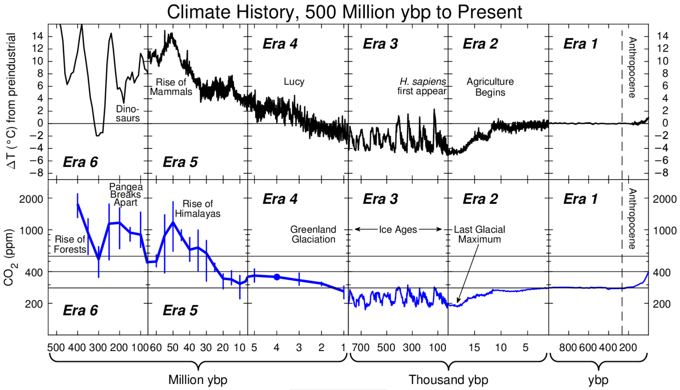
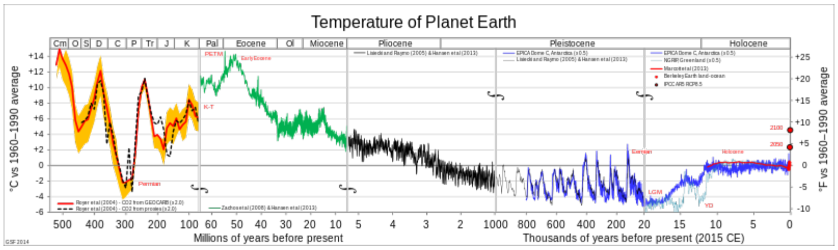
Long-term Carbon-Cycles
Paleoclimatology

I.a Introduction
Overview



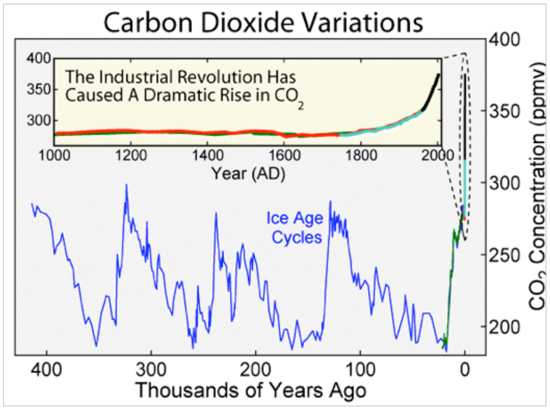

Springer Climate
Ross J. Salawitch
Timothy P. Canty
Austin P. Hope
Walter R. Tribett
Brian F. Bennett
Paris Climate Agreement: Beacon of Hope
Springer Open

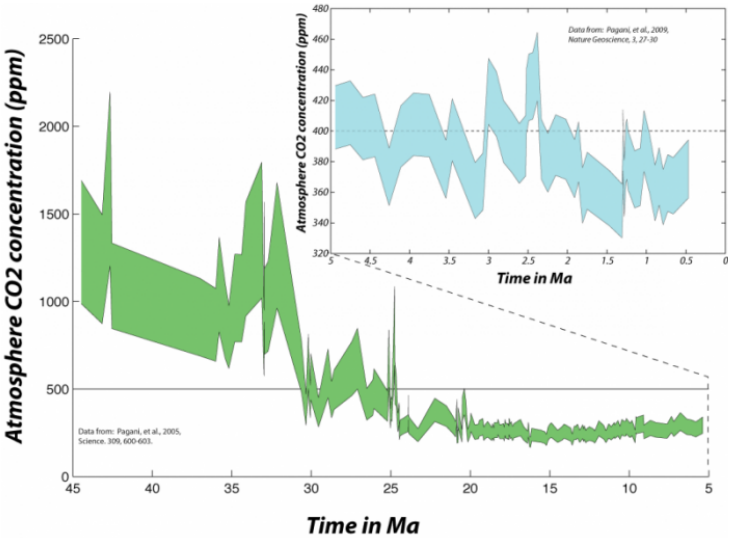
Quelle:
Ross J. Salawitch • Timothy P. Canty Austin P. Hope • Walter R. Tribett Brian F. Bennett
Paris Climate Agreement: Beacon of Hope,
Springer Climate, 2017,
https://link.springer.com/chapter/10.1007/978-3-319-46939-3_1 (DOI 10.1007/978-3-319-46939-3_1)



phanero-zoic = (Greek φανερός and ζωή) = visible life

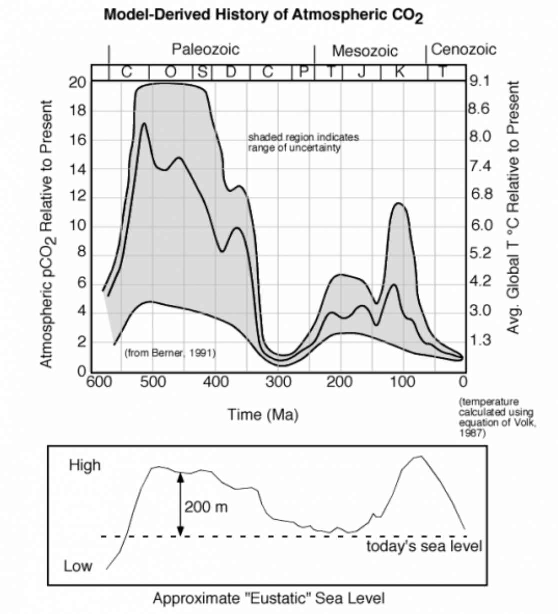
I.b Introduction
Glacial-Interglacial Cycles



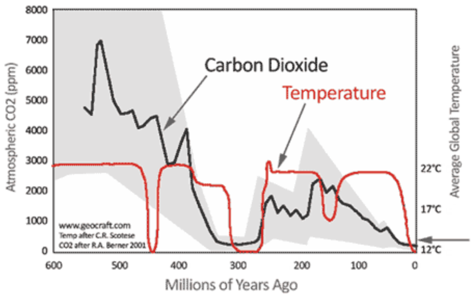


The longer history of atmospheric CO2 as reconstructed from studies of deep-sea sediments. In the upper right, the blue region represents the upper and lower estimates back through time — you can see that it is difficult to be too precise going back this far in time — and you can see that the last time the midpoint of these estimates rose above the current level was around 2.5 Myr ago. This was a time when there was far less ice on Earth; the Arctic was apparently 15 to 20°C warmer than it is today, and sea level was about 20 meters higher than the present. As we go further back in time, we see that the atmospheric CO2 concentration rises to very high levels. The Earth was a very different place before about 30 Myr ago — sea level was perhaps 100 m higher and there was practically no ice on Earth.

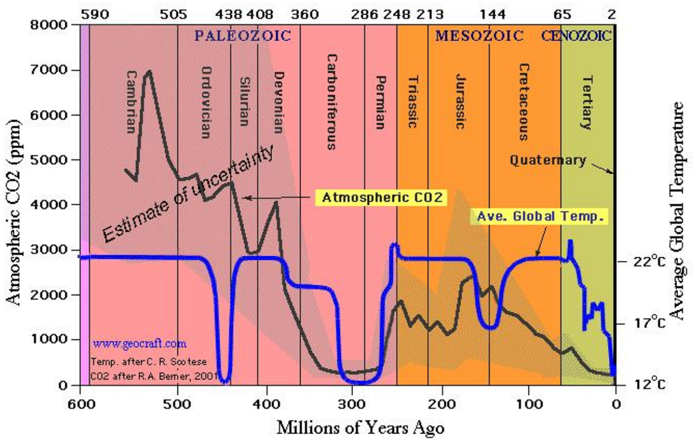
I.c Introduction
100 Million Year Cycles



The history of atmospheric CO2 over the last 550 Ma, based on modeling, shows extremely high levels about 100 Ma (million years ago) and before 350 Ma. Note that there are huge uncertainties associated with these estimates, but the mid-range of the estimates suggests that CO2 levels were very high during this time period. Interestingly, these periods of high CO2 more or less coincide with periods of high sea level as can be seen in the lower panel.

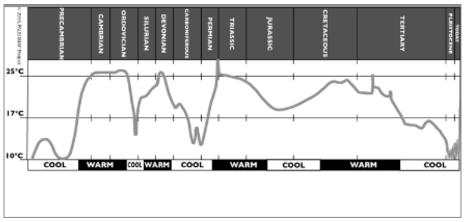


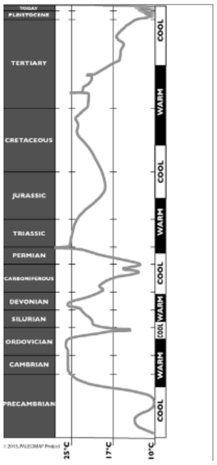
Temperature after C.R. Scotese http://www.scotese.com/climate.htm
CO2 after R.A. Berner, 2001 (GEOCARB III)



Late Carboniferous to **Early Permian** time (315 Ma -- 270 Ma) is the only time period in the last 600 million years when **both** atmospheric **CO2** and **temperatures** were as low as they are today **(Quaternary Period).**

Quelle: Guest post by David Grocott, How Jo Nova doesn't get past climate change
https://skepticalscience.com/print.php?n=238



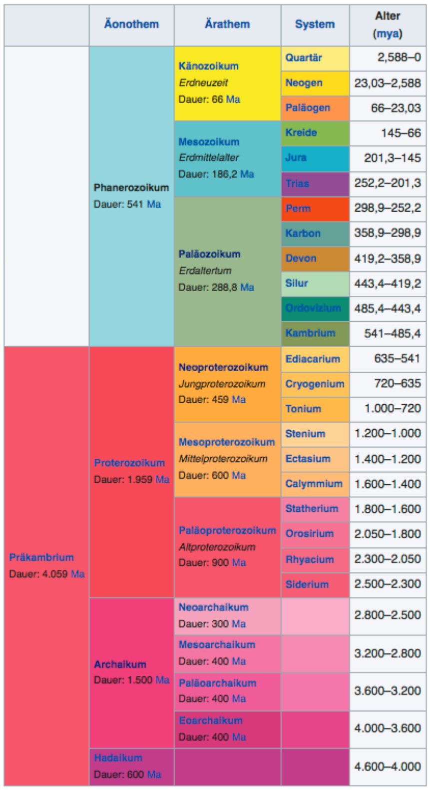


Pangäa existierte als zusammenhängende Landmasse vor etwa 300 bis 150 Millionen Jahren (Karbon bis Jura), also in dem Abschnitt der Erdgeschichte, in dem sich das große Massenaussterben am Ende des Perm abspielte und sich die Dinosaurier entwickelten.

vgl. Masks (Der Komet), Star Trek Das nächste Jahrhundert, Staffel 7, Episode 17

Masaka = Planet Erde mit CO2 entlassen in Atmosphäre: mittlere globale Temperatur: 14 Grad Celsius wärmer als heute
Korgano: Planet Erde mit CO2 gefangen in Felsen (Sediment-Gestein): mittlere globale Temperatur: 0 - 6 Grad Celsius kälter als heute
Personen in Data: IPCC - sie sprechen nicht klar verständlich, eher wie Priester, Orakel, die besten Ratgeber, die wir haben.

Die Erde atmet periodisch (Masaka - Korgano - Masaka - Korgano, ...)

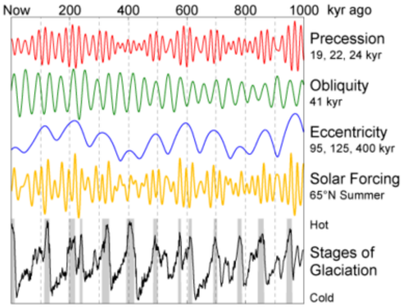


	Äonothem	Ärathem	System	Alter (mya)
	Phanerozoikum Dauer: 541 Ma	**Känozoikum** *Erdneuzeit* Dauer: 66 Ma	Quartär	2,588–0
			Neogen	23,03–2,588
			Paläogen	66–23,03
		Mesozoikum *Erdmittelalter* Dauer: 186,2 Ma	Kreide	145–66
			Jura	201,3–145
			Trias	252,2–201,3
		Paläozoikum *Erdaltertum* Dauer: 288,8 Ma	Perm	298,9–252,2
			Karbon	358,9–298,9
			Devon	419,2–358,9
			Silur	443,4–419,2
			Ordovizium	485,4–443,4
			Kambrium	541–485,4
Präkambrium Dauer: 4.059 Ma	**Proterozoikum** Dauer: 1.959 Ma	**Neoproterozoikum** *Jungproterozoikum* Dauer: 459 Ma	Ediacarium	635–541
			Cryogenium	720–635
			Tonium	1.000–720
		Mesoproterozoikum *Mittelproterozoikum* Dauer: 600 Ma	Stenium	1.200–1.000
			Ectasium	1.400–1.200
			Calymmium	1.600–1.400
		Paläoproterozoikum *Altproterozoikum* Dauer: 900 Ma	Statherium	1.800–1.600
			Orosirium	2.050–1.800
			Rhyacium	2.300–2.050
			Siderium	2.500–2.300
	Archaikum Dauer: 1.500 Ma	**Neoarchaikum** Dauer: 300 Ma		2.800–2.500
		Mesoarchaikum Dauer: 400 Ma		3.200–2.800
		Paläoarchaikum Dauer: 400 Ma		3.600–3.200
		Eoarchaikum Dauer: 400 Ma		4.000–3.600
	Hadaikum Dauer: 600 Ma			4.600–4.000

Durch plattentektonische Vorgänge begann Pangaea ab der späten Trias (etwa 230 mya) auseinanderzubrechen. Der Zerfall beschränkte sich zunächst auf den Südteil (Gondwana), mit Öffnung der Tethys nach Westen und Öffnung des Zentral- und Südatlantiks, sowie des Antarktischen und Indischen Ozeans. Geologische Zeugnisse des beginnenden Zerfalls sind unter anderem die triassisch-jurassischen Grabenbruch-Sedimente und Basalte der Newark-Becken im Osten Nordamerikas und die jurassischen Basalte (u. a. Drakensberge) und Dolerit-Gänge in den Karoo-Becken im südlichen Afrika. Der ehemalige Nordteil Pangaeas (Laurasia) bestand noch bis ins frühe Tertiär weiter, da sich der Nordatlantik erst dann zu öffnen begann.

Der Erdmantel unter Pangaeas ehemaliger Position ist noch immer heißer als anderswo. Daher liegt Afrika etwa zehn Meter höher als die übrigen Kontinente.

II. "The Ocean Breathes"
Glacial-Interglacial Cycles



390 × 296

https://de.wikipedia.org/wiki/Milankovi%C4%87-Zyklen

Glacial-Interglacial Cycles
Warming at the end of glacial periods tends to happen more abruptly than the increase in solar insolation. Several positive feedbacks are responsible for this.

- One is the ice-albedo feedback.
- A second feedback involves atmospheric CO2.

Paleoclimatology
The explanation for these glacial-interglacial climate changes is believed to be variations in the earth's orbit around the sun (The Milankovitch Theory), combined with positive feedbacks from albedo (reflection of sunlight from snow and ice) and decreases in Carbon Dioxide concentrations in the atmosphere. <p>

What is The Milankovitch Theory?
The Milankovitch or astronomical theory of climate change is an explanation for changes in the seasons which result from changes in the earth's orbit around the sun. The theory is named for Serbian astronomer Milutin Milankovitch, who calculated the slow changes in the earth's orbit by careful measurements of the position of the stars, and through equations using the gravitational pull of other planets and stars. He determined that the earth "wobbles" in its orbit.

- *The earth's "tilt" is what causes seasons, and*
- *changes in the tilt of the earth change the strength of the seasons.*
- *The seasons can also be accentuated or modified by the eccentricity (degree of roundness) of the orbital path around the sun, and the precession effect, the position of the solstices in the annual orbit.*

Obliquity
The earth wobbles in space so that its tilt changes between about 22 and 25 degrees on a cycle of about *41,000 years.*
It is the cool summers which are thought to allow snow and ice to last from year to year in high latitudes, eventually building up into massive ice sheets. There are positive feedbacks in the climate system as well, because an earth covered with more snow reflects more of the sun's energy into space, causing additional cooling. In addition, it appears that the amount of Carbon Dioxide in the atmosphere falls as ice sheets grow, also adding to the cooling of the climate.

Eccentricity
The earth's orbit around the sun is not quite circular, which means that the earth is slightly closer to the sun at some times of the year than others. The closest approach of the earth to the sun is called perihelion, and it now occurs in January, making northern hemisphere winters slightly milder. This change in timing of perihelion is known as the precession of the equinoxes, and occurs on a period of *22,000 years.* 11,000 years ago, perihelion occurred in July, making the seasons more severe than today.

The "roundness", or eccentricity, of the earth's orbit varies on cycles of *100,000 and 400,000 years*, and this affects how important the timing of perihelion is to the strength of the seasons.
The combination of

- the 41,000 year tilt cycle and
- the 22,000 year precession cycles, plus
- the 100,000 and 400,000 year smaller eccentricity signal,

affect the relative severity of summer and winter, and are thought to control the growth and retreat of ice sheets. Cool summers in the northern hemisphere, where most of the earth's land mass is located, appear to allow snow and ice to persist to the next winter, allowing the development of large ice sheets over hundreds to thousands of years. Conversely, warmer summers shrink ice sheets by melting more ice than the amount accumulating during the winter.

For more detailed [albeit boring] explanations of orbital variations with graphic representations, please see WDC Paleo's educational slide set "The Ice Ages":
ftp://ftp.ncdc.noaa.gov/pub/data/paleo/slidesets/iceage/

Reinhard Calov and Andrey Ganopolski, PIK

Multistability and hysteresis in the climate-cryosphere system under orbital forcing
Reinhard Calov and Andrey Ganopolski , PIK, 2005
cache

Using the Earth system model of intermediate complexity CLIMBER-2 we studied the stability diagram of the climate-cryosphere system in the phase space of Milankovitch Forcing (maximum summer insolation at 65 degrees N, abbreviated as MF).

- We have shown that the equilibrium response of the climate-cryosphere system to MF reveals pronounced hysteresis behavior within the range of Earth's orbital parameters.
- Depending on MF, the climate-cryosphere system has either one (glacial or interglacial) or two different equilibrium states.
- The MF thresholds of the transitions between the two states
  - depend on parameterizations of ice-sheet dynamics, but
  - are rather insensitive to the choice of the orbital parameters used to obtain the same value of MF.
- A change of atmospheric CO2 concentration from its interglacial to the glacial value, shifts the hysteresis curve by about 15 W/m2.

These results provide an important support to the conceptual models of glacial cycles based on multistability and hysteresis behavior.

The role of orbital forcing, carbon dioxide and regolith in 100 kyr glacial cycles
A. Ganopolski and R. Calov,
Clim. Past, 7, 1415–1425, 2011
www.clim-past.net/7/1415/2011/
doi:10.5194/cp-7-1415-2011
cache

Results of our experiments support the notion that 100 kyr cycles represent a direct, strongly nonlinear response of the climate-cryosphere system to orbital forcing and they are directly related to the corresponding eccentricity period.
In terms of nonlinear dynamics, this link can be interpreted as the phase-locking of the long glacial cycles to the shortest (100 kyr) eccentricity cycles.
Physically, this phase-locking is explained by the fact that the ice sheets tend to grow monotonously during periods of low eccentricity and reach their critical size (volume) around the minimum of eccentricity.

- When eccentricity starts to grow, the first sufficiently large positive anomaly in orbital forcing can lead to the rapid and irreversible meltback of the Northern Hemisphere ice sheets.
- This mechanism requires the existence of long glacial cycles that, in turn, require
  - sufficiently low CO2 concentrations and
  - a large area of the continents to be free of sediment.

The CO2 concentration not only determines the dominant regime of glacial variability, but also strongly amplifies 100 kyr cycles. Therefore, realistic simulations of the glacial cycles require comprehensive Earth system models that include both physical and bio-geochemical components of the Earth system.

CLIMate and BiosphERe Model (CLIMBER-2)

https://www.pik-potsdam.de/research/earth-system-analysis/models/climber/climber-2
https://www.pik-potsdam.de/research/earth-system-analysis/models/climber

PIK-Videos

CLIMBER-2 is an Earth-system model of intermediate complexity for long-term and paleo-climate simulations. It is based on the 2.5-dimensional statistical-dynamica atmospheric model Potsdam, a 2-dimensional 3-basin ocean model and the 3-dimensional polythermal ice sheet model SICOPOLIS (3D polythermal Ice Sheet Model)

We have succeeded in simulating eight full ice age cycles with prescribed CO2 concentration using CLIMBER-2. Preliminary simulations driven only by orbital cycles (with predicted greenhouse gas changes) show that glacial cycles during the Quaternary (the last 2.6 million years) represent a strongly nonlinear response of the climate-cryosphere system to astronomical forcing;

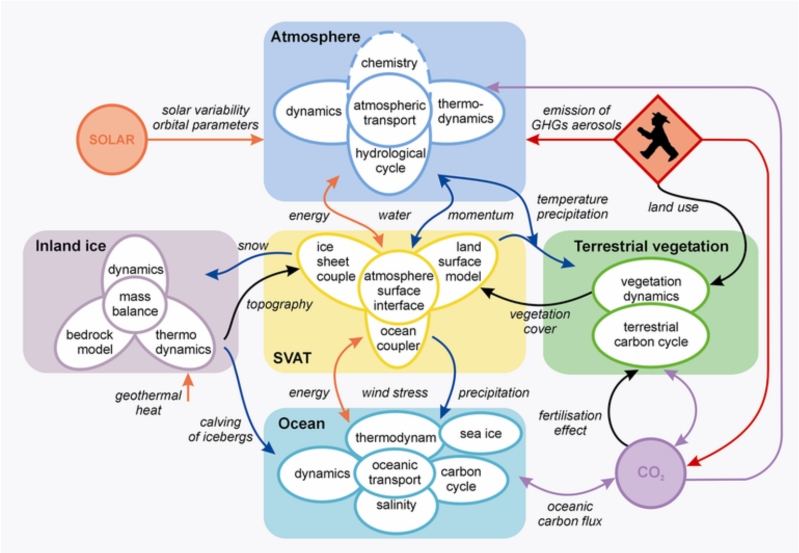
- aeolian dust,
- CO2 and other GHGs

provide positive feedbacks which amplify glacial cycles, and
the removal of terrestrial sediments by the ice sheets can explain the transition from short (41,000 yrs) to long (100,000 yrs) cycles around 1 million years ago.

CO2 evolution during the last glacial cycle has been successfully explained as a succession of key physical and biogeochemical processes (Brovkin et al. 2012).
Furthermore, we have demonstrated the mechanisms that lead to the vexing phase relationship of CO2 lagging temperature in Antarctic ice cores (Ganopolski & Roche 2009).

Orbital forcing is important during the mid-Pliocene warm period. Transient climate simulations for the mid-Pliocene (3.3-3.0 million years ago) with CLIMBER-2 agree best with reconstructions for the warmest periods during orbital cycles (Willeit, Ganopolski & Feulner 2013). This could imply a bias toward higher values for estimates of equilibrium climate sensitivity based on mid-Pliocene proxies.

Principal CLIMBER structure



Source:
Jose A. Rial, Jose A. Rial, Roger A. Pielke Sr. Roger A. Pielke Sr. Martin Beniston, et al.,
Nonlinearities, Feedbacks and Critical Thresholds within the Earth's Climate System, July 2004, Climatic Change 65(1): 11-38, 2004
DOI: 10.1023/B:CLIM.0000037493.89489.3f

Figure 1. Structure of CLIMBER-2, an Earth System Model of Intermediate Complexity (EMIC; Claussen et al., 2002). The model consists of four modules which describe the dynamics of the climate components

1. atmosphere,
2. ocean,
3. terrestrial vegetation (SVAT = Soil Vegetation Atmosphere Transfer Scheme), and
4. inland ice.

These components interact via fluxes of

- energy,
- momentum (e.g., wind stress on the ocean),
- water (e.g., precipitation, snow, and evaporation), and
- carbon.

Also, the land-surface structure is allowed to change in the case of changes in vegetation cover or the emergence and melting of inland ice masses, for example.

The interaction between climate components is described in a so-called Soil Vegetation Atmosphere Transfer Scheme (SVAT).

CLIMBER-2 is driven

- by insolation (which can vary owing to changes in the Earth orbit or in the solar energy flux),
- by the geothermal heat flux (which is very small, but important in the long run for inland ice dynamics), and
- by changes imposed on the climate system by human activities (such as land use or emission of greenhouse gases (GHG) and aerosols).

(1) While linear systems typically show smooth, regular motion in space and time that can be described in terms of well-behaved, continuous functions, nonlin- ear systems often undergo sharp transitions, even in the presence of steady forcing. These transitions usually result from crossing unstable equilibrium thresholds (e.g., abrupt climate change, as described by Alley et al., 2003).

(2) The response of a linear system to small changes in its parameters or to changes in external forcing is usually smooth and proportionate to the stimulation. In contrast, nonlinear systems are such that a very small change in some parameters can cause great qualitative differences in the resulting behavior (chaos) as sug- gested for instance by fluid dynamic models of atmospheric convection (Lorenz, 1963).

(3) After transients dissipate, an oscillatory linear system's frequency always equals that of the forcing, while the spectral response of a nonlinear system to oscillatory external forcing usually exhibits frequencies not present in the forcing (such as combination tones), phase and frequency coupling, synchronization and other indications of nonlinearity often detected in past climate data (e.g., Pisias et al., 1990).

Chaos and Complexity
Thus, nonlinearity gives rise to unexpected structures and events in the form of abrupt transitions across thresholds, unexpected oscillations, and chaos (Kaplan and Glass, 1995). Actually, the climate system is not only chaotic, it is also 'complex' (Rind, 1999), in the sense that it is composed of many parts whose interactions can, through a process still not completely understood (Cowan et al., 1999), provoke

- *spontaneous self-organization* and the
- *emergence of coherent, collective phenomena* that can be described only at higher levels than those of the individual parts (Goldenfeld and Kadanoff, 1999).

Therefore, it is useful to establish for clarity's sake that chaos and complexity are different aspects of nonlinear response.

Chaos refers to simple systems that exhibit complicated behavior, such as

- the intricate time series produced by a dripping faucet,
- the unpredictable oscillations of a double pendulum, or
- the random behavior of populations in models of logistic growth (May, 1976).

Conversely, complexity refers to complicated systems that exhibit simple, so-called emergent behavior. For instance,

- in the highly complex tectonic-geologic subsystem, the emergent behavior is an earthquake,
- in the world economy, a stock market crash, and
- in the biosphere, a massive extinction.

In the climate system, abrupt climate change is a likely example of unpredictable emergent behavior. In fact, observations indicate that the climate system is, and has been for millions of years, riddled with episodes of abrupt change, ranging

- form large, sudden global warming episodes (e.g., the end of the last ice age),
- to drastic and rapid regional changes in the hydroclimatic cycle, precipitation and aridity (e.g., the expansion of the Sahara).

Because of their obvious importance in understanding future climate trends, these and other examples of abrupt climate change are discussed in this paper.

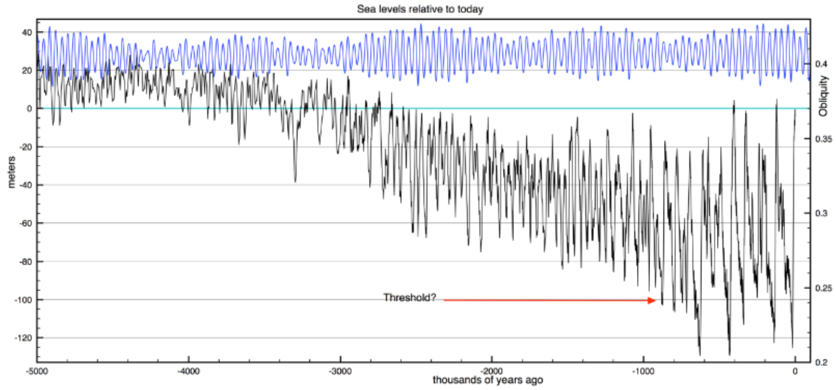
Within the climate system chaotic behavior exhibits sensitive dependence to initial conditions, confinement and typical aperiodicity. This is to say that tiny dif- ferences in initial states can exponentially blow up to big differences in later states, but the values of the relevant variables remain confined within fixed boundaries, never exactly repeating. In the climate system, and as we shall soon discuss, plau- sible examples of chaos are ENSO (El Niño, Southern Oscillation) and NAO (North Atlantic Oscillation). In fact, simple deterministic models that exhibit chaotic behavior qualitatively reproduce the irregular oscillations of ENSO for strong cou- pling between ocean and atmosphere (e.g., Tziperman et al., 1994). ENSO may in fact be chaotic in the sense that the equatorial Pacific climate may flip in a chaotic way (randomly) from one to another of its three preferred quasi-stable states (normal, La Niña, El Niño).

1.3. FEEDBACKS AND THRESHOLDS
Although chaotic dynamics and emergent properties may be surmised from data interpretation and from the comparison of data to models, feedbacks are the only climate processes whose presence and effects can often be quantified and, in some cases understood with almost certainty. In this paper we illustrate how the presence of several types of amplifying (positive) and controlling (negative) feedbacks, some physical (ice sheet-albedo interaction), some biogeophysical (albedo-vegetation interaction), and some biogeochemical (anthropogenic gases-atmosphere interaction) can be deduced from observations. Feedbacks are the most likely processes behind most of the nonlinearities in the climate.

- The relatively stable global temperature and benign climate the earth has enjoyed for billions of years is testimony to the action of regulating negative feedbacks which balance and neutralize amplifying (explosive) positive feedbacks continuously (e.g., Watson and Lovelock, 1984).
- It is quite likely that such a continuously active regulating feedback mechanism failed to develop in Venus, leading to the present hellish environment of its surface.

We can then imagine that nature has arranged things in such way that on Earth, and on the average, the net climate-driving feedback is negative, slightly stronger than the net positive feedback, at least for small values of some (external or internal) forcing. It is when the forcing grows to a point in which the positive feedback takes over that its explosive amplification produces the nonlinear effects that we see in the data. Thus, a critical threshold may in fact be the point at which the two competing feedback effects are just balanced.

- Since there are countless feedbacks and thresholds, rapid amplification of potentially exploding variables becomes highly probable, and sharp, abrupt climate change should then be the norm, as appears to be suggested by the past records of climate change. We must emphasize however that there is as yet no basic understanding of abrupt climate change (Clark et al., 2002).



5444 × 2640

The growth and reduction of Northern Hemisphere ice sheets over the past million years is dominated by an approximately 100,000-year periodicity and a sawtooth pattern (gradual growth and fast termination). Milankovitch theory proposes that summer insolation at high northern latitudes drives the glacial cycles, and statistical tests have demonstrated that the glacial cycles are indeed linked to eccentricity, obliquity and precession cycles.

Yet insolation alone cannot explain the strong 100,000-year cycle, suggesting that internal climate feedbacks may also be at work. Earlier conceptual models, for example, showed that glacial terminations are associated with the build-up of Northern Hemisphere 'excess ice', but the physical mechanisms underpinning the 100,000-year cycle remain unclear.

Here we show, using comprehensive climate and ice-sheet models, that
- insolation and
- internal feedbacks between
    - the climate,
    - the ice sheets and
    - the lithosphere-asthenosphere system

explain the 100,000-year periodicity.

The responses of equilibrium states of ice sheets to summer insolation show hysteresis, with the shape and position of the hysteresis loop playing a key part in determining the periodicities of glacial cycles. The hysteresis loop of the North American ice sheet is such that after inception of the ice sheet, its mass balance remains mostly positive through several precession cycles, whose amplitudes decrease towards an eccentricity minimum. The larger the ice sheet grows and extends towards lower latitudes, the smaller is the insolation required to make the mass balance negative. Therefore, once a large ice sheet is established, a moderate increase in insolation is sufficient to trigger a negative mass balance, leading to an almost complete retreat of the ice sheet within several thousand years. This fast retreat is governed mainly by rapid ablation due to the lowered surface elevation resulting from delayed isostatic rebound, which is the lithosphere-asthenosphere response.

Carbon dioxide is involved, but is not determinative, in the evolution of the 100,000-year glacial cycles.

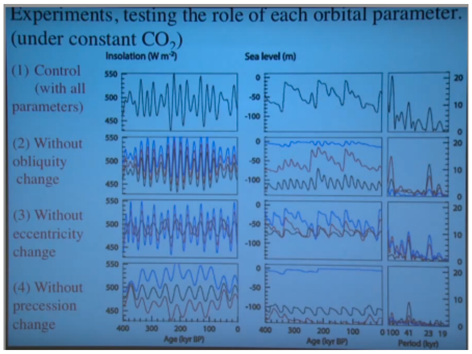
Ayako Abe-Ouchi,et al.

Abe-Ouchi A[1], Saito F, Kawamura K, Raymo ME, Okuno J, Takahashi K, Blatter H.
Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume
Nature 500(7461):190-3, August 2013
DOI: 10.1038/nature12374
Source PubMed

Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume
Nature Letter vol 500, pp 190 - 193, 8 August 2013
doi:10.1038/nature12374
(cache)

Ayako Abe-Ouchi on YouTube

Modeling the 100,000-year Glacial-interglacial Cycles: Forcing and Feedback
Published on Nov 12, 2013

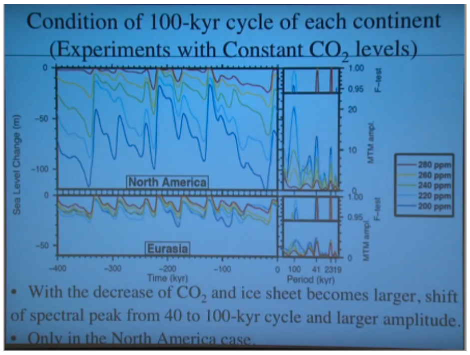

Experiments, testing the role of each orbital parameter.
(under constant CO_2)

(1) Control (with all parameters)

(2) Without obliquity change

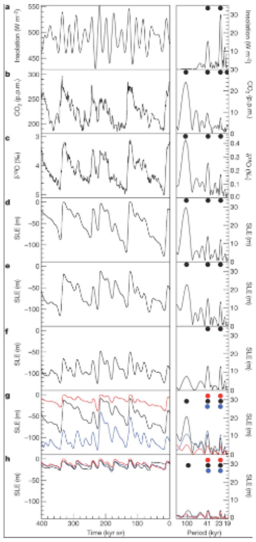
(3) Without eccentricity change

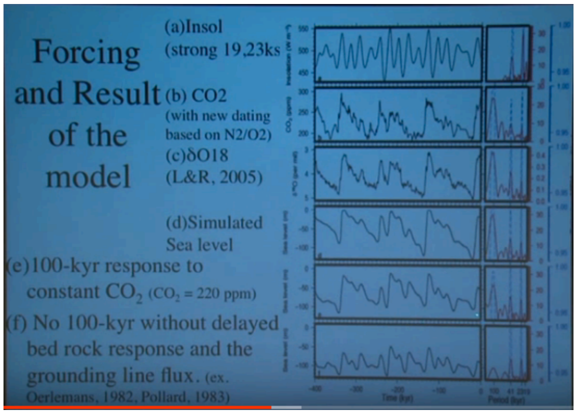
(4) Without precession change



Condition of 100-kyr cycle of each continent (Experiments with Constant CO_2 levels)

- With the decrease of CO_2 and ice sheet becomes larger, shift of spectral peak from 40 to 100-kyr cycle and larger amplitude.
- Only in the North America case.





Forcing and Result of the model

(a)Insol (strong 19,23ks

(b) CO2 (with new dating based on N2/O2)

(c)δO18 (L&R, 2005)

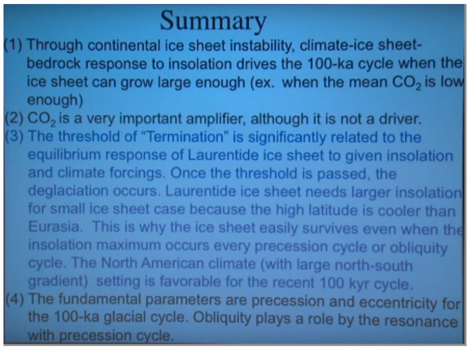
(d)Simulated Sea level

(e)100-kyr response to constant CO_2 (CO_2 = 220 ppm)

(f) No 100-kyr without delayed bed rock response and the grounding line flux. (ex. Oerlemans, 1982, Pollard, 1983)

a = observed insolation
b = observed CO2
c = observed delta O18
d = simulated sea level (SLE)
e = 100 kyr cycles at CO2 = 220 ppm
f = no 100 kyr cycles without delayed bedrock response and grounding line flux
g (h) = North America (Eurasia), 200 < CO2 < 280 ppm

rechtes Dia in bester Auflösung: file:///Users/msteenken/Jochen/Contents/Webs-/acamedia.info/sciences/sciliterature/globalw/reference/aeg-ag/literatur/Abe-Ouchi/forcing_and_model_results_best.png



Summary

(1) Through continental ice sheet instability, climate-ice sheet-bedrock response to insolation drives the 100-ka cycle when the ice sheet can grow large enough (ex. when the mean CO_2 is low enough)
(2) CO_2 is a very important amplifier, although it is not a driver.
(3) The threshold of "Termination" is significantly related to the equilibrium response of Laurentide ice sheet to given insolation and climate forcings. Once the threshold is passed, the deglaciation occurs. Laurentide ice sheet needs larger insolation for small ice sheet case because the high latitude is cooler than Eurasia. This is why the ice sheet easily survives even when the insolation maximum occurs every precession cycle or obliquity cycle. The North American climate (with large north-south gradient) setting is favorable for the recent 100 kyr cycle.
(4) The fundamental parameters are precession and eccentricity for the 100-ka glacial cycle. Obliquity plays a role by the resonance with precession cycle.

Insolation-driven 100,000-year glacial cycles and hysteresis of ice-sheet volume
Ayako Abe-Ouchi, Fuyuki Saito , Kenji Kawamura, Maureen E. Raymo , Jun'ichi Okuno1, Kunio Takahashi & Heinz Blatter

In summary, our model results suggest that the 100-kyr cycle is essentially produced by the eccentricity modulation of precession amplitude through the changes in summer insolation , with the support of obliquity for glacial terminations, especially when eccentricity remains small after its minimum (for example at termination I 20–10 kyr BP and at termination IV 340–330 kyr BP).

A remarkable conclusion from our model results is therefore that the 100-kyr glacial cycle exists only because of the unique geographic and climatological setting of the North American ice sheet with respect to received insolation. Only for the North American ice sheet is the upper hysteresis branch moderately inclined; that is, there is a gradual change between large and small equilibrium ice-sheet volumes over a large range of insolation forcings. For this reason, as demonstrated in Fig. 2b, the amplitude modulation of summer insolation variation in the precessional cycle, due primarily to eccentricity, is able to generate the 100-kyr cycles with large amplitude, gradual growth and rapid terminations.

They use a simplified climate model with an ice sheet model which can reproduce 100 ky sawtooth cycles. This result is independent of CO2 levels, dust albedo etc. all of which are considered feedbacks. The root 'cause' of this hysteresis effect is the slow isostatic rebound of ice free land.

By contrast, the spectral peak of ,100-kyr cycles is greatly reduced, and permanent large ice sheets remain, with the imposition of instantaneous isostatic rebound (Fig. 1f). This result supports the idea that the crucial mechanism for the ,100-kyr cycles is the delayed glacial isostatic rebound14,15, which keeps the ice elevation low, and, therefore, the ice ablation high, while the ice sheet retreats.

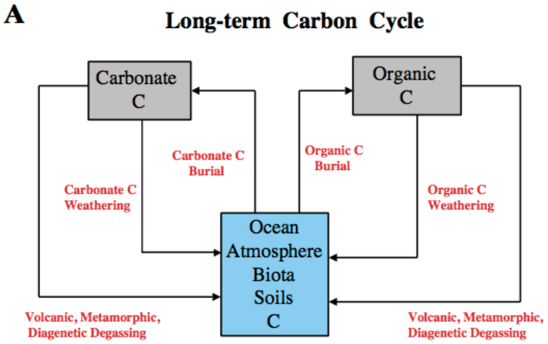
So their key physical explanation for hysteresis is deep glacial land compression with slow rebound.

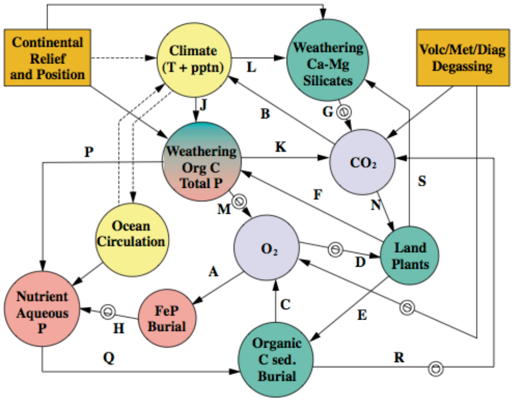
III. "The Rocks Breathe"
100 Million Year Cycles

GEOCARB III: A REVISED MODEL OF ATMOSPHERIC CO2 OVER PHANEROZOIC TIME
ROBERT A. BERNER and ZAVARETH KOTHAVALA,
Department of Geology and Geophysics, Yale University, New Haven, Connecticut 06520-8109,
American Journal of Science, Vol. 301, February, 2001, P. 182–204

and

A New Look at the Long-term Carbon Cycle
Robert A. Berner
GSA Today, Vol. 9, No. 11, November 1999, Pages 1-6
excerpts





The Phanerozoic Eon is the current geologic eon in the geologic time scale, and the one during which abundant animal and plant life has existed. It covers 541 million years to the present, and began with the Cambrian Period when animals first developed hard shells preserved in the fossil record. Its name was derived from the Ancient Greek words φανερός (phanerós) and ζωή (zōḗ), meaning visible life, since it was once believed that life began in the Cambrian, the first period of this eon. Quelle: Wikipedia

ABSTRACT.
Revision of the GEOCARB model (Berner, 1991, 1994) for paleolevels of atmospheric CO2, has been made with emphasis on factors affecting CO2 uptake by continental weathering. This includes:

1) new GCM (general circulation model) results for the dependence of global mean surface temperature and runoff on CO2, for both glaciated and non-glaciated periods, coupled with new results for the temperature response to changes in solar radiation;
2) demonstration that values for the weathering-uplift factor $f_R(t)$ based on Sr isotopes as was done in GEOCARB II are in general agreement with independent values calculated from the abundance of terrigenous sediments as a measure of global physical erosion rate over Phanerozoic time;
3) more accurate estimates of the timing and the quantitative effects on Ca-Mg silicate weathering of the rise of large vascular plants on the continents during the Devonian (419 - 359 million years ago. Also informally known as the "Age of the Fish", the Devonian features a huge diversification in fish);
4) inclusion of the effects of changes in paleogeography alone (constant CO2 and solar radiation) on global mean land surface temperature as it affects the rate of weathering;
5) consideration of the effects of volcanic weathering, both in subduction zones and on the seafloor;
6) use of new data on the delta13C values for Phanerozoic limestones and organic matter;
7) consideration of the relative weathering enhancement by gymnosperms versus angiosperms; (gymnosperms = naked-seed plants, e.g. conifers, ginko, angiosperms = fruit producing plants)
8) revision of paleo-land area based on more recent data and use of this data, along with GCM-based paleo-runoff results, to calculate global water discharge from the continents over time.

Results show a similar overall pattern to those for GEOCARB II:

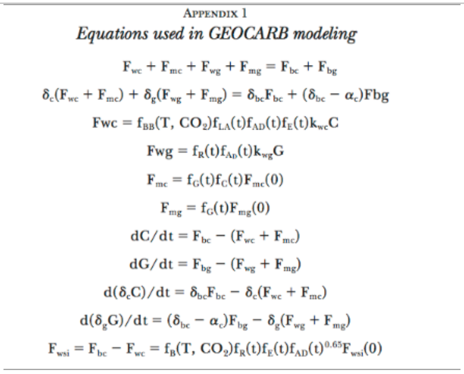
- very high CO2 values during the early Paleozoic,
- a large drop during the Devonian and Carboniferous,
- high values during the early Mesozoic, and
- a gradual decrease from about 170 Ma to low values during the Cenozoic.

However, the new results exhibit considerably higher CO2 values during the Mesozoic, and their downward trend with time agrees with the independent estimates of Ekart and others (1999). Sensitivity analysis shows that results for paleo-CO2 are especially sensitive to:

- the effects of CO2 fertilization and temperature on the acceleration of plant-mediated chemical weathering;
- the quantitative effects of plants on mineral dissolution rate for constant temperature and CO2;
- the relative roles of angiosperms and gymnosperms in accelerating rock weathering; and
- the response of paleo-temperature to the global climate model used.

This emphasizes the need for further study of the role of plants in chemical weathering and the application of GCMs to study of paleo-CO2 and the long term carbon cycle.

run GEOCARB-Model for a CO2 spike:
http://climatemodels.uchicago.edu/geocarb/



APPENDIX 1
Equations used in GEOCARB modeling

$$F_{wc} + F_{mc} + F_{wg} + F_{mg} = F_{bc} + F_{bg}$$

$$\delta_c(F_{wc} + F_{mc}) + \delta_g(F_{wg} + F_{mg}) = \delta_{bc}F_{bc} + (\delta_{bc} - \alpha_c)Fbg$$

$$Fwc = f_{BB}(T, CO_2)f_{LA}(t)f_{AD}(t)f_E(t)k_{wc}C$$

$$Fwg = f_R(t)f_{A_D}(t)k_{wg}G$$

$$F_{mc} = f_G(t)f_C(t)F_{mc}(0)$$

$$F_{mg} = f_G(t)F_{mg}(0)$$

$$dC/dt = F_{bc} - (F_{wc} + F_{mc})$$

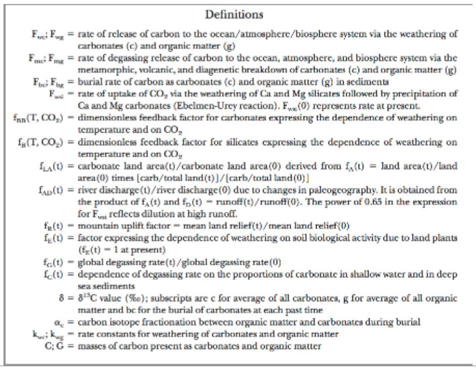
$$dG/dt = F_{bg} - (F_{wg} + F_{mg})$$

$$d(\delta_c C)/dt = \delta_{bc}F_{bc} - \delta_c(F_{wc} + F_{mc})$$

$$d(\delta_g G)/dt = (\delta_{bc} - \alpha_c)F_{bg} - \delta_g(F_{wg} + F_{mg})$$

$$F_{wsi} = F_{bc} - F_{wc} = f_B(T, CO_2)f_R(t)f_E(t)f_{AD}(t)^{0.65}F_{wsi}(0)$$

C = mass of carbon in lithosphere
c = carbon as carbonate, g = carbon as organic matter
w = weathering, m = metamorphism, b = burial
F = release rate
F_{wc} = release rate of carbon to the ocean/atmosphere/biosphere system via weathering
F_{mc} = release rate via degassing from metamorphic breakdown of carbonates
F_{bc} = burial rate of carbon as carbonate
f_{BB}(T, CO2) = feedback factor for carbonates weathering dependence on (T, CO2)
f_B(T, CO2) = feedback factor for silicates weathering dependence on (T, CO2)
k = weathering rate constants



Definitions

$F_{wc}; F_{wg}$ = rate of release of carbon to the ocean/atmosphere/biosphere system via the weathering of carbonates (c) and organic matter (g)
$F_{mc}; F_{mg}$ = rate of degassing release of carbon to the ocean, atmosphere, and biosphere system via the metamorphic, volcanic, and diagenetic breakdown of carbonates (c) and organic matter (g)
$F_{bc}; F_{bg}$ = burial rate of carbon as carbonates (c) and organic matter (g) in sediments
F_{wsi} = rate of uptake of CO_2 via the weathering of Ca and Mg silicates followed by precipitation of Ca and Mg carbonates (Ebelmen-Urey reaction). $F_{wsi}(0)$ represents rate at present.
$f_{BB}(T, CO_2)$ = dimensionless feedback factor for carbonates expressing the dependence of weathering on temperature and on CO_2
$f_B(T, CO_2)$ = dimensionless feedback factor for silicates expressing the dependence of weathering on temperature and on CO_2
$f_{LA}(t)$ = carbonate land area(t)/carbonate land area(0) derived from $f_A(t)$ = land area(t)/land area(0) times [carb/total land(t)]/[carb/total land(0)]
$f_{AD}(t)$ = river discharge(t)/river discharge(0) due to changes in paleogeography. It is obtained from the product of $f_A(t)$ and $f_D(t)$ = runoff(t)/runoff(0). The power of 0.65 in the expression for F_{wsi} reflects dilution at high runoff.
$f_R(t)$ = mountain uplift factor = mean land relief(t)/mean land relief(0)
$f_E(t)$ = factor expressing the dependence of weathering on soil biological activity due to land plants ($f_E(t)$ = 1 at present)
$f_G(t)$ = global degassing rate(t)/global degassing rate(0)
$f_C(t)$ = dependence of degassing rate on the proportions of carbonate in shallow water and in deep sea sediments
δ = $\delta^{13}C$ value (‰); subscripts are c for average of all carbonates, g for average of all organic matter and bc for the burial of carbonates at each past time
α_c = carbon isotope fractionation between organic matter and carbonates during burial
$k_{wc}; k_{wg}$ = rate constants for weathering of carbonates and organic matter
C; G = masses of carbon present as carbonates and organic matter

Tyler Volk. Feedbacks between weathering and atmospheric CO2 over the last 100 million years, American Journal of Science, Volume 287, Issue 8, Pages 763-779, 1987
Feedbacks between weathering and atmospheric CO 2 over the last ...www.ajsonline.org

carbon transfer (Archer book page 92)
because

atmosphere -> ocean: 90 GtC/a
atmosphere -> weathering -> sediments: 0.1 GtC/a

the C depletion of the atmosphere via atmosphere -> ocean transfer is 1000 times faster than via the atmosphere -> sediment transfer.

with atmosphere -> ocean cycles: 100 ka it might follow that atmosphere -> sediment cycles: 100 Ma

----

How to cite

Further info
https://www.ncdc.noaa.gov/abrupt-climate-change

Why do glacial periods end abruptly? [Oceans inhale CO2]

Notice the asymmetric shape of the Antarctic temperature record (black line), with abrupt warmings shown in yellow preceding more gradual coolings (Kawamura et al. 2007; Jouzel et al. 2007). Warming at the end of glacial periods tends to happen more abruptly than the increase in solar insolation. Several positive feedbacks are responsible for this.

- One is the ice-albedo feedback.
- A second feedback involves atmospheric CO2.

Direct measurement of past CO2 trapped in ice core bubbles shows that the amount of atmospheric CO2 decreased during glacial periods (Kawamura et al. 2007; Siegenthaler et al. 2005; Bereiter et al. 2015), in part because the *deep ocean stored more CO2 due to changes in either ocean mixing or biological activity*. Lower CO2 levels weakened the atmosphere's greenhouse effect and helped to maintain lower temperatures. Warming at the end of the glacial periods liberated CO2 from the ocean, which strengthened the atmosphere's greenhouse effect and contributed to further warming.

Version: 16.9.2019
Address of this page
Home
Joachim Gruber