at present-day
Xvolc_0	constant	Fraction of total Ca and Mg silicate weathering derived from volcanic rocks at present-day
CAPd13C_0	constant	Stable carbon isotopic fractionation between shallow-marine carbonate and shallow-marine organic matter at present-day
CAPd34S_0	constant	Stable sulfur isotopic fractionation between shallow-marine CaSO4 sulfur and pyrite sulfur at present-day
oxygen_570	constant	Mass of atmospheric O2 (7.5 and 143 correspond to 5% and 50% O2) at 570 Myrs ago
Gy_570	constant	Mass of young crustal organic carbon at 570 Myrs ago (value in Berner 2006a is a typo)
Cy_570	constant	Mass of young crustal carbonate carbon at 570 Myrs ago (value in Berner 2006a is a typo)
Ca_570	constant	Mass of old crustal carbonate carbon at 570 Myrs ago (value in Berner 2006a is a typo)
Ssy_570	constant	Mass of young CaSO4 sulfur at 570 Myrs ago
Spy_570	constant	Mass of young pyrite sulfur at 570 Myrs ago
dlsy_570	constant	d34S of young CaSO4 sulfur at 570 Myrs ago
dlcy_570	constant	d13C of young carbonate carbon at 570 Myrs ago
dlpy_570	constant	d34S of young pyrite sulfur at 570 Myrs ago
dlpa_570	constant	d34S of old pyrite sulfur at 570 Myrs ago
dlgy_570	constant	d13C of young organic matter at 570 Myrs ago
dlga_570	constant	d13C of old organic matter at 570 Myrs ago
Rcy_570	constant	87Sr/86Sr of young carbonates undergoing weathering at 570 Myrs ago
Rca_570	constant	87Sr/86Sr of old carbonates undergoing weathering at 570 Myrs ago
Rv_570	constant	87Sr/86Sr of sub-aerial and submarine volcanic rocks at 570 Myrs ago
Rg_570	constant	87Sr/86Sr of non-volcanic silicates at 570 Myrs ago
Fob	constant	Ca and Mg flux between basalt and seawater
COC	constant	Mass of carbon in ocean
Ga	constant	Mass of old crustal organic carbon (value in Berner 2006a is a typo)
Ssa	constant	Mass of old CaSO4 sulfur
Spa	constant	Mass of old pyrite sulfur
ST	constant	Mass of sulfur in oceans + "interacting rocks" (i.e., sulfur in rocks undergoing weathering, burial, etc.)
dlst	constant	d34S of ST
CT	constant	Mass of carbon in oceans + "interacting rocks" (i.e., carbon in rocks undergoing weathering, burial, etc.)
dlct	constant	d13C of CT
kwpy	constant	Rate constant expressing mass dependence for young pyrite sulfur
kwsy	constant	Rate constant expressing mass dependence for young CaSO4 sulfur
kwgy	constant	Rate constant expressing mass dependence for young organic matter weathering
kwcy	constant	Rate constant expressing mass dependence for young carbonate weathering