Supporting Online Material for

The Heartbeat of the Oligocene Climate System

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This PDF file includes:

Methods
SOM Text
Figs. S1 to S3
Tables S1 to S3
References

Supporting Online Material

We generated astronomical age models for the Oligocene Pacific stable isotope and physical property data as follows and note that the process of time scale adjustment, spectral analysis and further refinement is an iterative process (*S1*). The first step consists of generating an internally consistent composite data set from the several boreholes that were drilled at Site 1218 during ODP Leg 199. This step is important to (i) splice gaps between cores from individual holes, to (ii) verify the continuity of the record, and to (iii) integrate the various stratigraphic markers in the record that allow extrapolation to other sites. The results from this analysis (*S2*) showed that the records are continuous, at least on a spatial scale of ∼700 km in the Pacific, and that stacking of data improved the signal-to-noise ratio of physical property data such as magnetic susceptibility and sediment bulk density. Applying literature ages to bio- and magnetostratigraphic markers resulted in the first time scale for these data, which showed convincing cyclicity in the data, at frequency ratios that are compatible with an orbital forcing origin, but with much stronger short and long eccentricity amplitude responses than those predicted by seasonal insolation curves. The next step consisted of generating an astronomical target curve with which the data could be compared. We computed a synthetic astronomical target ("ETP curve, as devised in (*S3*)), which combines the astronomical parameters that control insolation curves (eccentricity, obliquity, climatic precession) with arbitrary relative amplitudes, with the aim to more closely resemble the frequency spectrum calculated from the data. In detail, the ETP curve was constructed by taking the eccentricity, obliquity, and climatic precession values from (*S4*), using present day values for the dynamical ellipticity and tidal dissipation (*S5*), and normalizing the three individual time series by subtracting their long term average, and dividing by their long term standard deviation. For each time step, normalized eccentricity, obliquity and climatic precession were then added together in amplitude ratios of 1:0.5:-0.4. This process enhances the relative contribution of eccentricity to the target curve, to more closely resemble the data and facilitate the tuning process. The negative sign for climatic precession makes the resulting curve technically resemble northern hemisphere insolation. We stress, though, that the uncertainties in the Earth model which control tidal dissipation are such that it is currently not possible to make a meaningful distinction between the phasing of northern versus southern hemisphere forcing during the Oligocene (*S1*), and the choice to use the equivalent of northern hemisphere forcing was made only to facilitate comparison with previous studies that also used this convention (*S1, S6*). The next step consisted in conducting a spectral analysis of the additional stable isotope data in the depth domain, by way of wavelet spectral analysis using software provided together with (*S7*). This analysis quantified a strong eccentricity amplitude in the benthic stable isotope datasets that is also apparent by visual inspection. The original age models were then refined by fine-scale adjustment of the time scale, first to the ∼405 kyr eccentricity cycle in the carbon isotope time series, and then the shorter astronomical frequencies seen in the data. The final step consisted in refining this age model, obtained by manual matching of the data with the target curve with as few tie-points as possible, by algorithmic means. This automated tuning

method (*S8*), which was independently developed but is very similar to (*S9*), simultaneously matches the available data to the target curve. This automated refinement resulted in only small changes to the manual method, confirming the relative robustness of our interpretation. The wavelet spectral analysis of the stable isotope data is shown in WebFig. S1.

The complete Pacific Oligocene stable isotope data set is summarized in extended form in WebFig. S2. The data that make up these curves are available in electronic form at a designated data repository (`http://www.pangaea.de`). Data were generated in five different laboratories. A lower resolution record across the entire interval (*S10*) shows that there are no discernible inter-laboratory offsets. Sedimentation rates varied between 1 and 2 cm/kyr.

Site 1218 has moved northward during the duration of the Oligocene, due to the northward movement of the Pacific plate. Two studies indicate that the northward movement during the Oligocene amounted to about 2-3° latitude, with Site 1218 crossing the equator prior to Oligocene time (*S11, S12*). From this perspective it is possible that there have been small changes in the position with respect to the presently very narrow productivity gradient. However, (*S13*) evaluated the sedimentation rate history of Site 1218 over Paleocene to Miocene time, and during the Oligocene Site 1218 has always remained in the highest productivity zone (which was broader during Oligocene/Eocene time).

Prior to ODP Leg 199, there was a lack of continuous records spanning the onset of the O/M transient event. A description of the nature of the previously conjectured Late Oligocene Warming" was previously given (*S10*), based on a lower resolution subset of the data presented here. This lower resolution data set was also used in a different summary (*S14*). Additional new data across the O/M transition were also recovered from a recent Ocean Drilling Program Leg (*S15*).

Here we give an additional account based on a higher-resolution data set of this important event, based on two combined data sets (*S10, S16*). The data from the equatorial Pacific provide a valuable new archive that significantly advances our understanding of the global magnitude of this event. In particular, the record provides insights into: (i) the transition from high benthic oxygen isotope values in the middle Oligocene to the low values observed in the latest Oligocene (the apparent "Late Oligocene Warming" (*S17*)), and (ii) a detailed comparison of three independently age calibrated high-resolution stable isotope records across the O/M transition, two of which have a well defined magnetostratigraphy. WebFig. S3 illustrates that the transition from maximum glacial conditions during the middle Oligocene to the deglacial conditions prior to cycle $58_{Ol-C6Cn}$ took longer ($\sim$2.5 Myr) than previously apparent. The very rapid step in a multi-site compilation (*S17*) results from a switch from high southern-latitude sites, with high oxygen isotope ratios, to data from ODP Leg 154, with lower $\delta^{18}O$ values (see WebFig. S3, also (*S18*)).

Refined integrated bio- and magnetostratigraphies for Site 690 (*S19*), which contributes to the high-latitude data from the compilation, also suggest ages for these samples that would move the heaviest $\delta^{18}O$ values from Site 690 closer to the "Oligocene glacial maximum", at $\sim$27 Ma on our time scale, implying a less rapid deglaciation. The overall deglaciation trend,

as recorded in Site 1218, however, is more gradual, extending from $\sim$27 Ma to 25 Ma, though with a prominent initial step at the top of polarity chron C9n. We observe an asymmetric warming and/or decreased ice-volume trend (*S10*) between glacial and interglacial conditions: "warm" δ^{18}O values are attained faster than the more gradual trend of heavy δ^{18}O values, implying a decreasing glacial–interglacial amplitude during the warming trend. Interestingly, the overall trend exhibited in the δ^{18}O values is not reflected in the δ^{13}C record, although the lightest δ^{13}C values during the entire Oligocene are found during a $\sim$100 kyr interglacial at around 26.1 Ma, after the warming trend began.

Comparison of data from Site 1218 with previous high resolution records from ODP Leg 154 Sites 926 and 929, Ceara Rise (*S20*), and ODP Leg 177 Site 1090, subantarctic Southern Ocean (*S6*) reveals new insights into the global pattern of deep water-mass ocean-to-ocean gradients of δ^{18}O and δ^{13}C. WebFig. S3 indicates that there are negligible gradients for benthic δ^{13}C between the sites, extending this observation back in time from previous findings (*S21*). The present water depths for these sites (1218 (*S11*): 4828m , 926 (*S20*): 3598m, 1090 (*S22*): 3702m) compares with the following estimated paleo-depths during the late Oligocene for Sites 1218 (*S23*): 4.2 km, 926 (*S24*): 3.4 km , 1090 (*S25*): 3.7 km.

Remarkably, there is a negligible δ^{18}O offset between the equatorial Pacific Site 1218 and the Southern Ocean Leg 177 Site 1090, implying water masses with similar temperatures and salinities bathing these two sites. In contrast, the equatorial Atlantic data from Leg 154 are consistently about 0.5 per mil lighter throughout the late Oligocene and early Miocene, possibly caused by the influence of a North Atlantic source of deep water (*S21*).

Despite the independently derived astronomical age models for the three sites, we observe remarkably close correspondence between the isotope curves down to obliquity scale periods ($\sim$40 kyr), indicating that small scale isotope and lithological cycles are of global significance.

Finally, we present a summary of the stratigraphic data and calibrations from ODP Leg 199, Site 1218, in Web Tables S1 (magnetostratigraphy) and S2 (biostratigraphy). For each datum in Web Table S1, we provide three ages: the first one is the traditional age according to (*S26*), the second one arises from a "manual" astronomical calibration, while the third is obtained by refining the manual ages with an automatic tuning procedure (*S8*), which was independently developed but is very similar to (*S9*). It is important to stress that the astronomically calibrated ages given here are robust for the carbonate bearing section of Site 1218 (the entire Oligocene), but are still open for refinement, particularly for the Eocene part of the record. For the figures we used the ages from this final column.

References and Notes

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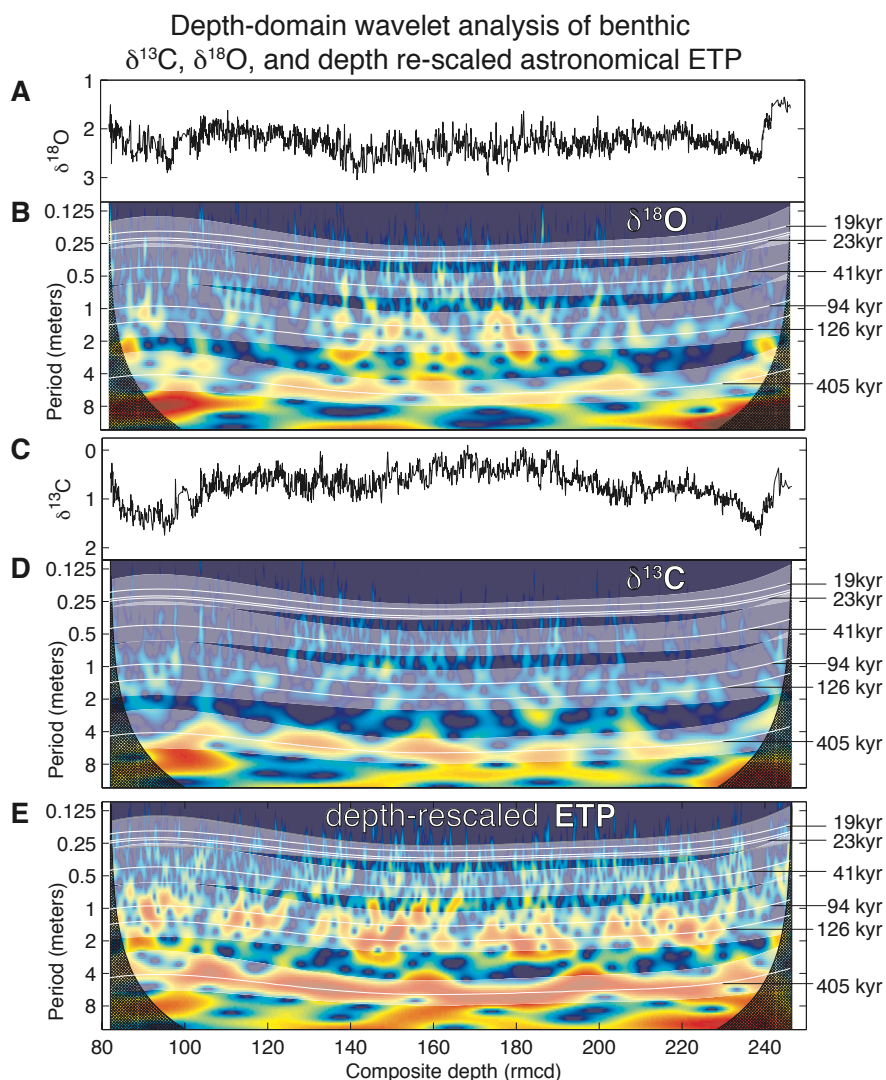
Web Fig. S 1: (**A**) Benthic δ^{18}O depth series, interpolated at equal depth steps of 5 cm, and adjusted to seawater equilibrium values by adding 0.64 permil. (**B**) Wavelet spectrum of benthic δ^{18}O depth series, obtained using software from (*S7*). The cross-hatched area marks the "cone-of-influence, where results are affected by edge effects. The white lines mark the predicted position of astronomical frequency traces, using a 9-degree smoothed polynomial fitted to our final age model. The white shading, around the white lines, marks the area of uncertainty caused by astronomical signal variations, and shorter term fluctuations in sedimentation rate. (**C**) Benthic δ^{13}C depth series, interpolated at equal depth steps of 5 cm. (**D**) Wavelet spectrum of benthic δ^{13}C depth series, as in (**B**). (**E**) Wavelet spectrum of astronomical ETP curve, after depth-scaling the ages back to depth by using the smoothed age model. This graph shows what a pure astronomical signal would look like if it had been deposited in sedimentary layers according to our age model.
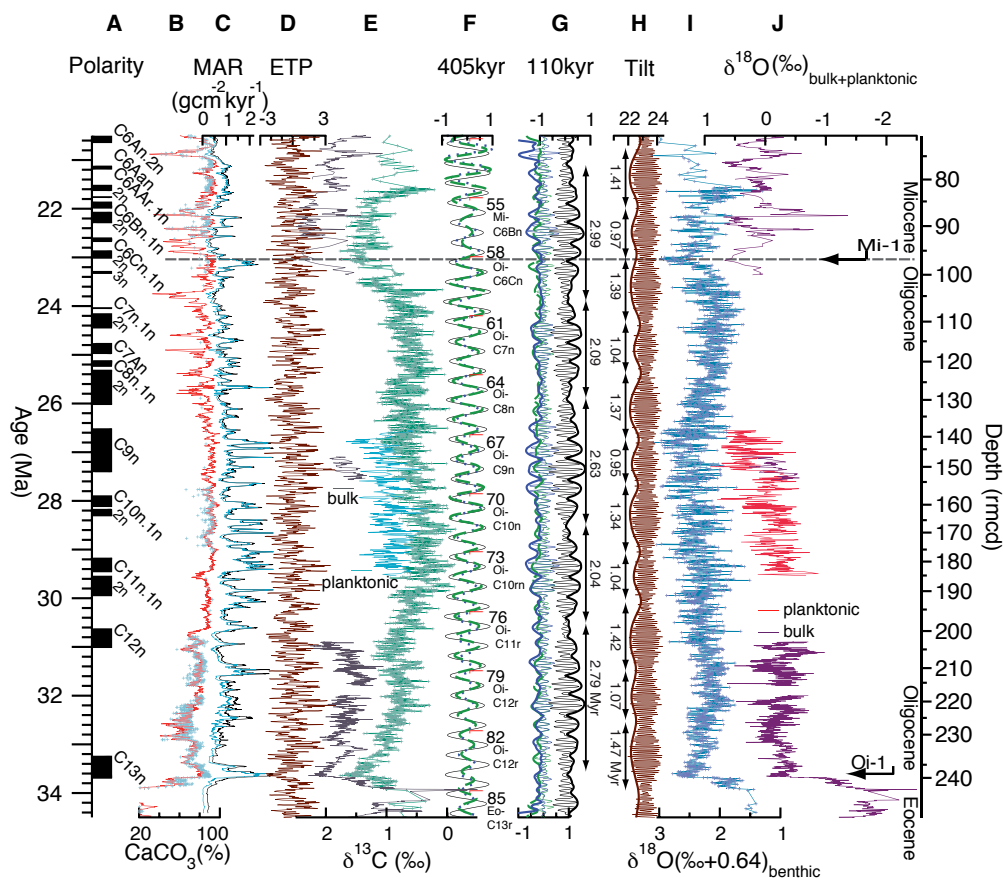
Web Fig. S 2: Pacific Oligocene data from ODP Site 1218. **(A)** Astronomically age calibrated magnetic polarity record for Leg 199, based on (*S2, S11, S27*). **(B)** Measured (data points) and calculated (continuous line) calcium carbonate content for Site 1218. **(C)** Mass and carbonate accumulation rates. **(D)** Calculated mix of eccentricity, obliquity (tilt), and climatic precession ("ETP"), using (*S4*). **(E)** Benthic (continuous line), bulk and planktonic carbon isotope (*S28*) measurements from Site 1218. **(F)** Band-pass filtering as in main manuscript to extract the 405 kyr eccentricity component from astronomical eccentricity (solid line), benthic inverted δ^{13}C (dashed), and benthic inverted δ^{18}O isotopes (dotted). Also marked are absolute 405 kyr eccentricity cycle numbers, counted from the present, according to a new naming scheme (*S28*). **(G)** Short eccentricity (9±3 Myr^{-1}) gaussian band-pass filtering of astronomical data from (*S4*) (black, on right) and stable isotope data: δ^{18}O (blue, solid), δ^{13}C (green, dashed). Also annotated are durations of individual ∼2.4 Myr eccentricity amplitude modulation cycles (in Myr). **(H)** Obliquity, and obliquity amplitude envelope (in degrees) from (*S4*). Also marked are durations of individual ∼1.2 Myr cycles (in Myr). **(I)** Benthic oxygen isotope measurements from foraminiferal calcite, Site 1218. Foraminiferal isotope measurements were adjusted by adding 0.64 per mil (*S29*). **(J)** Oxygen isotope measurements of bulk (fine-fraction) sediment and planktonic foraminifera (*S28*) from Site 1218. "Mi–1" and "Oi–1" isotope events (*S17*) are indicated along the core depth axis. Depth values are "revised meters composite depth" (*S2*).
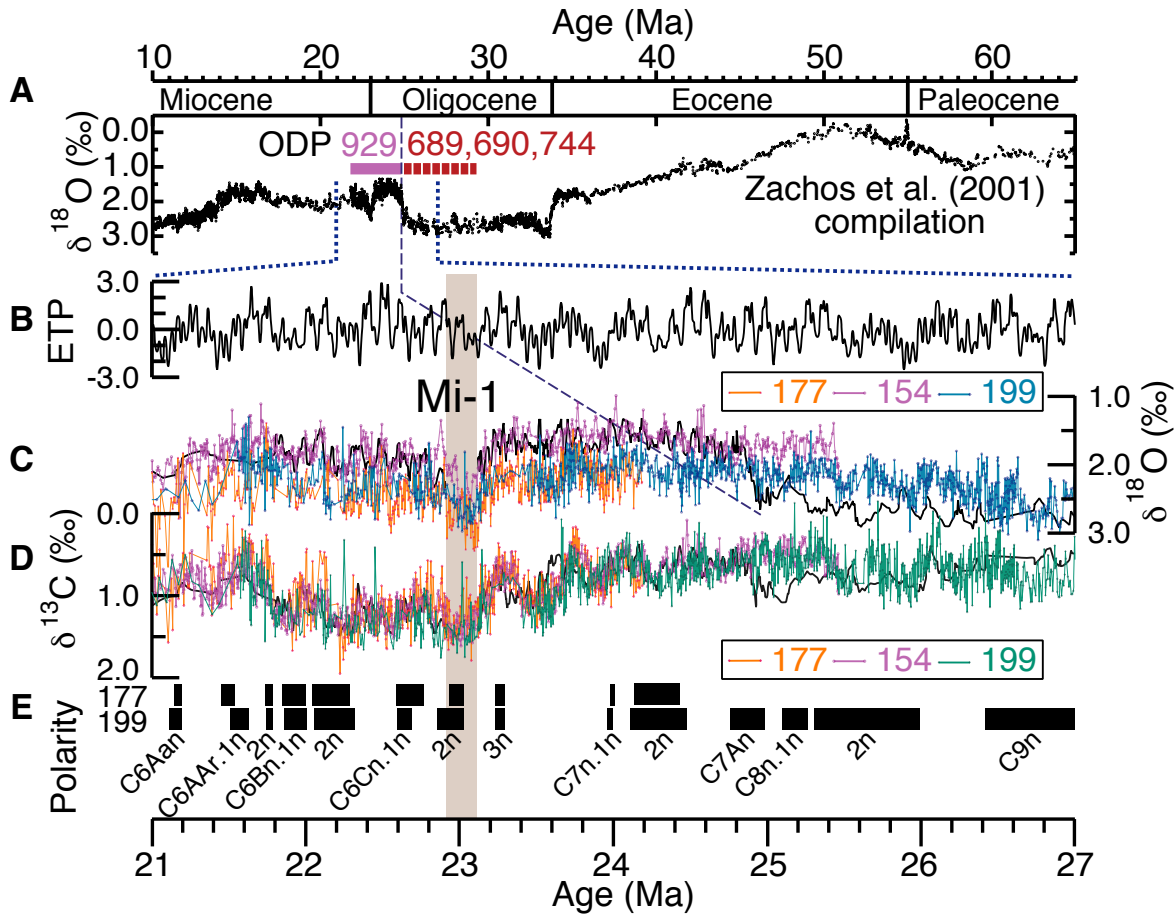
Web Fig. S 3: **(A)** $\delta^{18}O$ time series from previous multi-site compilation (*S17*), with geo-magnetic polarity ages re-scaled to new astronomical solution, late Oligocene interval indicated. **(B)** Eccentricity, tilt, climatic precession (ETP) mix calculated from (*S4*). **(C)** and **(D)** $\delta^{18}O$ and $\delta^{13}C$ data from ODP 199 (this study), ODP 177 (*S6*) (extending to ∼24 Ma), ODP 154 (*S20*) (extending to ∼25.4 Ma), and a 5 point running average from a multi-site compilation (*S17*). All oxygen isotope measurements were adjusted by adding 0.64 per mil (*S29*). Records from 199, 177, and 154 are independently astronomically age calibrated; the multi-site compilation was re-adjusted using magnetic reversal ages from this study. The $\delta^{18}O$ jump in the compilation at around 24.8 Ma results from a switch of the site composite from Leg 154 data for ages younger than ∼ 24.8 Ma to high-latitude ODP Sites 744, 689 and 690 for older ages, verified by the continuation of the Leg 154 $\delta^{18}O$ data at around 1.8 per mil. **(E)** Independently age calibrated magnetostratigraphies from ODP 177 (*S6*) and this study.

Web Table S 1: Magnetic reversal age calibration, ODP Site 1218

Chron	rmcd (meters)	CK95 Age[1] (Ma)	Neogene Age [2] (Ma)	Age (man.) (Ma)	Age (auto) (Ma)
T_C1n	0.00	0.000	0.000	0.000	0.000
B_C1n	3.55	0.780	0.781	0.781	0.781
T_C1r.1n	4.60	0.990	0.988	0.988	0.988
B_C1r.1n	4.90	1.070	1.072	1.072	1.072
T_C2n	7.79	1.770	1.778	1.778	1.778
T_C3n.1n	18.98	4.180	4.187	4.187	4.187
B_C3n.1n	19.44	4.290	4.300	4.300	4.300
T_C3n.2n	20.29	4.480	4.493	4.493	4.493
B_C3n.2n	20.50	4.620	4.631	4.631	4.631
T_C3n.3n	20.83	4.800	4.799	4.799	4.799
B_C3n.3n	21.01	4.890	4.896	4.896	4.896
T_C3n.4n	21.23	4.980	4.997	4.997	4.997
B_C3n.4n	21.64	5.230	5.235	5.235	5.235
T_C3An.1n	23.50	5.894	6.033	6.033	6.033
B_C3An.1n	24.23	6.137	6.252	6.252	6.252
T_C3An.2n	24.77	6.269	6.436	6.436	6.436
B_C3An.2n	25.80	6.567	6.733	6.733	6.733
T_C3Bn	27.04	6.935	7.140	7.140	7.140
B_C3Bn	27.27	7.091	7.212	7.212	7.212
T_C3Br.1n	27.31	7.135	7.251	7.251	7.251
B_C3Br.1n	27.44	7.170	7.285	7.285	7.285
T_C3Br.2n	27.92	7.341	7.454	7.454	7.454
B_C4n.1n	28.81	7.562	7.642	7.642	7.642
T_C4n.2n	28.98	7.650	7.695	7.695	7.695
B_C4n.2n	30.49	8.072	8.108	8.108	8.108
T_C4r.1n	30.73	8.225	8.254	8.254	8.254
B_C4r.1n	30.76	8.257	8.300	8.300	8.300
T_C4An	31.96	8.699	8.769	8.769	8.769
B_C4An	32.89	9.025	9.098	9.098	9.098
T_C4Ar.1n	33.21	9.230	9.312	9.312	9.312
B_C4Ar.1n	33.48	9.308	9.409	9.409	9.409
T_C4Ar.2n	34.01	9.580	9.656	9.656	9.656

[1] (*S26*)

[2] (*S30*)

Web Table S 1: (continued) Magnetic reversal age calibration, ODP Site 1218

Chron	rmcd (meters)	CK95 Age[1] (Ma)	Neogene Age [2] (Ma)	Age (man.) (Ma)	Age (auto) (Ma)
B_C4Ar.2n	34.24	9.642	9.717	9.717	9.717
T_C5n.1n	34.35	9.740	9.779	9.779	9.779
B_C5n.2n	36.52	10.949	11.040	11.040	11.041
T_C5r.1n	36.67	11.052	11.118	11.118	11.119
B_C5r.1n	36.77	11.099	11.154	11.154	11.155
T_C5r.2n	37.82	11.476	11.554	11.554	11.555
B_C5r.2n	38.07	11.531	11.614	11.614	11.615
T_C5An.1n	38.97	11.935	12.014	12.014	12.015
B_C5An.1n	39.33	12.078	12.116	12.116	12.117
T_C5An.2n	39.67	12.184	12.207	12.207	12.208
B_C5An.2n	40.19	12.401	12.415	12.415	12.416
T_C5Ar.1n	41.22	12.678	12.730	12.730	12.731
B_C5Ar.1n	41.38	12.708	12.765	12.765	12.766
T_C5Ar.2n	41.66	12.775	12.820	12.820	12.821
B_C5Ar.2n	41.85	12.819	12.878	12.878	12.879
T_C5AAn	42.30	12.991	13.015	13.015	13.016
B_C5AAn	42.77	13.139	13.183	13.183	13.184
T_C5ABn	43.23	13.302	13.369	13.369	13.370
B_C5ABn	43.95	13.510	13.605	13.605	13.606
T_C5ACn	44.29	13.703	13.734	13.734	13.735
B_C5ACn	44.99	14.076	14.095	14.095	14.096
T_C5ADn	45.11	14.178	14.194	14.194	14.195
B_C5ADn	46.16	14.612	14.581	14.581	14.582
T_C5Bn.1n	46.64	14.800	14.784	14.784	14.785
B_C5Bn.1n	46.85	14.888	14.877	14.877	14.878
T_C5Bn.2n	47.20	15.034	15.032	15.032	15.033
B_C5Bn.2n	47.62	15.155	15.160	15.160	15.161
T_C5Cn.1n	51.19	16.014	15.974	15.898	15.899
B_C5Cn.1n	52.34	16.293	16.268	16.161	16.162
T_C5Cn.2n	52.38	16.327	16.303	16.255	16.256
B_C5Cn.2n	52.55	16.488	16.472	16.318	16.319
T_C5Cn.3n	52.95	16.556	16.543	16.405	16.406
B_C5Cn.3n	53.29	16.726	16.721	16.498	16.499
T_C5Dn	55.22	17.277	17.235	17.003	17.004
B_C5Dn	55.94	17.615	17.533	17.327	17.328
T_C5Dr.1n	56.50	17.825	17.717	17.511	17.512
B_C5Dr.1n	56.54	17.853	17.740	17.550	17.551

Web Table S 1: (continued) Magnetic reversal age calibration, ODP Site 1218

Chron	rmcd (meters)	CK95 Age[1] (Ma)	Neogene Age [2] (Ma)	Age (man.) (Ma)	Age (auto) (Ma)
T_C5En	57.40	18.281	18.056	17.947	17.948
B_C5En	58.91	18.781	18.524	18.431	18.432
T_C6n	59.35	19.048	18.748	18.615	18.616
B_C6n	66.76	20.131	19.722	19.598	19.599
T_C6An.1n	69.30	20.518	20.040	20.000	20.001
B_C6An.1n	70.25	20.725	20.213	20.226	20.227
T_C6An.2n	71.43	20.996	20.439	20.425	20.425
B_C6An.2n	73.16	21.320	20.709	20.651	20.652
T_C6AAn	76.71	21.768	21.083	21.114	21.114
B_C6AAn	77.68	21.859	21.159	21.196	21.197
T_C6AAr.1n	81.20	22.151	21.403	21.506	21.507
B_C6AAr.1n	82.57	22.248	21.483	21.627	21.636
T_C6AAr.2n	83.89	22.459	21.659	21.744	21.743
B_C6AAr.2n	84.31	22.493	21.688	21.783	21.780
T_C6Bn.1n	85.05	22.588	21.767	21.861	21.853
B_C6Bn.1n	86.34	22.750	21.936	22.010	21.998
T_C6Bn.2n	86.74	22.804	21.992	22.056	22.062
B_C6Bn.2n	89.48	23.069	22.268	22.318	22.299
T_C6Cn.1n	92.49	23.353	22.564	22.595	22.588
B_C6Cn.1n	93.37	23.535	22.754	22.689	22.685
T_C6Cn.2n	94.91	23.677	22.902	22.852	22.854
B_C6Cn.2n	96.20	23.800	23.030	23.024	23.026
T_C6Cn.3n	98.80	23.999		23.233	23.278
B_C6Cn.3n	99.62	24.118		23.295	23.340
T_C7n.1n	106.87	24.730		23.962	24.022
B_C7n.1n	107.21	24.781		24.000	24.062
T_C7n.2n	108.17	24.835		24.109	24.147
B_C7n.2n	111.67	25.183		24.474	24.459
T_C7An	115.49	25.496		24.761	24.756
B_C7An	117.88	25.648		24.984	24.984
T_C8n.1n	119.49	25.823		25.099	25.110
B_C8n.1n	121.78	25.951		25.264	25.248
T_C8n.2n	122.34	25.992		25.304	25.306
B_C8n.2n	131.26	26.554		25.987	26.032
T_C9n	137.70	27.027		26.420	26.508
B_C9n	151.77	27.972		27.439	27.412
T_C10n.1n	157.89	28.283		27.859	27.886

Web Table S 1: (continued) Magnetic reversal age calibration, ODP Site 1218

Chron		rmcd (meters)	CK95 Age[1] (Ma)	Neogene Age [2] (Ma)	Age (man.) (Ma)	Age (auto) (Ma)
B_C10n.1n		161.29	28.512		28.087	28.126
T_C10n.2n		162.17	28.578		28.141	28.164
B_C10n.2n		164.08	28.745		28.278	28.318
T_C11n.1n		178.45	29.401		29.183	29.166
B_C11n.1n		184.41	29.662		29.477	29.467
T_C11n.2n		185.11	29.765		29.527	29.536
B_C11n.2n		191.42	30.098		29.970	29.957
T_C12n		199.47	30.479		30.591	30.617
B_C12n		204.45	30.939		31.034	31.021
T_C13n		233.88	33.058		33.157	33.232
B_C13n		240.29	33.545		33.705	33.705
E/O(C13r(.14))	interpolated:	241.23	33.700		33.790	33.790
T_C13r.1n?		243.21			34.151	34.151
B_C13r.1n?		243.86			34.285	34.285
T_C15n		246.98	34.655		35.126	35.126
B_C15n		247.52	34.940		35.254	35.254
T_C16n.1n		247.94	35.343		35.328	35.328
B_C16n.1n		249.13	35.526		35.554	35.554
T_C16n.2n		249.45	35.685		35.643	35.643
B_C16n.2n		252.99	36.341		36.355	36.355
T_C17n.1n		254.64	36.618		36.668	36.668
B_C17n.1n		258.40	37.473		37.520	37.520
T_C17n.2n		259.35	37.604		37.656	37.656
B_C17n.2n		260.30	37.848		37.907	37.907
T_C17n.3n		260.57	37.920		37.956	37.956
B_C17n.3n		261.43	38.113		38.159	38.159
T_C18n.1n		262.67	38.426		38.449	38.449
B_C18n.1n		269.97	39.552		39.554	39.554
T_C18n.2n		270.34	39.631		39.602	39.602
B_C18n.2n		273.85	40.130		40.084	40.084
T_C19n		291.08	41.257		41.358	41.358
B_C19n		293.38	41.521		41.510	41.510

[1] (*S26*)
[2] (*S30*)

Web Table S 2: Selected nannofossil datums, ODP Site 1218 (taken from (S2))

	Event (Top, Base)	Depth rmcd	±	Site	H	Top (cm)	Base (cm)	Top (rmcd)	Base (rmcd)	Age (man.) (Ma)	Age (auto) (Ma)
B	*Discoaster kugleri*	40.28	0.16	1218	B	5H-2, 56	5H-2, 88	40.12	40.44	12.444	12.444
B	*Catinaster coalitus*	41.33	0.43	1218	A	4H-7, 50	4H-CC	40.90	41.75	12.753	12.754
T	*Cyclicargolithus floridanus*	48.07	0.32	1218	B	5H-7, 45	5H-CC	47.75	48.38	15.252	15.253
T	*Sphenolithus heteromorphus*	50.93	0.28	1218	A	5H-7, 15	5H-CC	50.65	51.20	15.843	15.844
T	*Discoaster deflandrei acme*	50.93	0.28	1218	A	5H-7, 15	5H-CC	50.65	51.20	15.843	15.844
T	*Triquetrorhabdulus carinatus*	63.63	1.28	1218	A	6H-CC	7H-1, 120	62.35	64.91	19.183	19.184
T	*Triquetrorhabdulus carinatus acme*	87.51	0.25	1218	A	9H-2, 80	9H-2, 130	87.26	87.76	22.132	22.159
B	*Sphenolithus disbelemnos*	90.51	0.25	1218	A	9H-4, 80	9H-4, 130	90.26	90.76	22.413	22.411
B	*Discoaster druggii*	92.46	0.20	1218	A	9H-5, 130	9H-6, 20	92.26	92.66	22.592	22.585
T	*Sphenolithus delphix*	97.00	0.40	1218	B	10H-4, 140	10H-5, 70	96.60	97.40	23.089	23.079
T	*Sphenolithus delphix*	97.55	0.11	1218	A	10H-1, 140	10H-2, 10	97.44	97.65	23.133	23.141
B	*Sphenolithus delphix*	99.25	0.35	1218	B	10H-6, 70	10H6, 140	98.90	99.60	23.267	23.312
B	*Sphenolithus delphix*	100.40	0.10	1218	A	10H-3, 120	10H-3, 140	100.30	100.50	23.356	23.371
B	*Sphenolithus ciperoensis*	110.33	0.75	1218	B	11H-5, 80	11H-6, 80	109.58	111.08	24.357	24.357
T	*Sphenolithus ciperoensis*	110.56	0.71	1218	A	11H-2, 130	11H-3, 130	109.85	111.27	24.383	24.371
T	*Cyclicargolithus abisectus acme*	113.19	0.29	1218	A	11H-4, 130	11H-5, 38	112.90	113.48	24.596	24.596
T	*Sphenolithus distentus*	131.99	0.57	1218	A	13H-3, 75	13H-4, 45	131.42	132.56	26.033	26.070
T	*Dictyococcites bisectus*	132.53	0.34	1218	B	13H-6, 80	13H-6, 148	132.19	132.87	26.067	26.101
B	*Sphenolithus distentus*	132.54	0.15	1218	B	13H-6, 100	13H-6, 130	132.39	132.69	26.068	26.101
B	*Sphenolithus ciperoensis*	145.17	0.75	1218	A	14H-5, 80	14H-6, 80	144.42	145.92	26.983	26.948
B	*Sphenolithus ciperoensis*	146.32	0.10	1218	B	15H-1, 100	15H-1, 120	146.22	146.42	27.067	27.048
B	*Sphenolithus distentus*	190.58	0.70	1218	A	18H-CC	19H-1, 120	189.87	191.28	29.910	29.892
T	*Reticulofenestra umbilicus* ≥14μm	220.85	0.38	1218	A	22X-2, 70	22X-2, 147	220.47	221.23	32.167	32.180
T	*Ericsonia formosa*	231.91	0.19	1218	A	23X-2, 148	23X-3, 35	231.72	232.09	32.968	32.975
T	*Discoaster saipanensis*	244.57	0.06	1218	A	24X-4, 78	24X-4, 90	244.51	244.62	34.430	34.430
T	*Discoaster barbadiensis*	245.79	0.13	1218	A	24X-5, 56	24X-5, 85	245.66	245.91	34.740	34.740
T	*Chiasmolithus grandis*	260.27	0.21	1218	A	25X-7, 70	25X-CC	260.06	260.48	37.900	37.900
B	*Dictyococcites bisectus*	268.01	1.04	1218	A	26X-5, 60	26X-6, 125	266.97	269.05	39.201	39.201
T	*Chiasmolithus solitus*	277.82	1.58	1218	A	27X-CC	28X-1, 50	276.24	279.40	40.658	40.658
T	*Nannotetrina spp.*	298.78	0.31	1218	A	30X-2, 90	30X-3, 2	298.47	299.09	42.647	42.647

The following section contains a detailed description of the "Model A" that we use in our study.
The model is a modified version of that originally published by Zachos and Kump (2005).
The main modification to the model as used in our study is that orbital forcing
terms are explicitly included. We used an Euler integration method, with
a time step of 50 yrs. Data were recorded every 2.5 kyr.

Welch transferfunction from white noise input to d13C output

Frequency (1/Myr)

Welch transferfunction

$y = 15.838x^{-0.9431}$
$R^2 = 0.9991$

$\delta^{13}C$ model output power
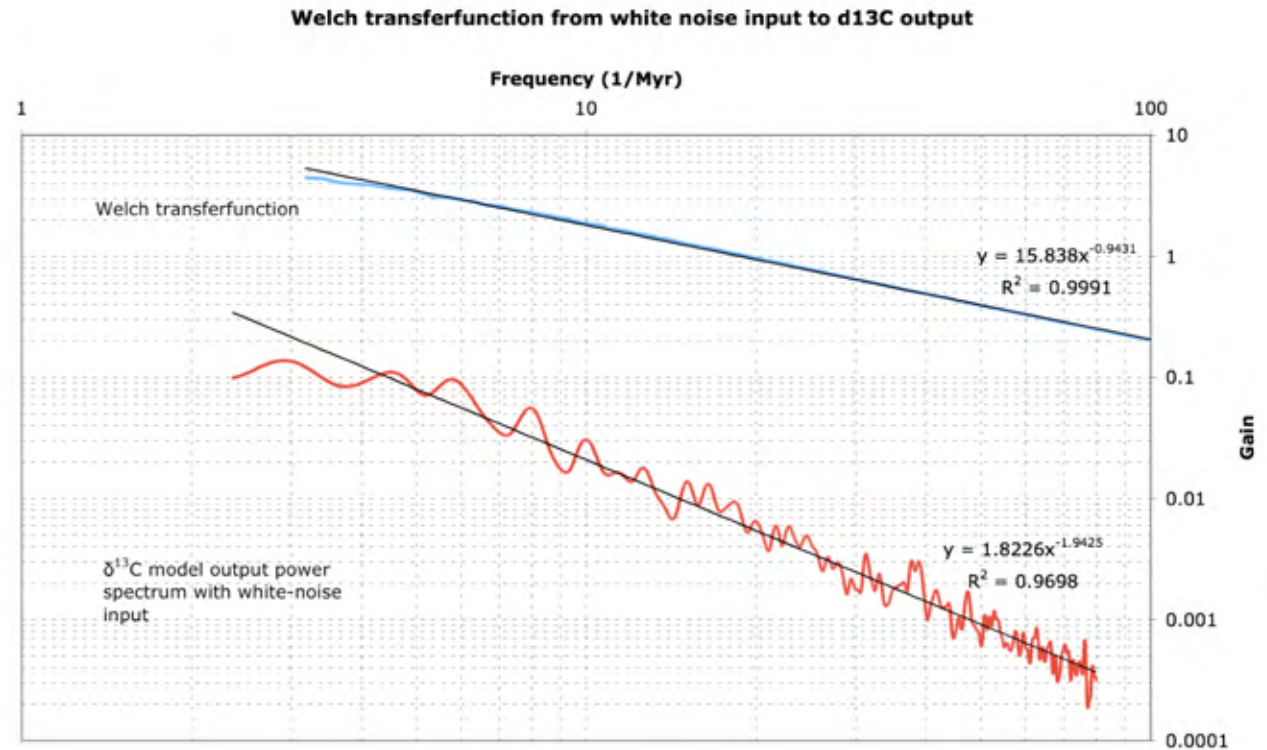spectrum with white-noise
input

$y = 1.8226x^{-1.9425}$
$R^2 = 0.9698$

Gain

Figure 1: Transfer function for Model A, from white (flat) noise input to d13C output

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.	(mol yr^-1)	Prod =	Circ*deepPO4/P0*2e10*(1-orbitetp/4)	"Productivity"
				flux of organic phosphorous from the euphotic
				zone to the deep ocean
VARI.	(-)	Circ =	if ice_volume>50 then 1 else 0.9	"ocean circulation" proxy: lower when less ice
COMP.	(mol)	deepPO4	Init.Val.=P0; d/dt=Riv-inorgSink-burial	average deep ocean phosphate content
FLOW	(mol yr^-1)	Riv =	4e10* tectonism *ClimWeathFac/0.9	Riverine P delivery rate
FLOW	(mol yr^-1)	inorgSink =	1e10*deepPO4/P0	inorganic P burial
FLOW	(mol yr^-1)	burial =	burialfrac*Prod*100	organic P burial rate
VARI.	(mol)	P0 =	2.09E+15	Initial value for deepPO4
VARI.		burialfrac =	0.01	fraction of "rain" that is not re-mineralised
VARI.	(-)	orbitetp	synthetic orbital forcing (Laskar et al. (2004)):	
			eccentricity (E), obliquity=tilt (T), and climatic precession (P)	
			E, T and P are first normalised by subtracting mean and dividing	
			by standard deviation for time period 0–40 Ma.	
			E:T:P are then added in amplitude ratios of ~1:2:0.75, and with	
			a phase lag of ~7kyr for obliquity.	
			The resulting curve is again normalised, and sampled every 2kyr.	
COMP.	(mol)	TCO2	Init.Val.=4E18;d/dt=Fworg+volcanism-Fwsil-Fborg	Total dissolved carbon reservoir
FLOW	(mol yr^-1)	Fworg	10e12*ClimWeathFac* tectonism /0.9	org. C weathering flux
FLOW	(mol yr^-1)	Fwsil =	6e12*ClimWeathFac*tectonism*exposed_area/0.9	silicate weathering flux
FLOW	(mol yr^-1)	Fborg =	burial*500	organic carbon burial rate coupled to P burial
FLOW	(mol yr^-1)	volcanism =	step decreases from 6.32E12 prior to 36.3Ma to 5.75E+12 to simulate pCO2 drawdown in late Eocene	
VARI.	(-)	ClimWeathFac =	(pCO2/280)^0.5	Weathering relationship with atm. pCO2
VARI.	(mol yr^-1)	Fwcarb =	40e12*tectonism*ClimWeathFac/0.9	carbonate weathering
VARI.	(-)	tectonism=	0.632	tectonic forcing of continental weatherability
VARI.	(-)	exposed_area =	1-0.1*ice_volume/100	fraction of exposed area available for weathering
VARI.	(ppm)	pCO2 =	((TCO2/4E18)^0.5)*280	atm. pCO2 calculated from dissolved carbon
COMP.	(%)	ice_volume	Init.Val.=50;d/dt=Growth-Ablation	Ice volume, 100 scaled to present day Antarctica
FLOW	(% yr^-1)	Ablation =	ablation_rate/100/1000*ice_volume	Ice ablation, Growth rate (f(Temp))
FLOW	(% yr^-1)	Growth =	if ice_volume<150 then (growth_rate)/1000 else 0	Ice volume, 100 scaled to present day Antarctica
VARI.		ablation_rate =	graph(temp)	
			(K,rate) {273.0,5.0; 278,0.0; 283,0.0; 288,0.0; 293,5.0; 298,10.0}	
VARI.		growth_rate =	graph(temp)	
			(Temp in K, rate) {273.0,5.0; 278,0.0; 283,10.0; 288,0.0; 293,0.0; 298,0.0}	

VARI.	(permil)	del18O =	-1+ice_volume/100	d18O of sea water
VARI.	(permil)	d18Ocarb =	(temp-7-273-16.9)/-4+del18O	calculated d18O in carbonate
VARI.	(-)	fixedalbedo =	0.3	nominal fixed albedo, used in Zachos & Kump 2005
VARI.	(Kelvin)	temp =	(288.5+(log10(pCO2/280))*10)*((1-fixedalbedo)/0.7)^0.25+orbitetp/2	
COMP.	(permil)	del13Ci	Init.Val.=1;d/dt=Fwdelw-Fborgdelorg	global average d13C composition
FLOW	(permil yr^-1)	Fwdelw =	(Fwcarb*(delcarbw-del13Ci)+	
			Fworg*(delorgw-del13Ci)+	
			volcanism*(-5-del13Ci))/TCO2	
FLOW	(permil yr^-1)	Fborgdelorg =	Fborg*bigdelta/TCO2	
VARI.	(permil)	bigdelta =	-25	difference betw. Organic and carbonate flux from oc.
VARI.	(permil)	delcarbw =	0.6	assumed isotopic comp. of carbonate
VARI.	(permil)	delorg =	del13Ci+bigdelta	isotopic composition or organic matter
VARI.	(permil)	delorgw =	-25	

The following section contains a detailed description of the "Model B" that we use in our study.
The model is a modified version of that originally published by Walker and Kasting (1992),
with an added simple ice-volume component taken from Zachos and Kump (2005).
The main modification to the model as used in our study is that orbital forcing
terms are explicitly included.

The overall model topology is represented
in Figure 1 on the right, and consists of
separate boxes for the three deep oceans,
the thermocline, two surface reservoirs,
the atmospere and a very simple biosphere.

The model was run using Euler integration, with
time steps of 0.5 yrs (0.1 yrs for the carbon
isotope sub-model). Data were collected every 2.5 kyr.
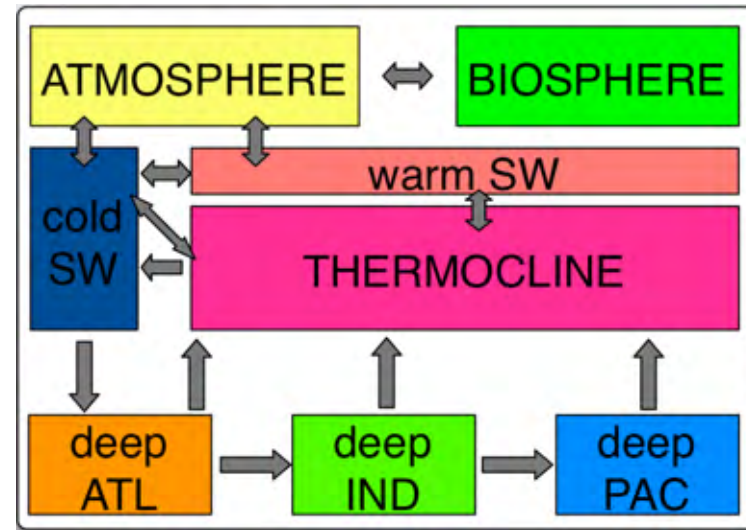
Figure 2: Topology for Model B

The model configuration, including the ice-volume component, and the
astronomical forcing, are shown on Figure 2 on the next page.
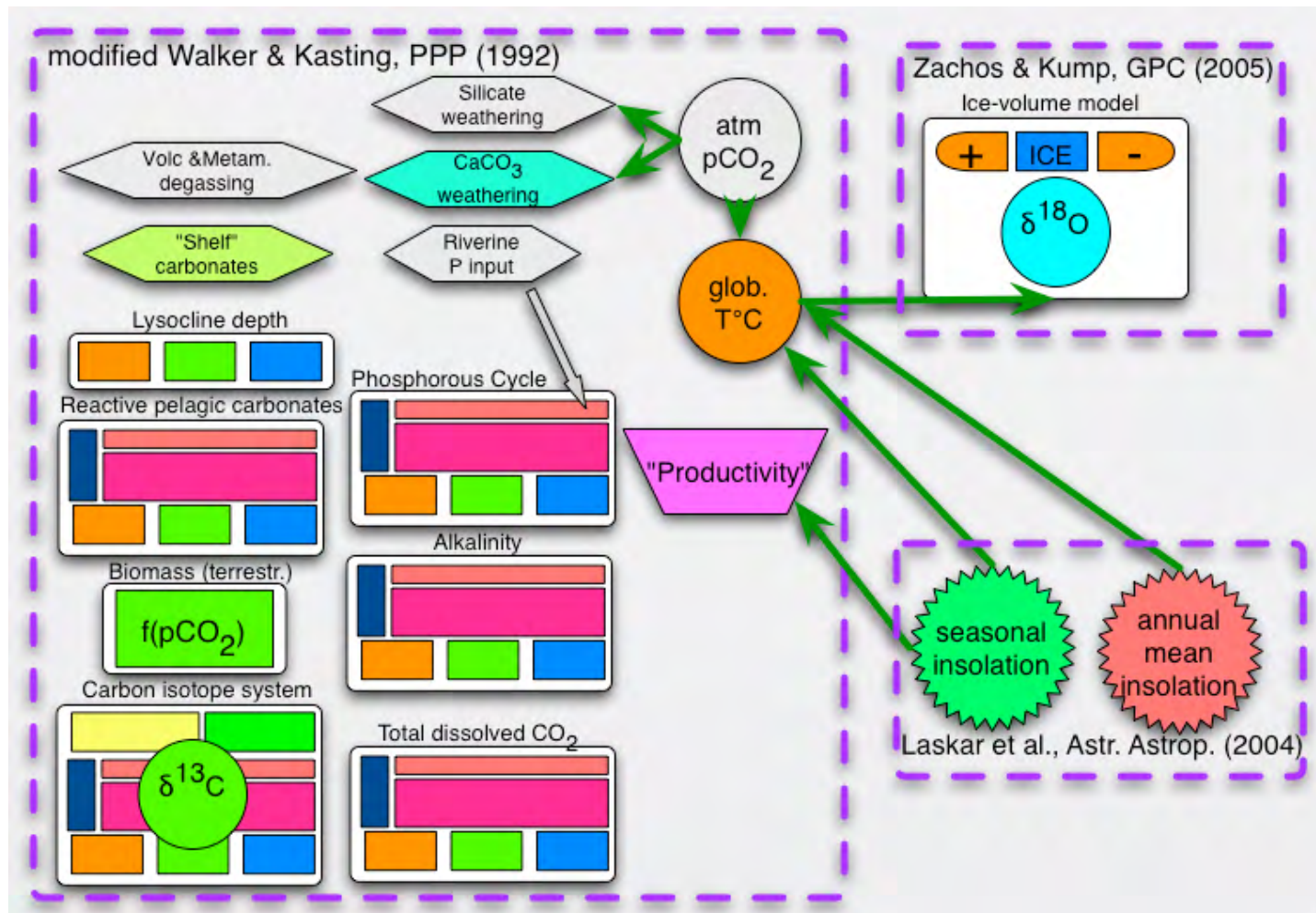
Figure 3: Model B configuration

Welch transferfunction from white noise input to d13C output

Frequency (1/Myr)

Welch transferfunction

$y = 5.0859x^{-0.5642}$

$R^2 = 0.9515$

$\delta^{13}C$ model output power spectrum with white-noise input

$y = 0.0527x^{-1.245}$

$R^2 = 0.9496$

Gain
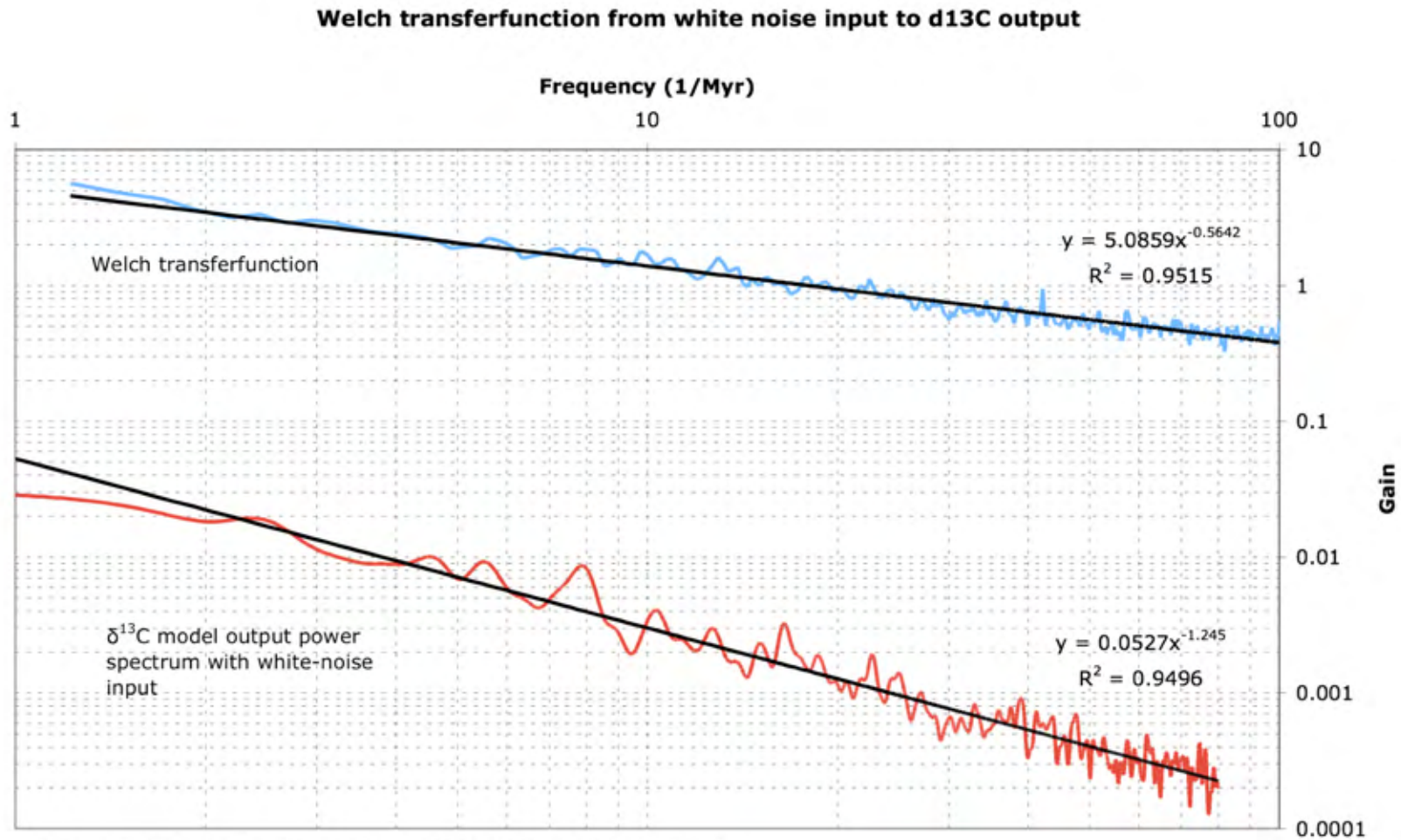
Figure 4: Transfer function response of Model B to white (flat) noise

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.	(-)	ClimWeathFact =	pco2^0.5	
		Where:	pco2=CO2/pco2	
		Comment:	Weathering Factor á la Zachos & Kump (2005)	
VARI.	(-)	orbit_factor =	0.05	Scaling factor
VARI.	(-)	orbit_polarity =	-25	Scaling factor
VARI.		normJunLul65Ninsol =	Laskar et al. (2004) June July insolation 65°N, normalised by subtracting mean and dividing by standard deviation, sampled every 2kyr	
VARI.	(-)	orbittemp_factor =	2	Scaling factor
VARI.		orbittest =	normJunLul65Ninsol*orbit_factor	
VARI.	(-)	riv_factor =	1	Scaling factor
VARI.	(-)	riv_switch =	0	Astr. Forcing on run-off (switch, 0=off)
VARI.	(m^3 yr^-1)	rivflux =	3.97E+13	Global runoff per year
VARI.	(mmol yr^-1)	rivp =	rivflux* 1.0*riv_factor*ClimWeathFact	Global phosphorous in runoff per year (adjusted)
VARI.	(m^3 yr^1)	shphos =	3.97e13/0.1*shphos_factor	Factor for flux of phosphorous into shelf sediments
VARI.	(-)	shphos_factor =	1	Scaling factor
VARI.	(-)	shphos_switch =	1	Astr. Forcing on shelf carbonates (switch, 1=on)
VARI.	(-)	tcpfrac =	0.925	Fraction of decay in the thermocline reservoir

Submodel Fluxes

VARI.	(m^2)	ocarea =	3.62E+14	Total ocean surface area
VARI.	(m^3)	ocvol =	1.35E+18	Total ocean volume
VARI.	(-)	careafr =	0.0025	fraction of surface that is "cold surface water" box
VARI.	(m^2)	adarea =	8.49E+13	Atlantic Ocean surface area
VARI.	(m^2)	idarea =	6.89E+13	Indian Ocean surface area
VARI.	(m^2)	pdarea =	1.65E+14	Pacific Ocean surface area
VARI.	(m^2)	darea =	1.0*adarea+1.0*idarea+1.0*pdarea 3.19E+14	Total area of deep oceans
VARI.	(m^3 yr^-1)	fadid =	fcsad-fadtc	Advected flux Atlantic->Indian
VARI.	(m^3 yr^-1)	fadtc =	adarea*uv/1	Advected flux Atlantic->Thermocline
VARI.	(m^3 yr^-1)	fcsad =	ftccs	Advected flux Cold Surface->Atlantic
VARI.	(m^3 yr^-1)	fidpd =	fadid-fidtc	Advected flux Indian->Pacific
VARI.	(m^3 yr^-1)	fidtc =	idarea*uv/1.0	Advected flux Indian->Thermocline
VARI.	(m^3 yr^-1)	fpdtc =	fidpd	Advected flux Pacific->Thermocline
VARI.	(m^3 yr^-1)	ftccs =	darea*uv/1	Advected flux Thermocline->Cold Surface
VARI.	(mol yr^-1)	tcdecay =	prod*tcpfrac	Return of particulates into dissolved form in thermocline (in carbon units)
		Where:	tcpfrac= ../tcpfrac	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.	(mol yr^-1)	addecay =	prod*(1-tcpfrac)*adarea/darea	Return of particulates into dissolved form in Atlantic
		Where:	tcpfrac= ../tcpfrac	
VARI.	(mol yr^-1)	iddecay =	prod*(1-tcpfrac)*idarea/darea	Return of particulates into dissolved form in Indian
		Where:	tcpfrac= ../tcpfrac	
VARI.	(mol yr^-1)	pddecay =	prod*(1-tcpfrac)*pdarea/darea	Return of particulates into dissolved form in Pacific
		Where:	tcpfrac= ../tcpfrac	
VARI.	(m^3 yr^-1)	mtcad =	adarea*uv	Mixing Atlantic<->Thermocline
VARI.	(m^3 yr^-1)	mtcid =	idarea*uv	Mixing Indian<->Thermocline
VARI.	(m^3 yr^-1)	mtcpd =	pdarea*uv	Mixing Pacific<->Thermocline
VARI.	(m^3 yr^-1)	mtccs =	vtc/tcmt	Mixing Cold Surface<->Thermocline
VARI.	(m^3 yr^-1)	mtcws =	ocarea*(1-careafr)*vmv/1.0	Mixing Warm Surface<->Thermocline
VARI.	(m^3 yr^-1)	mwscs =	vws/swmt	Mixing Warm Surface<->Cold Surface
VARI.	(mol yr^-1)	prod =	((mwscs*(pcs-pws)+mtcws*(ptc-pws)+ rivp*(1+orbittest*orbit_polarity*riv_switch)- shphos*pws*(1+orbittest*orbit_polarity*shphos_switch))*ctpr)	Downward flux of particulate organic matter ("Productivity")
		Where:	rivp= ../rivp	
			shphos= ../shphos	
			orbit_polarity= ../orbit_polarity	
			riv_switch= ../riv_switch	riv_switch=0: not used
			shphos_switch= ../shphos_switch	
			ptc= ../Phosphate/ptc	
			pcs= ../Phosphate/pcs	
			pws= ../Phosphate/pws	
			ctpr= ../Phosphate/ctpr	
			orbittest= ../orbittest	
VARI.	(yr)	swmt =	50	Surface water mixing time
VARI.	(yr)	tcmt =	250	Thermocline mixing time
VARI.	(m yr^-1)	uv =	1.15	Upwelling velocity
VARI.	(m^3)	vad =	2.57E+17	Atlantic deep volume
VARI.	(m^3)	vcs =	ocarea*careafr*1000	Cold surface volume
VARI.	(m^3)	vid =	2.13E+17	Indian deep volume
VARI.	(m yr^-1)	vmv =	10.5	Vertical mixing velocity
VARI.	(m^3)	vpd =	5.42E+17	Pacific deep volume
VARI.	(m^3)	vtc =	ocvol-vws-vad-vid-vpd-vcs	Thermocline volume
VARI.	(m^3)	vws =	ocarea*(1-careafr)*75	Warm surface volume (75m thick)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
Submodel Ice_model				
COMP.	(%)	ice_volume	Init. Val.= ice0; d/dt = + Growth - Ablation	Ice volume, 100 scaled to present
				Ice volume expressed in percent: 100 = modern
FLOW	(% yr^-1)	Ablation =	if (ice_switch!=0) then ablation_rate/1000*ice_volume/100 else 0	
				Ablation rate (f(Temp))
FLOW	(% yr^-1)	Growth =	if (ice_volume<150 and ice_switch!=0) then (growth_rate)/1000 else 0	
				Growth rate (f(Temp))
VARI.		ablation_rate =	graph(temp)	
			(K,rate) {273.0,5.0; 278,0.0; 283,0.0; 288,0.0; 293,5.0; 298,10.0}	
		Where:	temp= ../Temperature/tbar	
VARI.	(-)	albedo_0 =	(0.298+0.004*(ice_volume/100))	calculated Albedo (f(ice))
VARI.	(permil)	d18Ocarb =	(80.7142857-sqrt(6513.7959-(16.998-(temp-10-273))/.028))+del18O	
		Where:	temp= ../Temperature/tbar	calculated d18O in carbonate
VARI.	(permil)	del18O =	-1+ice_volume/100	d18O of sea water
VARI.	(-)	exposed_area =	if ((ice_switch!=0)&&(ice_volume<=100)) then (1-0.1*ice_volume/100) else 1	
				fraction of exposed area available for weathering
VARI.	(-)	fixedalbedo =	0.3	nominal fixed albedo (not used)
VARI.		grow-abl =	Growth-Ablation	Net ice volume change (diagnostic)
VARI.		growth_rate =	graph(temp)	
			(K, rate) {273.0,5.0; 278,0.0; 283,10.0; 288,0.0; 293,0.0; 298,0.0}	
		Where:	temp= ../Temperature/tbar	
VARI.	(%)	ice0 =	50	Initial ice volume
VARI.	(-)	ice_switch =	1	Switch (1=on, use ice-model)
VARI.		net_growth_rate =	Growth-ablation_rate	
Submodel Reactive_carbonates				
COMP.	(mol)	acalc	Init. Val.= acalc0; d/dt = + dacalc	Reactive carbonate reservoir (Atlantic)
COMP.	(mol)	icalc	Init. Val.= icalc0; d/dt = + dicalc	Reactive carbonate reservoir (Pacific)
COMP.		pcalc	Init. Val.= pcalc0; d/dt = + dpcalc	
FLOW		dacalc =	(-acdr+alsr)	
FLOW		dicalc =	(-icdr+ilsr)	
FLOW		dpcalc =	(-pcdr+plsr)	
VARI.	(mol yr^-1)	acdr =	acalc/cdt*dissolution_switch	Diss. rate of reactive surface carbonates (Atlantic)
VARI.	(mol yr^-1)	icdr =	icalc/cdt*dissolution_switch	Diss. rate of reactive surface carbonates (Indian)
VARI.	(mol yr^-1)	pcdr =	pcalc/cdt*dissolution_switch	Diss. rate of reactive surface carbonates (Pacific)
VARI.	(mol yr^-1)	alsr =	-6000*dafroa*adarea*dissolution_switch	Addition to reactive carbonate (6000 mol per m^2)
		Where:	adarea= ../Fluxes/adarea	(Ocean area)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			dafroa= ../carbon_chem/dafroa	(Rate of change of fractional area above lysocline)
VARI.		ilsr =	(-6000 m^2 yr^-1)*difroa*idarea*dissolution_switch	
		Where:	idarea= ../Fluxes/idarea	
			difroa= ../carbon_chem/difroa	
VARI.		plsr =	(-6000 m^2 yr^-1)*dpfroa*pdarea*dissolution_switch	
		Where:	pdarea= ../Fluxes/pdarea	
			dpfroa= ../carbon_chem/dpfroa	
VARI.	(yr)	cdt =	10	first order rate carbonate dissolution time
VARI.	(-)	dissolution_switch =	1	Switch (1=on, use carbonate dissolution on sea-floor)
VARI.	(mol)	acalc0 =	0	Initial size of reactive carbonate reservoir
VARI.	(mol)	icalc0 =	0	Initial size of reactive carbonate reservoir
VARI.	(mol)	pcalc0 =	0	Initial size of reactive carbonate reservoir

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(mmol m^-3)	pad	Init. Val.= pad0; d/dt = + dpad	Phosphate concentration in deep Atlantic Ocean
COMP.	(mmol m^-3)	pid	Init. Val.= pid0; d/dt = + dpid	Phosphate concentration in deep Indian Ocean
COMP.	(mmol m^-3)	ppd	Init. Val.= ppd0; d/dt = + dppd	Phosphate concentration in deep Pacific Ocean
COMP.	(mmol m^-3)	ptc	Init. Val.= ptc0; d/dt = + dptc	Phosphate concentration in thermocline
COMP.	(mmol m^-3)	pcs	Init. Val.= pcs0; d/dt = + dpcs	Phosphate concentration in cold surface waters
VARI.	(mmol m^-3)	pws =	ppd*pfp	Phosphate concentration in warm surface waters (fixed to Pacific deep)
FLOW	(mmol m^-3 yr^-1)	dpad =	max((fcsad*pcs-pad*(fadtc+fadid)+ addecay/ctpr)/vad,-pad/dt())	Rate of change of Phosphorous (Atlantic)
		Where:	vad= ../Fluxes/vad	
			fadtc= ../Fluxes/fadtc	
			fcsad= ../Fluxes/fcsad	
			fadid= ../Fluxes/fadid	
			addecay= ../Fluxes/addecay	
FLOW	(mmol m^-3 yr^-1)	dpid =	max((fadid*pad-pid*(fidtc+fidpd)+ iddecay/ctpr)/vid,-pid/dt())	Rate of change of Phosphorous (Indian)
		Where:	vid= ../Fluxes/vid	
			fidtc= ../Fluxes/fidtc	
			fadid= ../Fluxes/fadid	
			fidpd= ../Fluxes/fidpd	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			iddecay= ../Fluxes/iddecay	
FLOW	(mmol m^-3 yr^-1)	dppd =	max((fidpd*pid-ppd*fpdtc+	Rate of change of Phosphorous (Pacific)
			pddecay/ctpr)/vpd,-ppd/dt())	
		Where:	vpd= ../Fluxes/vpd	
			fpdtc= ../Fluxes/fpdtc	
			fidpd= ../Fluxes/fidpd	
			pddecay= ../Fluxes/pddecay	
FLOW	(mmol m^-3 yr^-1)	dptc =	max((fadtc*pad+fidtc*pid+	Rate of change of Phosphorous (thermocline)
			fpdtc*ppd-ftccs*ptc+	
			mtccs*(pcs-ptc)+	
			mtcws*(pws-ptc)+tcdecay/ctpr)/vtc,-ptc/dt())	
		Where:	ftccs= ../Fluxes/ftccs	
			mtccs= ../Fluxes/mtccs	
			vtc= ../Fluxes/vtc	
			fadtc= ../Fluxes/fadtc	
			fidtc= ../Fluxes/fidtc	
			fpdtc= ../Fluxes/fpdtc	
			mtcws= ../Fluxes/mtcws	
			tcdecay= ../Fluxes/tcdecay	
FLOW	(mmol m^-3 yr^-1)	dpcs =	max((ftccs*ptc-fcsad*pcs+	Rate of change of Phosphorous (cold surface waters)
			mwscs*(pws-pcs)+	
			mtccs*(ptc-pcs))/vcs,-pcs/dt())	
		Where:	mwscs= ../Fluxes/mwscs	
			ftccs= ../Fluxes/ftccs	
			mtccs= ../Fluxes/mtccs	
			vcs= ../Fluxes/vcs	
			fcsad= ../Fluxes/fcsad	
VARI.		ctpr =	0.12	Ratio of carbon to phosphorus in particulates/1000
VARI.	(mmol m^-3)	pad0 =	1.2222	Init. val. of phosporous concentration in Atlantic
VARI.	(mmol m^-3)	pid0 =	1.5129	Init. val. of phosporous concentration in Indian
VARI.	(mmol m^-3)	ppd0 =	2.5	Init. val. of phosporous concentration in Pacific
VARI.	(mmol m^-3)	pcs0 =	0.9594	Init. val. of phosporous conc. in cold surf. waters
VARI.	(mmol m^-3)	ptc0 =	1.2498	Init. val. of phosporous concentration in thermocline

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.	(-)	pfp =	0.04	Fraction of phosphorous in warm surface water compared to deep Pacific Ocean
VARI.	(mmol)	totP =	pcs*vcs+pws*vws+ptc*vtc+ pad*vad+pid*vid+ppd*vpd	Total Phosphorous in all reservoirs
		Where:	vad= ../Fluxes/vad	
			vid= ../Fluxes/vid	
			vpd= ../Fluxes/vpd	
			vcs= ../Fluxes/vcs	
			vws= ../Fluxes/vws	
			vtc= ../Fluxes/vtc	

Submodel carbon_chem

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(mol m^-3)	co3a	Init. Val.= (aad-hco3a)/2; d/dt = + dco3a	Calculated carbonate ion concentration (Atlantic)
		Where:	aad= ../Alkalinity/aad	
COMP.	(mol m^-3)	co3i	Init. Val.= (aid-hco3i)/2; d/dt = + dco3i	Calculated carbonate ion concentration (Indian)
		Where:	aid= ../Alkalinity/aid	
COMP.	(mol m^-3)	co3p	Init. Val.= (apd-hco3p)/2; d/dt = + dco3p	Calculated carbonate ion concentration (Pacific)
		Where:	apd= ../Alkalinity/apd	
COMP.	(mol m^-3)	hco3a	Init. Val.= hco3a0; d/dt = + dhco3a	Calculated bicarbonate ion concentration (Atlantic)
COMP.	(mol m^-3)	hco3i	Init. Val.= hco3i0; d/dt = + dhco3i	Calculated bicarbonate ion concentration (Indian)
COMP.	(mol m^-3)	hco3p	Init. Val.= hco3p0; d/dt = + dhco3p	Calculated bicarbonate ion concentration (Pacific)
COMP.	(m)	lydpa	Init. Val.= lydpa0; d/dt = + dlydpa	Calculated lysocline depth (Atlantic)
COMP.	(m)	lydpi	Init. Val.= lydpi0; d/dt = + dlydpi	Calculated lysocline depth (Indian)
COMP.	(m)	lydpp	Init. Val.= lydpp0; d/dt = + dlydpp	Calculated lysocline depth (Pacific)
COMP.	(-)	afroa	Init. Val.= 0.1+(lydpa/6000)^2.5; d/dt=+dafroa	Fract. area above lysocline Atlantic (betw. 0 and 1)
COMP.	(-)	ifroa	Init. Val.= 0.1+(lydpi/6000)^2.5; d/dt=+difroa	Fract. area above lysocline Indian
COMP.	(-)	pfroa	Init. Val.= 0.1+(lydpp/6000)^2.5; d/dt=+dpfroa	Fract. area above lysocline Pacific
FLOW	(yr^-1)	dafroa =	max(2.5/6000.0*((lydpa/6000)^1.5)*dlydpa,-afroa/dt())	
				Rate of change of Fract. area above lysocline Atlantic
FLOW	(yr^-1)	difroa =	max((2.5/6000.0*((lydpi/6000)^1.5)*dlydpi),-ifroa/dt())	
				Rate of change of Fract. area above lysocline Indian
FLOW	(yr^-1)	dpfroa =	max((2.5/6000.0*((lydpp/6000)^1.5)*dlydpp),-pfroa/dt())	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
				Rate of change of Fract. area above lysocline Pacific
FLOW	(mol m^-3 yr^-1)	dco3a =	(daad-dhco3a)/2	Rate of change
		Where:	daad= ../Alkalinity/daad	
FLOW	(mol m^-3 yr^-1)	dco3i =	(daid-dhco3i)/2	Rate of change
		Where:	daid= ../Alkalinity/daid	
FLOW	(mol m^-3 yr^-1)	dco3p =	(dapd-dhco3p)/2	Rate of change
		Where:	dapd= ../Alkalinity/dapd	
FLOW	(mol m^-3 yr^-1)	dhco3a =	(dcad-(0.5/sqrt(cad^2-aad*(2*cad-aad)*(1-4*kcarbcs)))*dtempa)/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. rate of hco3 concentration change (Atlantic)
			cad= ../TDC/cad	
			aad= ../Alkalinity/aad	
			dcad= ../TDC/dcad	
FLOW	(mol m^-3 yr^-1)	dhco3i =	(dcid-(0.5/sqrt(cid^2-aid*(2*cid-aid)*(1-4*kcarbcs)))*dtempi)/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. rate of hco3 concentration change (Indian)
			cid= ../TDC/cid	
			aid= ../Alkalinity/aid	
			dcid= ../TDC/dcid	
FLOW	(mol m^-3 yr^-1)	dhco3p =	(dcpd-(0.5/sqrt(cpd^2-apd*(2*cpd-apd)*(1-4*kcarbcs)))*dtempp)/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. rate of hco3 concentration change (Pacific)
			cpd= ../TDC/cpd	
			apd= ../Alkalinity/apd	
			dcpd= ../TDC/dcpd	
FLOW	(m yt^-1)	dlydpa =	max(lycon2*dco3a,-lydpa/dt())	calculate rate of change of lysocline depth (Atlantic)
		Where:	lycon2= ../Lysocline/lycon2	
FLOW	(m yt^-1)	dlydpi =	max(lycon2*dco3i,-lydpi/dt())	calculate rate of change of lysocline depth (Indian)
		Where:	lycon2= ../Lysocline/lycon2	
FLOW	(m yt^-1)	dlydpp =	max(lycon2*dco3p,-lydpp/dt())	calculate rate of change of lysocline depth (Pacific)
		Where:	lycon2= ../Lysocline/lycon2	
VARI.		dtempa =	2*cad*dcad-(daad*(2*cad-aad)+aad*(2*dcad-daad))*(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	temporary variable
			cad= ../TDC/cad	
			aad= ../Alkalinity/aad	
			daad= ../Alkalinity/daad	
			dcad= ../TDC/dcad	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.		dtempi =	2*cid*dcid-(daid*(2*cid-aid)+aid*(2*dcid-daid))*(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	temporary variable
			aid= ../Alkalinity/aid	
			cid= ../TDC/cid	
			daid= ../Alkalinity/daid	
			dcid= ../TDC/dcid	
VARI.		dtempp =	2*cpd*dcpd-(dapd*(2*cpd-apd)+apd*(2*dcpd-dapd))*(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	temporary variable
			apd= ../Alkalinity/apd	
			cpd= ../TDC/cpd	
			dapd= ../Alkalinity/dapd	
			dcpd= ../TDC/dcpd	
VARI.	(mol m^-3)	hco3a0 =	(cad-sqrt(cad^2-aad*(2*cad-aad)*(1-4*kcarbcs)))/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. Init. val. hco3 concentration (Atlantic)
			cad= ../TDC/cad	
			aad= ../Alkalinity/aad	
VARI.	(mol m^-3)	hco3i0 =	(cid-sqrt(cid^2-aid*(2*cid-aid)*(1-4*kcarbcs)))/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. Init. val. hco3 concentration (Indian)
			cid= ../TDC/cid	
			aid= ../Alkalinity/aid	
VARI.	(mol m^-3)	hco3p0 =	(cpd-sqrt(cpd^2-apd*(2*cpd-apd)*(1-4*kcarbcs)))/(1-4*kcarbcs)	
		Where:	kcarbcs= ../Lysocline/kcarbcs	calc. Init. val. hco3 concentration (Pacific)
			cpd= ../TDC/cpd	
			apd= ../Alkalinity/apd	
VARI.	(m)	lydpa0 =	max(lycon1+lycon2*(co3a-0.1),0.0001)	calculate initial lysocline depth (Atlantic)
		Where:	lycon1= ../Lysocline/lycon1	
			lycon2= ../Lysocline/lycon2	
VARI.	(m)	lydpi0 =	max(lycon1+lycon2*(co3i-0.1),0.0001)	calculate initial lysocline depth (Indian)
		Where:	lycon1= ../Lysocline/lycon1	
			lycon2= ../Lysocline/lycon2	
VARI.	(m)	lydpp0 =	max(lycon1+lycon2*(co3p-0.1),0.0001)	calculate initial lysocline depth (Pacific)
		Where:	lycon1= ../Lysocline/lycon1	
			lycon2= ../Lysocline/lycon2	

Submodel carbon isotopes Time step index: 2

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(permil)	dsad	Init. Val.= dsad0; d/dt = + ddsad	Carbon isotope composition (Atlantic)
COMP.	(permil)	dsid	Init. Val.= dsid0; d/dt = + ddsid	Carbon isotope composition (Indian)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(permil)	dspd	Init. Val.= dspd0; d/dt = + ddspd	Carbon isotope composition (Pacific)
COMP.	(permil)	dstc	Init. Val.= dstc0; d/dt = + ddstc	Carbon isotope composition (thermocline)
COMP.	(permil)	dscs	Init. Val.= dscs0; d/dt = + ddscs	Carbon isotope composition (cold surface waters)
COMP.	(permil)	dsws	Init. Val.= dsws0; d/dt = + ddsws	Carbon isotope composition (warm surface waters)
COMP.	(permil)	dsat	Init. Val.= dsat0; d/dt = + ddsat	Carbon isotope composition (atmospheric carbon)
COMP.	(permil)	dsbm	Init. Val.= dsbm0; d/dt = + ddsbm	Carbon isotope composition (terrestrial forests)
FLOW	(permil yr^-1)	ddsad =	(fcsad*(ccs*dscs-cad*dsad)+addecay*(dsws-delcorg)+	
			prod*corat*(dsws-delcarb)*adarea/darea*(1-afroa)+	
			acdr*(dsws-delcarb)-dsad*ddcad)/vad	Rate of change of d13C (Atlantic)
		Where:	prod= ../Fluxes/prod	
			corat= ../Alkalinity/corat	
			fcsad= ../Fluxes/fcsad	
			addecay= ../Fluxes/addecay	
			adarea= ../Fluxes/adarea	
			darea= ../Fluxes/darea	
			afroa= ../carbon_chem/afroa	
			acdr= ../Reactive_carbonates/acdr	
			ddcad= ../TDC/ddcad	
			vad= ../Fluxes/vad	
			ccs= ../TDC/ccs	
			cad= ../TDC/cad	
FLOW	(permil yr^-1)	ddsid =	(fadid*(cad*dsad-cid*dsid)+iddecay*(dsws-delcorg)+	
			prod*corat*(dsws-delcarb)*idarea/darea*(1-ifroa)+	
			icdr*(dsws-delcarb)-dsid*ddcid)/vid	Rate of change of d13C (Indian)
		Where:	prod= ../Fluxes/prod	
			corat= ../Alkalinity/corat	
			iddecay= ../Fluxes/iddecay	
			idarea= ../Fluxes/idarea	
			darea= ../Fluxes/darea	
			fadid= ../Fluxes/fadid	
			ifroa= ../carbon_chem/ifroa	
			icdr= ../Reactive_carbonates/icdr	
			ddcid= ../TDC/ddcid	
			vid= ../Fluxes/vid	
			cad= ../TDC/cad	
			cid= ../TDC/cid	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
FLOW	(permil yr^-1)	ddspd =	(fidpd*(cid*dsid-cpd*dspd)+pddecay*(dsws-delcorg)+	
			prod*corat*(dsws-delcarb)*pdarea/darea*(1-pfroa)+	
			pcdr*(dsws-delcarb)-dspd*ddcpd)/vpd	Rate of change of d13C (Pacific)
		Where:	prod= ../Fluxes/prod	
			corat= ../Alkalinity/corat	
			pddecay= ../Fluxes/pddecay	
			pdarea= ../Fluxes/pdarea	
			darea= ../Fluxes/darea	
			fidpd= ../Fluxes/fidpd	
			pfroa= ../carbon_chem/pfroa	
			pcdr= ../Reactive_carbonates/pcdr	
			ddcpd= ../TDC/ddcpd	
			vpd= ../Fluxes/vpd	
			cid= ../TDC/cid	
			cpd= ../TDC/cpd	
FLOW	(permil yr^-1)	ddstc =	(fadtc*cad*dsad+fidtc*cid*dsid+fpdtc*cpd*dspd-ftccs*ctc*dstc+	
			mtccs*(ccs*dscs-ctc*dstc)+mtcws*(cws*dsws-ctc*dstc)+	
			tcdecay*(dsws-delcorg)-dstc*ddctc)/vtc	Rate of change of d13C (thermocline)
		Where:	mtcws= ../Fluxes/mtcws	
			mtccs= ../Fluxes/mtccs	
			ftccs= ../Fluxes/ftccs	
			fadtc= ../Fluxes/fadtc	
			fidtc= ../Fluxes/fidtc	
			fpdtc= ../Fluxes/fpdtc	
			tcdecay= ../Fluxes/tcdecay	
			vtc= ../Fluxes/vtc	
			ddctc= ../TDC/ddctc	
			cad= ../TDC/cad	
			cid= ../TDC/cid	
			cpd= ../TDC/cpd	
			ctc= ../TDC/ctc	
			ccs= ../TDC/ccs	
			cws= ../TDC/cws	
FLOW	(permil yr^-1)	ddscs =	(mwscs*(cws*dsws-ccs*dscs)+mtccs*(ctc*dstc-ccs*dscs)+	
			ftccs*(ctc*dstc-ccs*dscs)+(pco2*(dsat-delcatm)-	
			pco2cs*(dscs-delccs))/	
			distime*matmco2*careafr-dscs*ddccs)/vcs	Rate of change of d13C (cold surface waters)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
		Where:	careafr= ../Fluxes/careafr	
			pco2cs= ../Lysocline/pco2cs	
			pco2= ../CO2/pco2	
			distime= ../TDC/distime	
			matmco2= ../TDC/matmco2	
			mwscs= ../Fluxes/mwscs	
			mtccs= ../Fluxes/mtccs	
			ftccs= ../Fluxes/ftccs	
			ddccs= ../TDC/ddccs	
			vcs= ../Fluxes/vcs	
			cws= ../TDC/cws	
			ccs= ../TDC/ccs	
			ctc= ../TDC/ctc	
FLOW	(permil yr^-1)	ddsws =	((mwscs*(ccs*dscs-cws*dsws)+mtcws*(ctc*dstc-cws*dsws)-	
			prod*(1*(dsws-delcorg)+corat*(dsws-delcarb))+	
			(pco2*(dsat-delcatm)-pco2ws*(dsws-delcws))/distime*matmco2*(1-careafr)+	
			carbw*deltc-shcarb*(dsws-delcarb)-	Rate of change of d13C (warm surface waters)
			shcorg*(dsws-delcorg))/vws-dsws*ddcws)/cws	
		Where:	careafr= ../Fluxes/careafr	
			pco2ws= ../Lysocline/pco2ws	
			pco2= ../CO2/pco2	
			distime= ../TDC/distime	
			matmco2= ../TDC/matmco2	
			ddcws= ../TDC/ddcws	
			mwscs= ../Fluxes/mwscs	
			mtcws= ../Fluxes/mtcws	
			prod= ../Fluxes/prod	
			corat= ../Alkalinity/corat	
			carbw= ../CO2/carbw	
			shcarb= ../Lysocline/shcarb	
			shcorg= ../TDC/shcorg	
			vws= ../Fluxes/vws	
			ccs= ../TDC/ccs	
			cws= ../TDC/cws	
			ctc= ../TDC/ctc	
FLOW	(permil yr^-1)	ddsat =	(((pco2ws*(dsws-delcws)-pco2*(dsat-delcatm))*(1-careafr)+	
			(pco2cs*(dscs-delccs)-pco2*(dsat-delcatm))*careafr)/distime+	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			(volc*dsvolc+kerox*dsker+fuel*dsfuel)/matmco2-(forarea*fbiom*(dsat-psfrac)-fbm*dsbm)/fgrt/matmco2-dsat*ddpco2)/pco2	Rate of change of d13C (atmospheric carbon)
		Where:	careafr= ../Fluxes/careafr	
			pco2cs= ../Lysocline/pco2cs	
			pco2ws= ../Lysocline/pco2ws	
			pco2= ../CO2/pco2	
			distime= ../TDC/distime	
			volc= ../CO2/volc	
			kerox= ../CO2/kerox	
			fuel= ../CO2/fuel	
			forarea= ../forests/forarea	
			fbiom= ../forests/fbiom	
			fbm= ../forests/fbm	
			fgrt= ../forests/fgrt	
			matmco2= ../TDC/matmco2	
			ddpco2= ../CO2/ddpco2	
FLOW	(permil yr^-1)	ddsbm =	((forarea*fbiom*(dsat-psfrac)-fbm*dsbm)/fgrt-dsbm*ddfbm)/fbm	
		Where:	forarea= ../forests/forarea	Rate of change of d13C (terrestrial forests)
			fbiom= ../forests/fbiom	
			fbm= ../forests/fbm	
			fgrt= ../forests/fgrt	
			ddfbm= ../forests/ddfbm	
VARI.	(permil)	avgd13C =	(dsad*vad+dsid*vid+dspd*vpd)/(vad+vid+vpd)	weight averaged total d13C composition
		Where:	vad= ../Fluxes/vad	
			vid= ../Fluxes/vid	
			vpd= ../Fluxes/vpd	
VARI.	(permil)	delcarb =	1.7	fractionation of carbonate minerals w.r.t. dissolved carbon
VARI.	(permil)	delcatm =	1.6	fractionation from atmosphere to water
VARI.	(permil)	delccs =	9.5-(tcs-298)/10	fractionation from cold surface water to atmosphere
VARI.	(permil)	delcws =	9.5-(tws-298)/10	fractionation from warm surface water to atmosphere
VARI.	(permil)	delcorg =	25	fractionation by phytoplankton w.r.t warm surface water
VARI.	(permil)	deltc =	1.32	carbom isotope ratio of weathered carbonate rock
VARI.	(permil)	dsad0 =	0.9936	Init. val. Atlantic carbon isotope composition

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.	(permil)	dsid0 =	0.6167	Init. val. Indian carbon isotope composition
VARI.	(permil)	dspd0 =	-0.5121	Init. val. Pacific carbon isotope composition
VARI.	(permil)	dstc0 =	0.9392	Init. val. thermocline carbon isotope composition
VARI.	(permil)	dscs0 =	1.3524	Init. val. cold surface water carbon isotope composition
VARI.	(permil)	dsws0 =	2.5767	Init. val. warm surface water carbon isotope composition
VARI.	(permil)	dsat0 =	-6.3659	Init. val. atmospheric carbon isotope composition
VARI.	(permil)	dsbm0 =	-25.2783	Init. val. terrestrial forests carbon isotope composition
VARI.	(permil)	dsfuel =	-60	Carbon isotope composition of fossil fuel (not used)
VARI.	(permil)	dsker =	-22.3	Carbon isotope composition of oxidizing organic matter
VARI.	(permil)	dsvolc =	-0.7	Carbon isotope composition of volcanic degassing
VARI.	(1/yr)	lambda =	1/8267	Radiocarbon decay constant
VARI.	(permil)	psfrac =	20	avg 13C fractionation during photosynthesis (const. here)
VARI.	(K)	tcs =	275	cold surface water temperature
VARI.	(K)	tws =	(tbar-careafr*tcs)/(1-careafr)	warm surface water temperature
		Where:	tbar= ../Temperature/tbar	
			careafr= ../Fluxes/careafr	

Submodel Alkalinity

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(mol m^-3)	aad	Init. Val.= aad0; d/dt = + daad	Alkalinity (Atlantic)
COMP.	(mol m^-3)	aid	Init. Val.= aid0; d/dt = + daid	Alkalinity (Indian)
COMP.	(mol m^-3)	apd	Init. Val.= apd0; d/dt = + dapd	Alkalinity (Pacific)
COMP.	(mol m^-3)	atc	Init. Val.= atc0; d/dt = + datc	Alkalinity (thermocline)
COMP.	(mol m^-3)	acs	Init. Val.= acs0; d/dt = + dacs	Alkalinity (cold surface)
COMP.	(mol m^-3)	aws	Init. Val.= aws0; d/dt = + daws	Alkalinity (warm surface)
FLOW	(mol mr^-3 yr^-1)	daad =	max((fcsad*acs-aad*(fadid+fadtc)+addecay*(-0.15)+	
			2*(prod*corat*adarea/darea*(1-afroa)+acdr))/vad,-aad/dt())	
		Where:	addecay= ../Fluxes/addecay	Alkalinity rate of change (Atlantic)
			prod= ../Fluxes/prod	
			fcsad= ../Fluxes/fcsad	
			vad= ../Fluxes/vad	
			darea= ../Fluxes/darea	
			afroa= ../carbon_chem/afroa	
			fadid= ../Fluxes/fadid	
			fadtc= ../Fluxes/fadtc	
			adarea= ../Fluxes/adarea	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			acdr= ../Reactive_carbonates/acdr	
FLOW	(mol mr^-3 yr^-1)	dacs =	max((mwscs*(aws-acs)+mtccs*(atc-acs)+ftccs*atc-fcsad*acs)/vcs,-acs/dt()/2)	
		Where:	mwscs= ../Fluxes/mwscs	Alkalinity rate of change (Atlantic)
			mtccs= ../Fluxes/mtccs	
			ftccs= ../Fluxes/ftccs	
			vcs= ../Fluxes/vcs	
			fcsad= ../Fluxes/fcsad	
FLOW	(mol mr^-3 yr^-1)	daid =	max((fadid*aad-aid*(fidtc+fidpd)+	Alkalinity rate of change (Indian)
			iddecay*(-0.15)+2*(prod*corat*idarea/darea*(1-ifroa)+icdr))/vid,-aid/dt())	
		Where:	fidpd= ../Fluxes/fidpd	
			prod= ../Fluxes/prod	
			darea= ../Fluxes/darea	
			ifroa= ../carbon_chem/ifroa	
			vid= ../Fluxes/vid	
			fadid= ../Fluxes/fadid	
			iddecay= ../Fluxes/iddecay	
			idarea= ../Fluxes/idarea	
			fidtc= ../Fluxes/fidtc	
			icdr= ../Reactive_carbonates/icdr	
FLOW	(mol mr^-3 yr^-1)	dapd =	max((fidpd*aid-apd*fpdtc+	Alkalinity rate of change (Pacific)
			pddecay*(-0.15)+2*(prod*corat*pdarea/darea*(1-pfroa)+pcdr))/vpd,-apd/dt())	
		Where:	fidpd= ../Fluxes/fidpd	
			pddecay= ../Fluxes/pddecay	
			prod= ../Fluxes/prod	
			darea= ../Fluxes/darea	
			pfroa= ../carbon_chem/pfroa	
			vpd= ../Fluxes/vpd	
			fpdtc= ../Fluxes/fpdtc	
			pdarea= ../Fluxes/pdarea	
			pcdr= ../Reactive_carbonates/pcdr	
FLOW	mol mr^-3 yr^-1	datc =	max((fadtc*aad+fidtc*aid+fpdtc*apd-ftccs*atc+mtccs*(acs-atc)+	
			mtcws*(aws-atc)+tcdecay*(-0.15))/vtc,-atc/dt())	
		Where:	mtcws= ../Fluxes/mtcws	Alkalinity rate of change (thermocline)
			mtccs= ../Fluxes/mtccs	
			fadtc= ../Fluxes/fadtc	
			fpdtc= ../Fluxes/fpdtc	
			ftccs= ../Fluxes/ftccs	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			fidtc= ../Fluxes/fidtc	
			tcdecay= ../Fluxes/tcdecay	
			vtc= ../Fluxes/vtc	
FLOW	(mol mr^-3 yr^-1)	daws =	max((mwscs*(acs-aws)+mtcws*(atc-aws)-	Alkalinity rate of change (warm surface)
			prod*(2*corat-0.15)+2*(carbw+silw-shcarb))/vws,-aws/dt()/2)	
		Where:	prod= ../Fluxes/prod	
			mtcws= ../Fluxes/mtcws	
			mwscs= ../Fluxes/mwscs	
			carbw= ../CO2/carbw	
			silw= ../CO2/silw	
			shcarb= ../Lysocline/shcarb	
			vws= ../Fluxes/vws	
VARI.	(mol m^-3)	aad0 =	2.1483	Initial alkalinity (Atlantic)
VARI.	(mol m^-3)	aid0 =	2.1927	Initial alkalinity (Indian)
VARI.	(mol m^-3)	apd0 =	2.3764	Initial alkalinity (Pacific)
VARI.	(mol m^-3)	atc0 =	2.1138	Initial alkalinity (thermocline)
VARI.	(mol m^-3)	acs0 =	2.115	Initial alkalinity (cold surface water)
VARI.	(mol m^-3)	aws0 =	2.1188	Initial alkalinity (warm surface water)
VARI.	(-)	corat =	0.09	Ratio particulate calcite to particulate organic carbon
VARI.	(mol yr^-1)	shcarb0 =	1e12*shcarb_factor	to calculate carbonate flux to shallow shelves
VARI.	(-)	shcarb_factor =	1	Scaling factor

Submodel TDC

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(mol m^-3)	cad	Init. Val.= cad0; d/dt = + dcad	Total dissolved carbon (Atlantic)
COMP.	(mol m^-3)	cid	Init. Val.= cid0; d/dt = + dcid	Total dissolved carbon (Indian)
COMP.	(mol m^-3)	cpd	Init. Val.= cpd0; d/dt = + dcpd	Total dissolved carbon (Pacific)
COMP.	(mol m^-3)	ctc	Init. Val.= ctc0; d/dt = + dctc	Total dissolved carbon (thermocline)
COMP.	(mol m^-3)	cws	Init. Val.= cws0; d/dt = + dcws	Total dissolved carbon (cold surface)
COMP.	(mol m^-3)	ccs	Init. Val.= ccs0; d/dt = + dccs	Total dissolved carbon (warm surface)
FLOW	(mol mr^-3 yr^-1)	dcad =	max((fcsad*ccs-cad*(fadtc+fadid)+addecay +	Total dissolved carbon rate of change (Atlantic)
			prod*corat*adarea/darea*(1-afroa)+acdr)/vad,-cad/dt())	
		Where:	addecay= ../Fluxes/addecay	
			corat= ../Alkalinity/corat	
			prod= ../Fluxes/prod	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			adarea= ../Fluxes/adarea	
			darea= ../Fluxes/darea	
			vad= ../Fluxes/vad	
			fadtc= ../Fluxes/fadtc	
			fcsad= ../Fluxes/fcsad	
			afroa= ../carbon_chem/afroa	
			fadid= ../Fluxes/fadid	
			acdr= ../Reactive_carbonates/acdr	
FLOW	(mol mr^-3 yr^-1)	dccs =	max((mwscs*(cws-ccs)+mtccs*(ctc-ccs)+	Total dissolved carbon rate of change (Atlantic)
			ftccs*ctc-fcsad*ccs+(pco2-pco2cs)/distime*matmco2*careafr)/vcs,-ccs/dt())	
		Where:	careafr= ../Fluxes/careafr	
			mtccs= ../Fluxes/mtccs	
			mwscs= ../Fluxes/mwscs	
			vcs= ../Fluxes/vcs	
			ftccs= ../Fluxes/ftccs	
			fcsad= ../Fluxes/fcsad	
			pco2= ../CO2/pco2	
			pco2cs= ../Lysocline/pco2cs	
FLOW	(mol mr^-3 yr^-1)	dcid =	max((fadid*cad-cid*(fidtc+fidpd)+iddecay +	Total dissolved carbon rate of change (Indian)
			prod*corat*idarea/darea*(1-ifroa)+icdr)/vid,-cid/dt())	
		Where:	iddecay= ../Fluxes/iddecay	
			corat= ../Alkalinity/corat	
			prod= ../Fluxes/prod	
			idarea= ../Fluxes/idarea	
			darea= ../Fluxes/darea	
			vid= ../Fluxes/vid	
			fidtc= ../Fluxes/fidtc	
			ifroa= ../carbon_chem/ifroa	
			fadid= ../Fluxes/fadid	
			fidpd= ../Fluxes/fidpd	
			icdr= ../Reactive_carbonates/icdr	
FLOW	(mol mr^-3 yr^-1)	dcpd =	max((fidpd*cid-fpdtc*cpd+pddecay +	Total dissolved carbon rate of change (Pacific)
			prod*corat*pdarea/darea*(1-pfroa)+pcdr)/vpd,-cpd/dt())	
		Where:	pddecay= ../Fluxes/pddecay	
			corat= ../Alkalinity/corat	
			prod= ../Fluxes/prod	
			pdarea= ../Fluxes/pdarea	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
			darea= ../Fluxes/darea	
			vpd= ../Fluxes/vpd	
			fpdtc= ../Fluxes/fpdtc	
			pfroa= ../carbon_chem/pfroa	
			fidpd= ../Fluxes/fidpd	
			pcdr= ../Reactive_carbonates/pcdr	
FLOW	(mol mr^-3 yr^-1)	dctc =	max((fadtc*cad+fidtc*cid+fpdtc*cpd-ftccs*ctc+ mtccs*(ccs-ctc)+mtcws*(cws-ctc)+tcdecay)/vtc,-ctc/dt())	Total dissolved carbon rate of change (thermocline)
		Where:	tcdecay= ../Fluxes/tcdecay	
			mtccs= ../Fluxes/mtccs	
			mtcws= ../Fluxes/mtcws	
			vtc= ../Fluxes/vtc	
			ftccs= ../Fluxes/ftccs	
			fadtc= ../Fluxes/fadtc	
			fidtc= ../Fluxes/fidtc	
			fpdtc= ../Fluxes/fpdtc	
FLOW	(mol mr^-3 yr^-1)	dcws =	max((mwscs*(ccs-cws)+mtcws*(ctc-cws)- prod*(1+corat)+(pco2-pco2ws)/distime*matmco2*(1-careafr)+ 1.0*carbw+0.0*silw-shcarb-shcorg)/vws,-cws/dt())	Total dissolved carbon rate of change (warm surface)
		Where:	corat= ../Alkalinity/corat	
			prod= ../Fluxes/prod	
			careafr= ../Fluxes/careafr	
			mtcws= ../Fluxes/mtcws	
			mwscs= ../Fluxes/mwscs	
			vws= ../Fluxes/vws	
			shcarb= ../Lysocline/shcarb	
			pco2= ../CO2/pco2	
			pco2ws= ../Lysocline/pco2ws	
			carbw= ../CO2/carbw	
			silw= ../CO2/silw	
VARI.	(mol m^-3)	cad0 =	2.115	Initial Total dissolved carbon (Atlantic)
VARI.	(mol m^-3)	cid0 =	2.1747	Initial Total dissolved carbon (Indian)
VARI.	(mol m^-3)	cpd0 =	2.3939	Initial Total dissolved carbon (Pacific)
VARI.	(mol m^-3)	ctc0 =	2.1036	Initial Total dissolved carbon (thermocline)
VARI.	(mol m^-3)	ccs0 =	2.0645	Initial Total dissolved carbon (cold surface water)
VARI.	(mol m^-3)	cws0 =	1.9588	Initial Total dissolved carbon (warm surface water)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.		ddcad =	dcad	
VARI.		ddccs =	dccs	
VARI.		ddcid =	dcid	
VARI.		ddcpd =	dcpd	
VARI.		ddctc =	dctc	
VARI.		ddcws =	dcws	
VARI.	(yr)	distime =	10	Carbon dioxide dissolution time
VARI.	(mol)	matmco2 =	4.95E+16	mass of carbon dioxide in atmosphere
VARI.	(mol yr^-1)	shcorg =	1e13*shcorg_factor	Flux of organic carbon into shelf sediments
VARI.	(-)	shcorg_factor =	1	Scaling factor

Submodel Temperature Time step index: 1

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(K)	tbar	Init. Val.= 287.85; d/dt = + dtemp	global average surface temperature
FLOW	(K/yr)	dtemp =	(qbar-FNir)/hcap	Temperature rate of change
VARI.	(W m^-2)	FNir =	ira+irb*tbar	Outgoing flux of long-wave infrared radiation
VARI.	(-)	albedo =	0.3	albedo (fixed, not used)
VARI.	(W m^-2)	annual_insol =	data file, every 2000 yrs	annually+latitudinally averaged insolation (Laskar etal.(2004)), in 2kyr steps
VARI.	(J s m^-2 K^-1 yr^-1)	hcap =	50	4184 J/kg/K =4184000 J/m^3/K now, Walker paper says, use effective heat capacity of 377m of water, hence eHC=4184000*377 J/m^2/K = 1.577368E9 convert from Watts to J/year s/yr=60*60*24* 365.25=31 557 600 Hence HC=1.577368E9/ 31 557 600 J/m^2/yr=~50
VARI.	(W m^-2)	ira =	iraz+9.56*log(pco2)	used to calculate infrared flux
		Where:	pco2= ../CO2/pco2	Marshall et al. (1988) equation is obtained for 1 PAL pCO2 of 345 ppm, here we use 280 ppm. Apparently the equation is exact for <300ppm, and very uncertain above 1000ppm due to saturation effects at varions CO2 spectral bands.
VARI.		iraz =	-352.08	Constant to calculate infrared flux
VARI.	(W m^-2 K^-1)	irb =	irbz-0.0514*log(pco2)	used to calculate infrared flux
		Where:	pco2= ../CO2/pco2	
VARI.		irbz =	2.053	Constant to calculate infrared flux
VARI.	(W m^-2)	qbar =	solcon*(1-albedo 0)	Global average insolation

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
		Where:	albedo_0= ../Ice_model/albedo_0	
VARI.	(W m^-2)	solcon =	(annual_insol*solcon_factor+normJunLul65Ninsol*orbittemp_factor)*1365/1368	
		Where:	orbittemp_factor= ../orbittemp_factor	Insolation forced by annual insolation, and seasonal
			normJunLul65Ninsol= ../normJunLul65Ninsol	insolation, scaling to adjust from solar constant
				used in Laskar et al. 2004
VARI.	(-)	solcon_factor =	1	(Scaling Factor)
Submodel CO2				
COMP.	(ppm/280ppm)	pco2	Init. Val.= pco2_0; d/dt = + dpco2	Atmospheric pCO2 concentration, scaled to 280ppm
FLOW	(yr^-1)	dpco2 =	((pco2ws-pco2)*(1-careafr)+(pco2cs-pco2)*careafr)/distime+	
			(volc+kerox+fuel+forest)/matmco2	Rate of change of atmospheric pCO2
		Where:	careafr= ../Fluxes/careafr	
			distime= ../TDC/distime	
			matmco2= ../TDC/matmco2	
			pco2ws= ../Lysocline/pco2ws	
			pco2cs= ../Lysocline/pco2cs	
			forest= ../forests/forest	
VARI.	(mol yr^-1)	carbw =	carbwz*pco2	Carbonate weathering flux
VARI.	(mol yr^-1)	carbwz =	0.00015e17*carbwz_factor	Constant for carbonate weathering flux
VARI.	(-)	carbwz_factor =	1	Scaling Factor
VARI.		ddpco2 =	dpco2	dummy
VARI.	(mol yr^-1)	fuel =	if time()>=10000 and time()<=(10000+fueltime) then fuelz else 0	
				Fossil fuel combustion rate (not used)
VARI.	(yr)	fueltime =	10000	years of simulated fossil fuel burning (not used)
VARI.	(mol yr^-1)	fuelz =	0	Fossil fuel flux (not used)
VARI.	(mol yr^-1)	kerox =	1e13*kerox_factor	Oxidation of old kerogen (organic carbon)
VARI.	(-)	kerox_factor =	1	Scaling Factor
VARI.	(-)	pco2_0 =	1	Scaling Factor
VARI.	(ppm)	pco2_ppm =	280*pco2	Atmospheric pCO2 concentration
VARI.	(mol/yr)	silw =	silwz*ClimWeathFact*exposed_area	Silicate weathering flux
		Where:	ClimWeathFact= ../ClimWeathFact	
			exposed_area= ../Ice_model/exposed_area	
VARI.	(mol/yr)	silwz =	0.00005e17*silwz_factor	Constant for silicate weathering flux
VARI.	(-)	silwz_factor =	0.78--0.94	Weathering factor, initially 0.78,
				then linearly ramped from 0.78 to 0.94 over
				500 kyr starting at 35.25 Ma
VARI.	(mol)	tco2 =	ccs*vcs+cws*vws+ctc*vtc+cad*vad+cid*vid+cpd*vpd+	
			fbm+pco2*matmco2+acalc+icalc+pcalc	Total carbon budget (diagnostic)

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
		Where:	matmco2= ../TDC/matmco2	
			fbm= ../forests/fbm	
			acalc= ../Reactive_carbonates/acalc	
			icalc= ../Reactive_carbonates/icalc	
			pcalc= ../Reactive_carbonates/pcalc	
			vcs= ../Fluxes/vcs	
			vws= ../Fluxes/vws	
			vad= ../Fluxes/vad	
			vid= ../Fluxes/vid	
			vpd= ../Fluxes/vpd	
			vtc= ../Fluxes/vtc	
			cws= ../TDC/cws	
			ccs= ../TDC/ccs	
			cad= ../TDC/cad	
			cid= ../TDC/cid	
			cpd= ../TDC/cpd	
			ctc= ../TDC/ctc	
VARI.	(mol/yr)	volc =	5e12*volc_factor	Volcanic carbon flux
VARI.	(-)	volc_factor =	1	Scaling Factor
Submodel forests				
COMP.	(mol)	fbm	Init. Val.= fbm0; d/dt = + dfbm	Forest biomass
FLOW		dfbm =	-forest	
VARI.	(-)	biosphere_switch =	1	Switch (1=on,using co2 fertilization effect for forest)
VARI.		ddfbm =	dfbm	
VARI.		fbiom =	fbiomz*fert*biosphere_switch	
VARI.	(mol)	fbiomz =	2.0027e17*biosphere_switch	Forest biomass prior fertilization
VARI.	(mol)	fbm0 =	2.0923e17*biosphere_switch	Initial forest biomass
VARI.	(-)	fert =	2.22*(1-exp(-0.003*(280*pco2-80)))	pCO2 fertilization function
		Where:	pco2= ../CO2/pco2	
VARI.	(-)	fgrt =	fgrtz/(1+(tbar-288.262)/10)	Dependence of biomass decay on temperature
		Where:	tbar= ../Temperature/tbar	
VARI.	(yr)	fgrtz =	50	Forest growth time
VARI.	(-)	forarea =	1	Biomass potential (1=preindustr.)
VARI.	(mol yr^-1)	forest =	(-forarea*fbiom/fgrtz+fbm/fgrt)*biosphere_switch	Rate of change of forest biomass
Submodel Lysocline				
COMP.	(mol m^-3)	co3cs	Init. Val.= co3cs0; d/dt = + dco3cs	Carbonate concentration cold surface waters
COMP.	(mol m^-3)	co3ws	Init. Val.= co3ws0; d/dt = + dco3ws	Carbonate concentration warm surface waters

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
COMP.	(-)	froacs	Init. Val.= min(0.1+(lydpcs/6000)^2.5,1); d/dt = + dfroacs	
				Fractional area above lysocline cold surface water)
COMP.	(-)	froaws	Init. Val.= min(0.1+(lydpws/6000)^2.5,1.0); d/dt = + dfroaws	
				Fractional area above lysocline warm surface water)
COMP.	(mol m^-3)	hco3cs	Init. Val.= hco3cs0; d/dt = + dhco3cs	Bicarbonate concentration cold surface waters
COMP.	(mol m^-3)	hco3ws	Init. Val.= hco3ws0; d/dt = + dhco3ws	Bicarbonate concentration warm surface waters
COMP.	(m)	lydpcs	Init. Val.= lydpcs0; d/dt = + dlydpcs	Lysocline depth cold surface waters
COMP.	(m)	lydpws	Init. Val.= lydpws0; d/dt = + dlydpws	Lysocline depth warm surface waters
FLOW	(mol m^-3 yr^-1)	dco3cs =	max((dacs-dhco3cs)/2,-co3cs/dt())	Rate of change co3 cold surface water
		Where:	dacs= ../Alkalinity/dacs	
FLOW	(mol m^-3 yr^-1)	dco3ws =	max((daws-dhco3ws)/2,-co3ws/dt())	Rate of change co3 warm surface water
		Where:	daws= ../Alkalinity/daws	
FLOW	(yr^-1)	dfroacs =	if ((froacs+(2.5/6000.0*((lydpcs/6000)^1.5)*dlydpcs)*dt())<=1) then (max(2.5/6000.0*(lydpcs/6000)^1.5*dlydpcs,-froacs/dt())) else 0.0	
				d/dt area fraction above lysocline cold surface water
FLOW	(yr^-1)	dfroaws =	if ((froaws+(2.5/6000.0*((lydpws/6000)^1.5)*dlydpws)*dt())<=1) then (max(2.5/6000.0*(lydpws/6000)^1.5*dlydpws,-froaws/dt())) else 0.0	
				d/dt area fraction above lysocline warm surface water
FLOW	(mol m^-3 yr^-1)	dhco3cs =	max((dccs-(0.5/sqrt(ccs^2-acs*(2*ccs-acs)*(1-4*kcarbcs)))*dtempcs)/ (1-4*kcarbcs),-hco3cs/dt())	Rate of change hco3 cold surface water
		Where:	ccs= ../TDC/ccs	
			acs= ../Alkalinity/acs	
			dccs= ../TDC/dccs	
FLOW	(mol m^-3 yr^-1)	dhco3ws =	max((dcws-(0.5/sqrt(cws^2-aws*(2*cws-aws)*(1-4*kcarbws)))*dtempws)/ (1-4*kcarbws),-hco3ws/dt())	Rate of change hco3 warm surface water
		Where:	cws= ../TDC/cws	
			aws= ../Alkalinity/aws	
			dcws= ../TDC/dcws	
FLOW	(m yr^-1)	dlydpcs =	max(lycon2*dco3cs,-lydpcs/dt())	Rate of change cold surface water lysocline depth
FLOW	(m yr^-1)	dlydpws =	max(lycon2*dco3ws,-lydpws/dt())	Rate of change warm surface water lysocline depth
VARI.	(mol m^-3)	co3cs0 =	0.07835	Init. co3 in cold surface water
VARI.	(mol m^-3)	co3ws0 =	0.1711	Init. co3 in warm surface water
VARI.		dtempcs =	2*ccs*dccs-(dacs*(2*ccs-acs)+acs*(2*dccs-dacs))*(1-4*kcarbcs)	
		Where:	ccs= ../TDC/ccs	temporary variable
			acs= ../Alkalinity/acs	
			dacs= ../Alkalinity/dacs	
			dccs= ../TDC/dccs	

TYPE	UNITS	NAME	VALUE/FORMULA	COMMENTS
VARI.		dtempws =	2*cws*dcws-(daws*(2*cws-aws)+aws*(2*dcws-daws))*(1-4*kcarbws)	
		Where:	cws= ../TDC/cws	temporary variable
			aws= ../Alkalinity/aws	
			daws= ../Alkalinity/daws	
			dcws= ../TDC/dcws	
VARI.	(-)	froaws0 =	max(0.1+(lydpws/6)^2.5,1)	Init. val. Fractional area above lysocline (warm surf.)
VARI.	(mol m^-3)	hco3cs0 =	1.96	Initial bicarbonate ion concentration in cold surface
VARI.	(mol m^-3)	hco3ws0 =	1.78	Initial bicarbonate ion concentration in warm surface
VARI.		kcarbcs =	0.000575+0.000006*(tcs-278)	equilibrium constant cold suface water
		Where:	tcs= ../carbon isotopes/tcs	
VARI.		kcarbws =	0.000575+0.000006*(tws-278)	equilibrium constant warm suface water
		Where:	tws= ../carbon isotopes/tws	
VARI.		kco2cs =	0.035+0.0019*(tcs-278)	equilibrium constant cold suface water
		Where:	tcs= ../carbon isotopes/tcs	
VARI.		kco2ws =	0.035+0.0019*(tws-278)	equilibrium constant warm suface water
		Where:	tws= ../carbon isotopes/tws	
VARI.	(m)	lycon1 =	5800	const. for calculation of lysocline depth from [co3]
VARI.	(m mol^-1 m^-3)	lycon2 =	50000	const. for calculation of lysocline depth from [co3]
VARI.	(m)	lydpcs0 =	max(lycon1+lycon2*(co3cs-0.1),0.0)	Initial lysocline depth for cold surface water
VARI.	(m)	lydpws0 =	max(lycon1+lycon2*(co3ws-0.1),0.000)	Initial lysocline depth for warm surface water
VARI.	(ppm/280ppm)	pco2cs =	kco2cs*(hco3cs^2.0)/co3cs	pCO2 in cold surface scaled to 280ppm
VARI.	(ppm)	pco2cs_ppm =	280*pco2cs	pCO2 concentration in cold surface water
VARI.	(ppm/280ppm)	pco2ws =	kco2ws*(hco3ws^2.0)/co3ws	pCO2 in warm surface scaled to 280ppm
VARI.	(ppm)	pco2ws_ppm =	280*pco2ws	pCO2 concentration in warm surface water
VARI.	(mol yr^-1)	shcarb =	shcarb0*co3ws/(0.26 mol m^-3)	Carbonate flux to shallow shelves
		Where:	shcarb0= ../Alkalinity/shcarb0	