(Models: Tools for exploring and testing hypotheses of the Cretaceous world)

Andy Ridgwell

UCR University of BRISTOL THE ROYAL SOCIETY CELEBRATING 350 YEARS European Research Council Established by the European Commission erc

fun with models and data

(Models: Tools for exploring and testing hypotheses of the Cretaceous world)

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Challenges (model world):

- Bringing model output and data sufficiently close together to allow for a correct interpretation.
- Cretaceous ocean circulation – how can we constrain it? (proxies, model physics/resolution)
And surface climate and lack of polar warmth in many GCMs, whilst we are about it ...
- Are we looking at steady states or dynamical transients and can we (numerically afford to) model either?
- Can we adequately constrain the bulk chemistry of the ocean (e.g. DIC, ALK, Ca^{2+}, Mg^{2+}) and hence carbonate chemistry (e.g. *p*H).
Also: time-scale of change.
- How finely can we resolve ocean redox? Can we do rather better than 'significant vs. no' euxinia?
- Can we (develop and) use models to help interpret the micropaleontological record?
- Where do the 'wiggles' (in $\delta^{13}C$ / $\delta^{18}O$ / wt% $CaCO_3$) come from? What do they 'mean?
- Who can drive models? Is a driving test necessary? Can it all be made much easier and models more accessible?

Consider:
Global mean annual average surface air temperature
(n-steps removed from the 'data')

T = 23.776831°C

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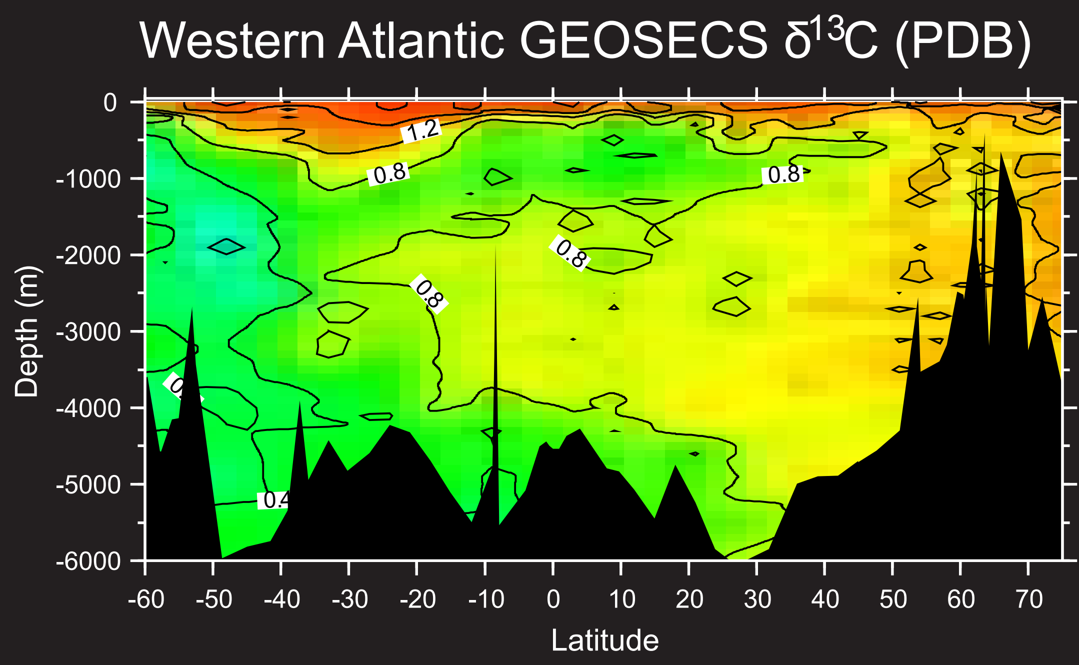
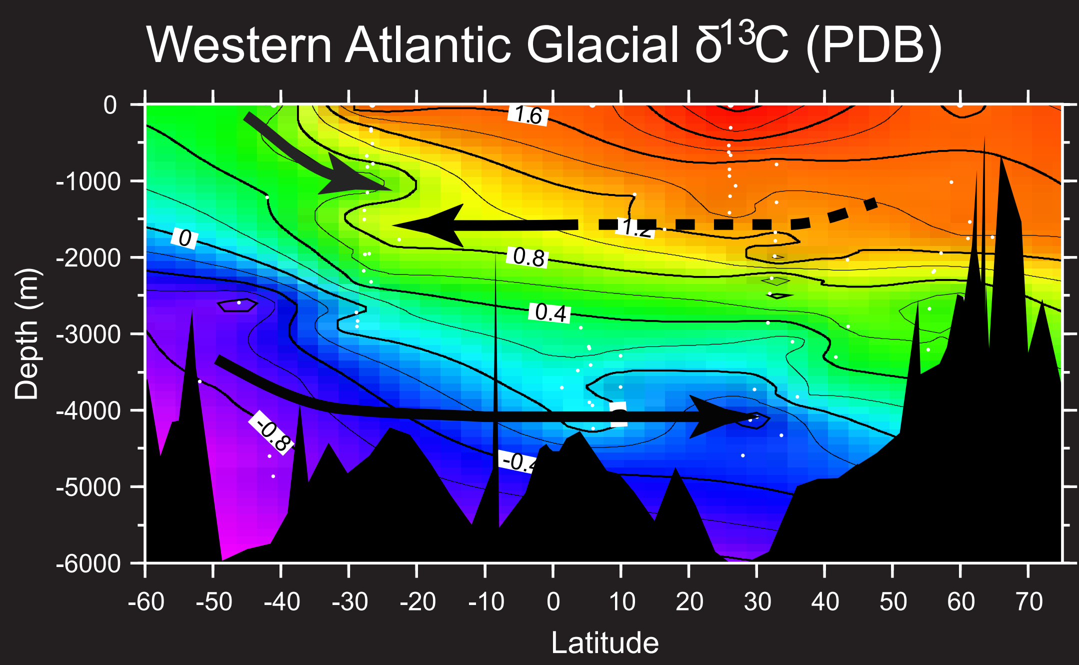
Global mean annual average surface air temperature
(n-steps removed from the 'data')

~~T = 23.776831°C~~

T = 23.77683083691290°C

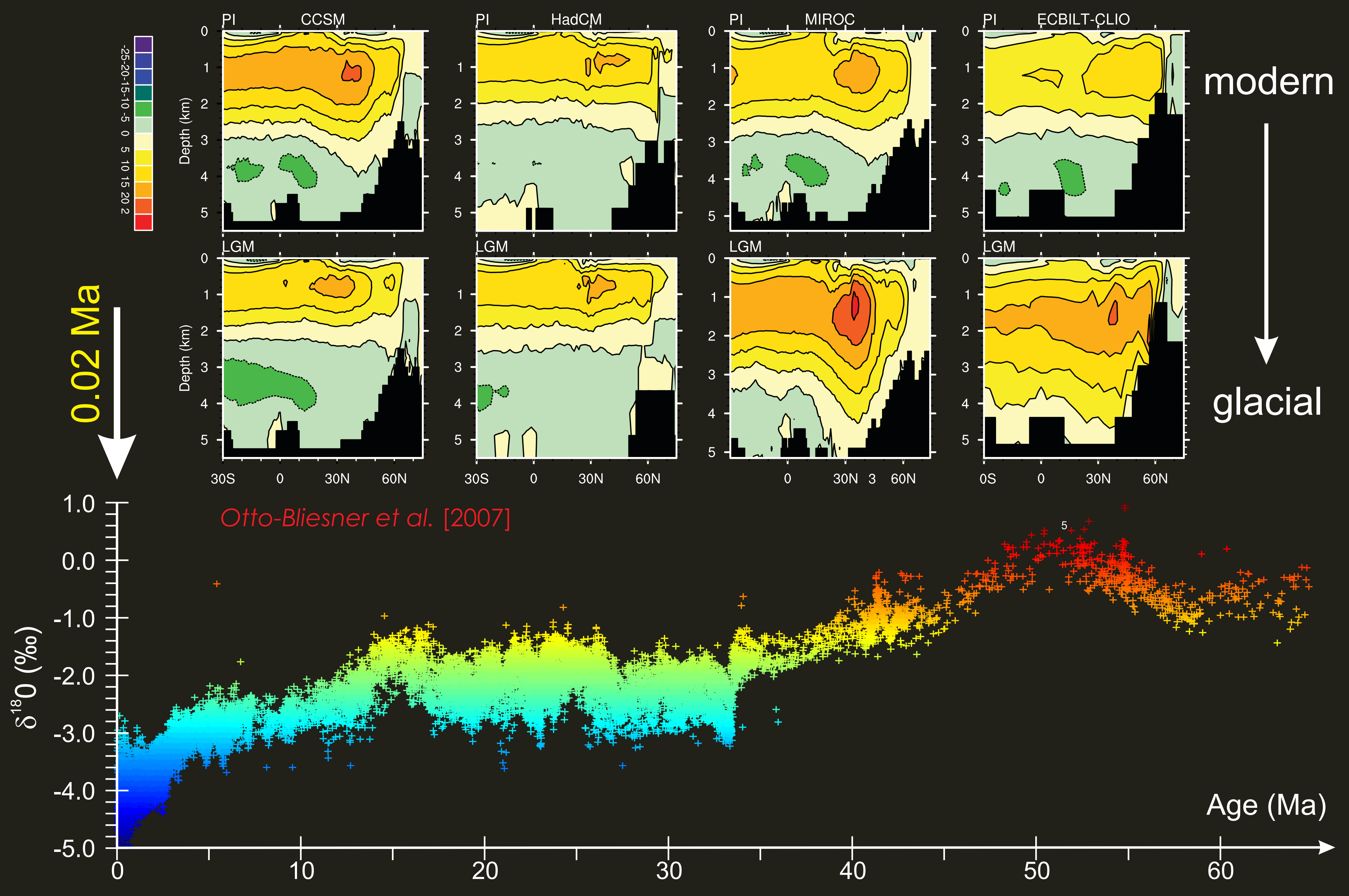
Meanwhile, in the ocean ...





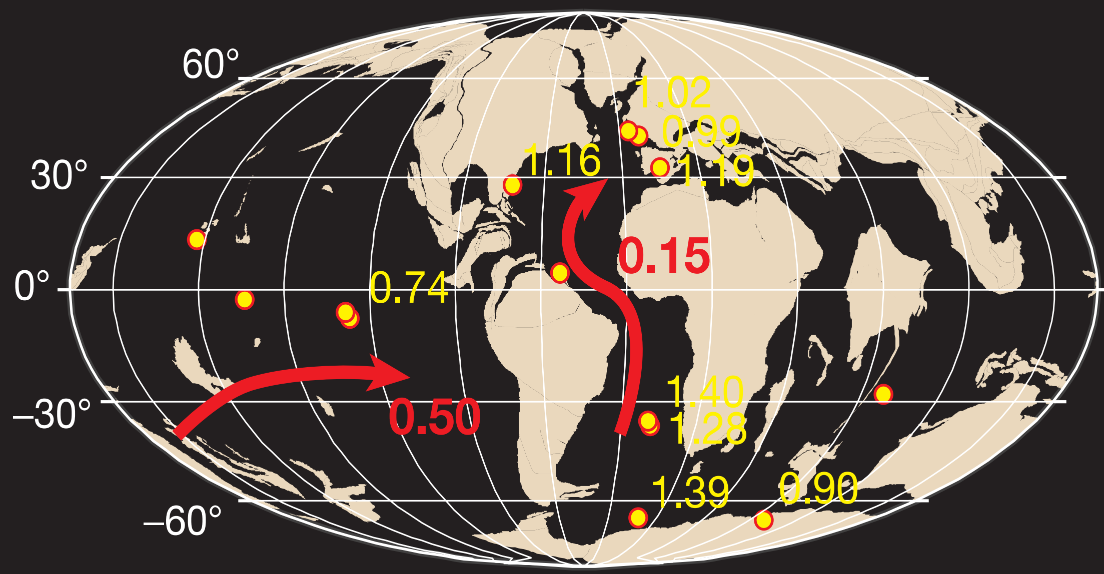
The distribution of $\delta^{13}C$ of ΣCO_2 in the modern western Atlantic [*Kroopnick*, 1985] vs. a recently updated glacial transect of $\delta^{13}C$ of ΣCO_2 for the western Atlantic Ocean basins [*Curry and Oppo*, 2005].

Spatial patterns, but still (n-1)-steps removed from the 'data'



Meanwhile, in the ocean ...

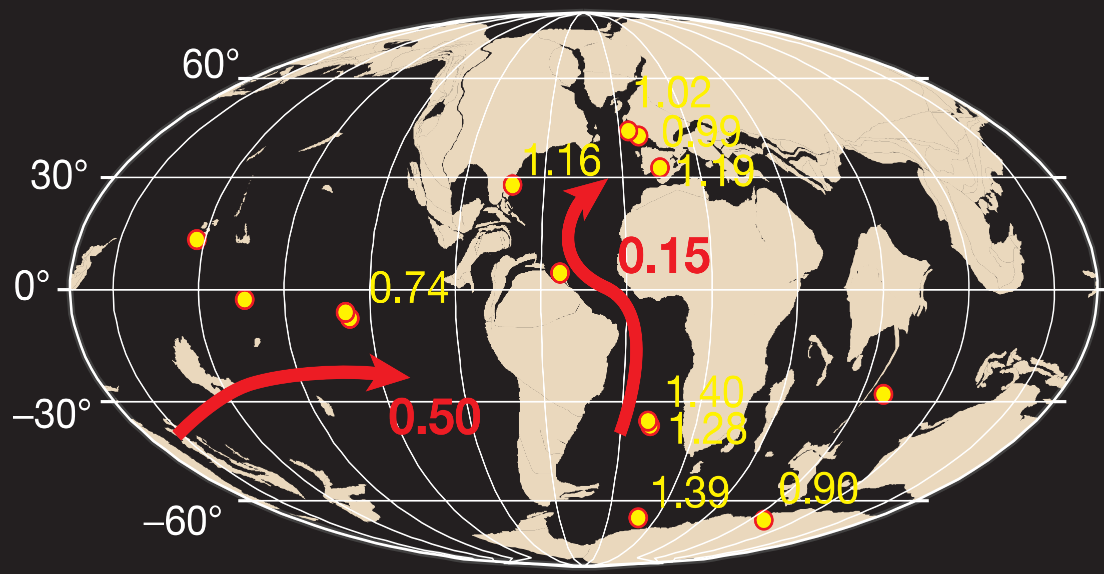
DATA:
Nunes and Norris [2006]



Late Paleocene
benthic δ^{13}C patterns

Closer ... 2-steps removed from the 'data'

DATA:
Nunes and Norris [2006]

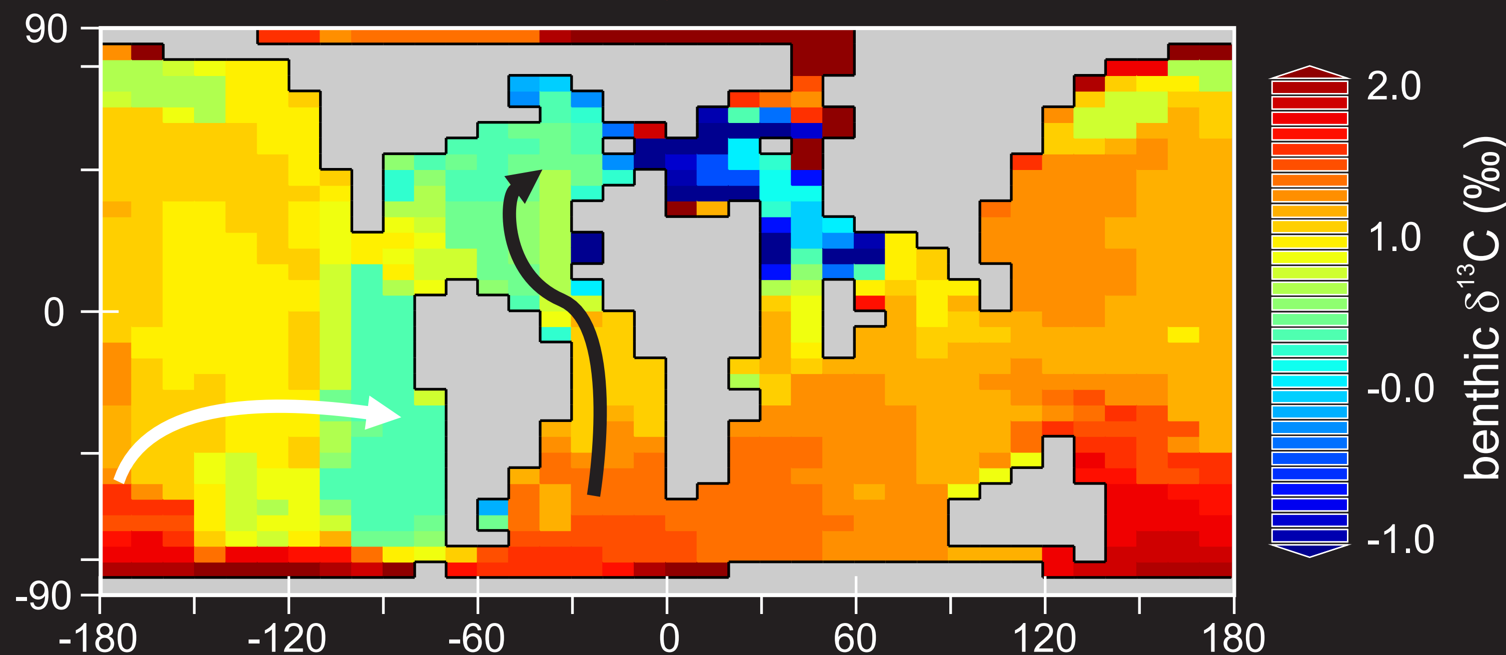


Late Paleocene benthic δ^{13}C patterns

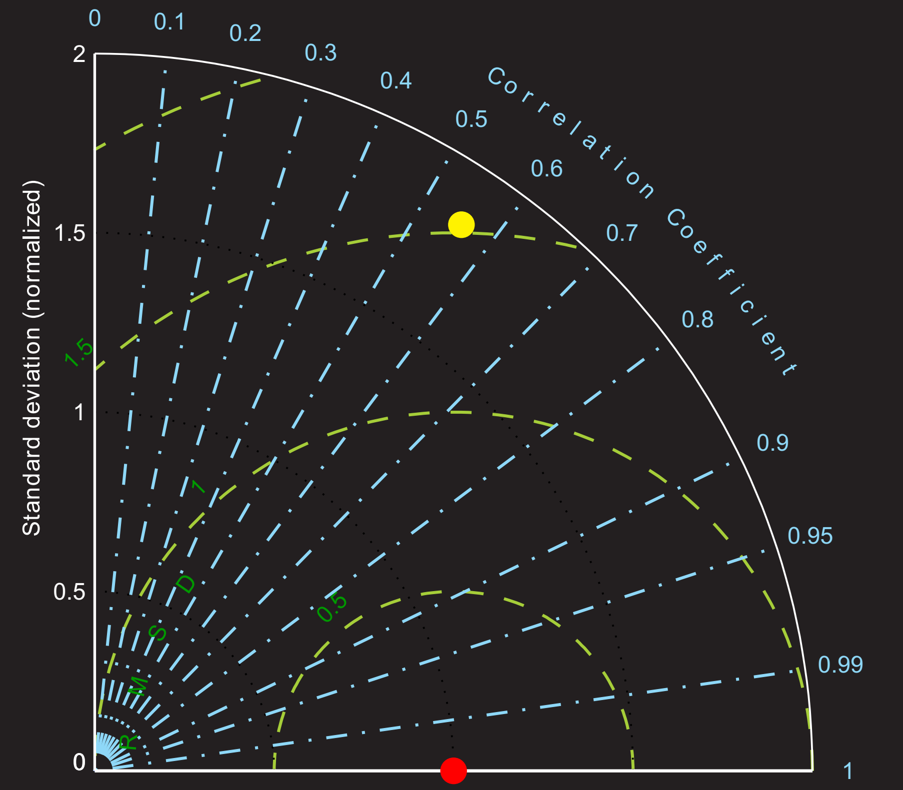
Model-predicted gradients in benthic δ^{13}C (both direction and approximate magnitude) can be compared to available data-based reconstructions.

evaluation

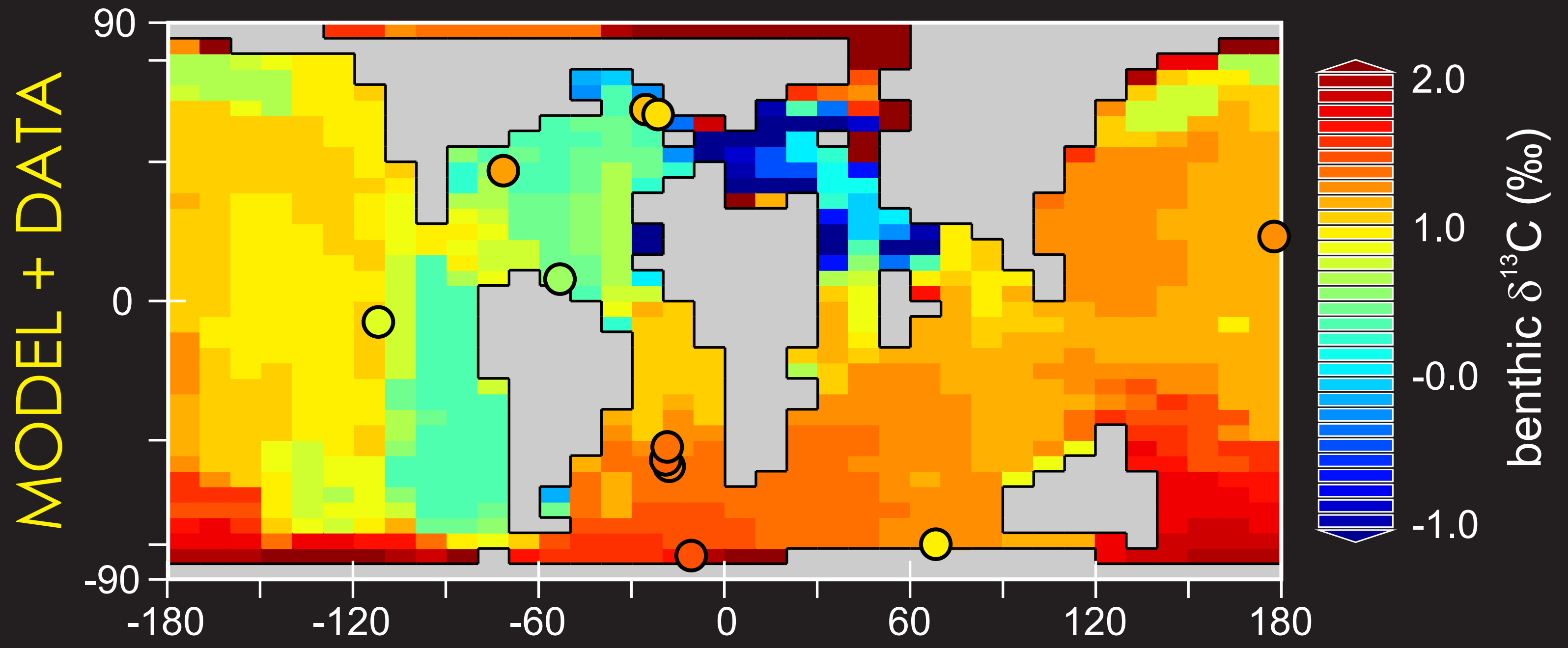
MODEL



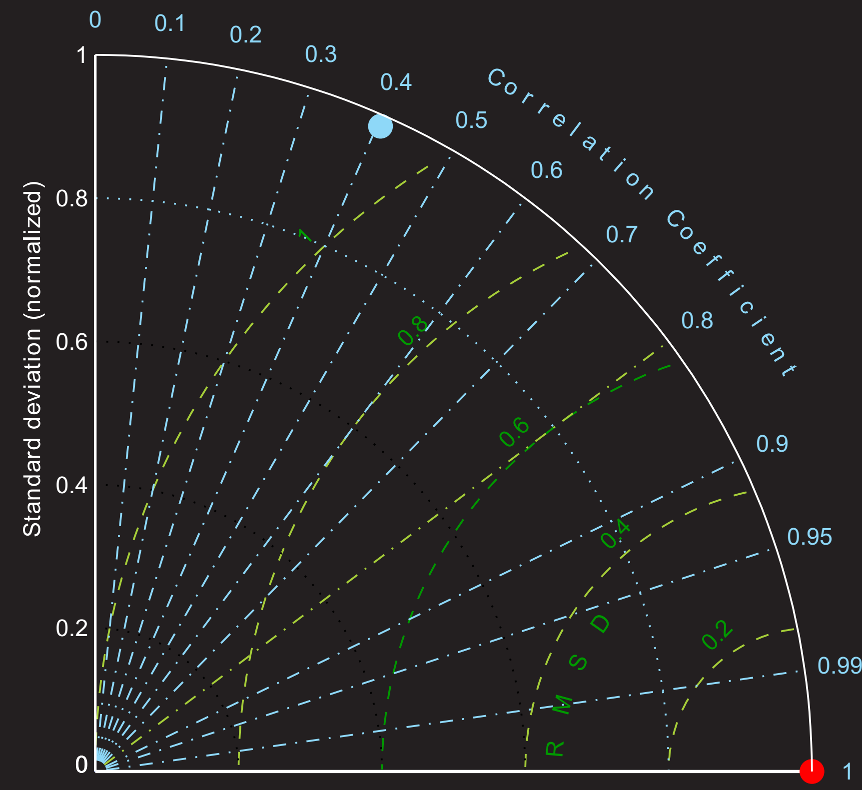
Closer ... 2-steps removed from the 'data'

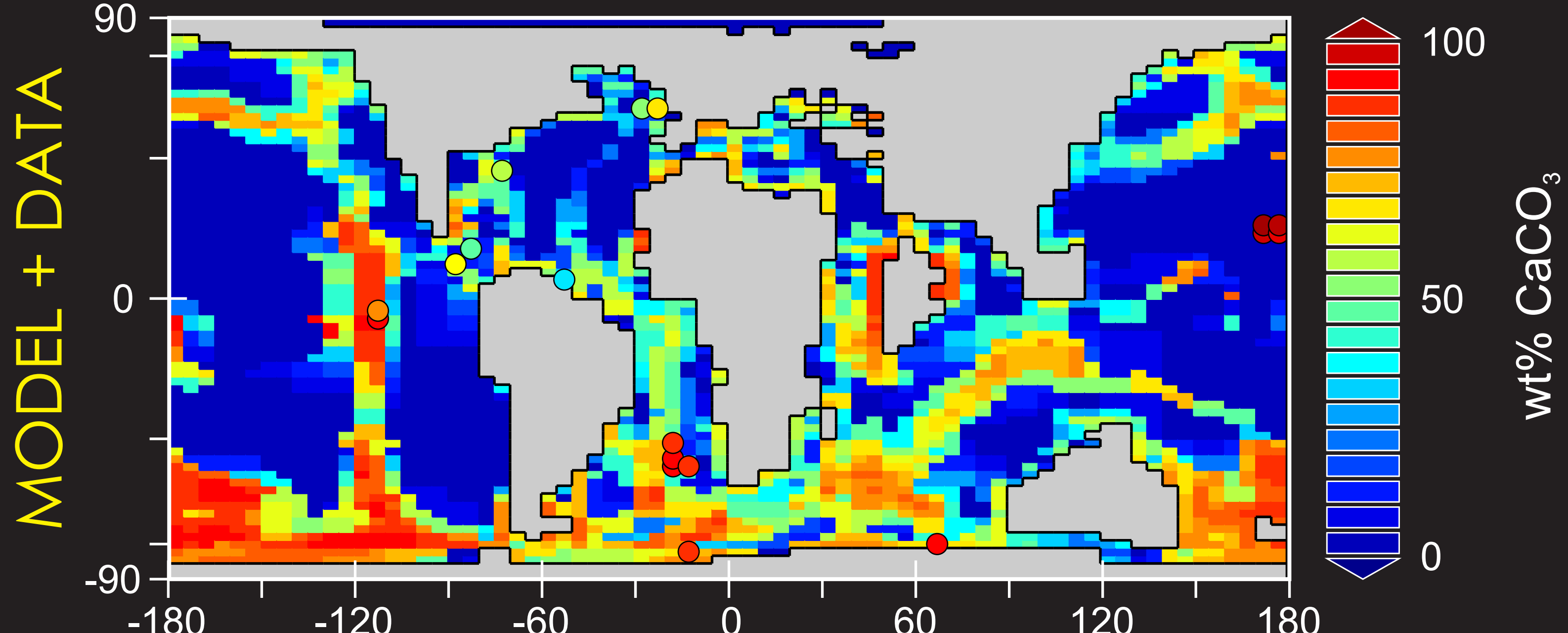


Model-predicted benthic $\delta^{13}C$ can be assessed statistically vs. observations by e.g., 'Taylor diagrams'

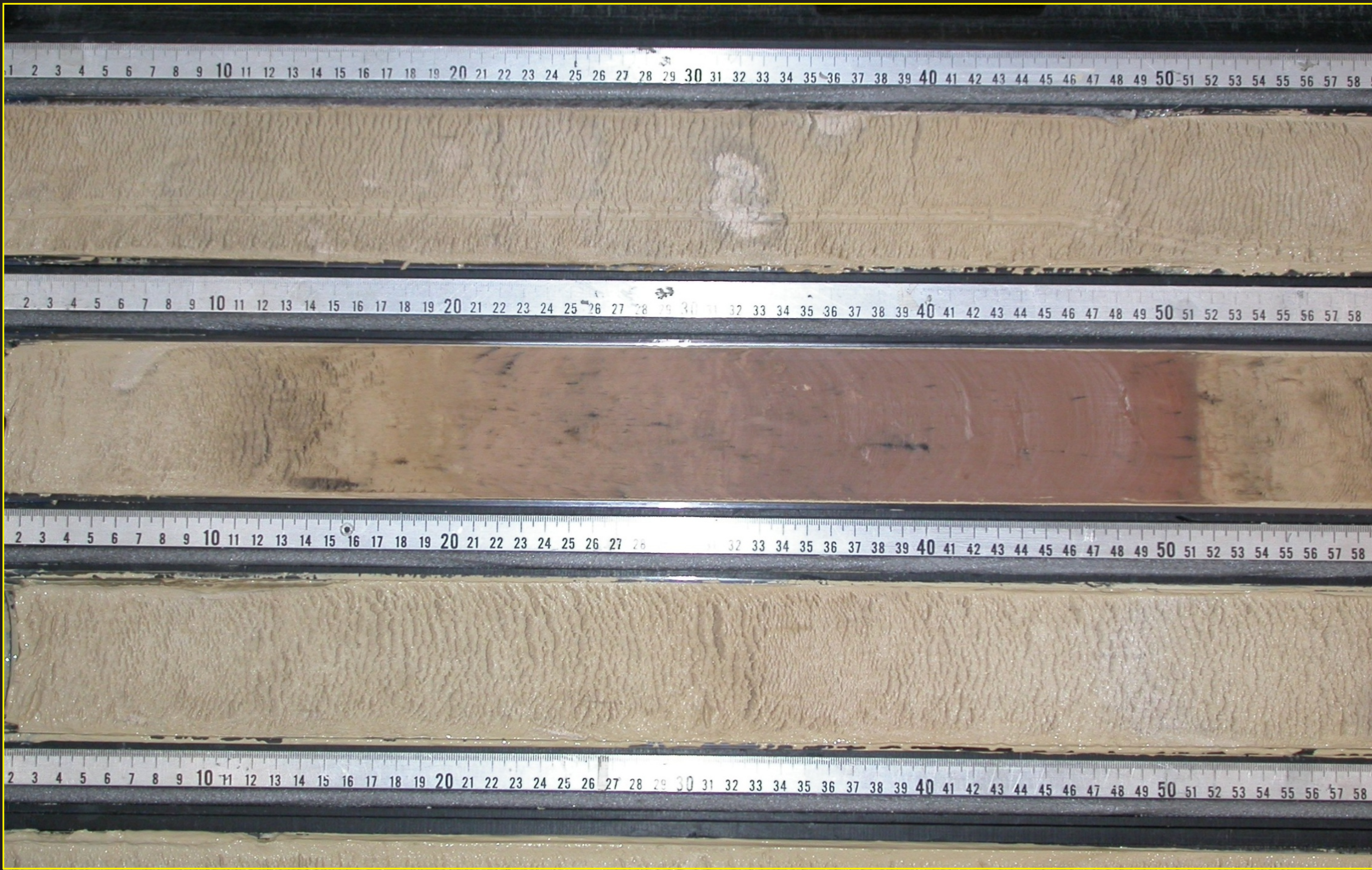


Down to 1-step removed from the 'data'





The data ...



Sediments spanning the Palaeocene-Eocene boundary recovered from ODP Leg 208 (Walvis Ridge)
Picture courtesy of Daniela Schmidt (University of Bristol)

Can we bring sufficient process-based 'realism' to models that they can be contrasted unambigeousy with data?

What do we know about ... ocean circulation (in a warm climate)?

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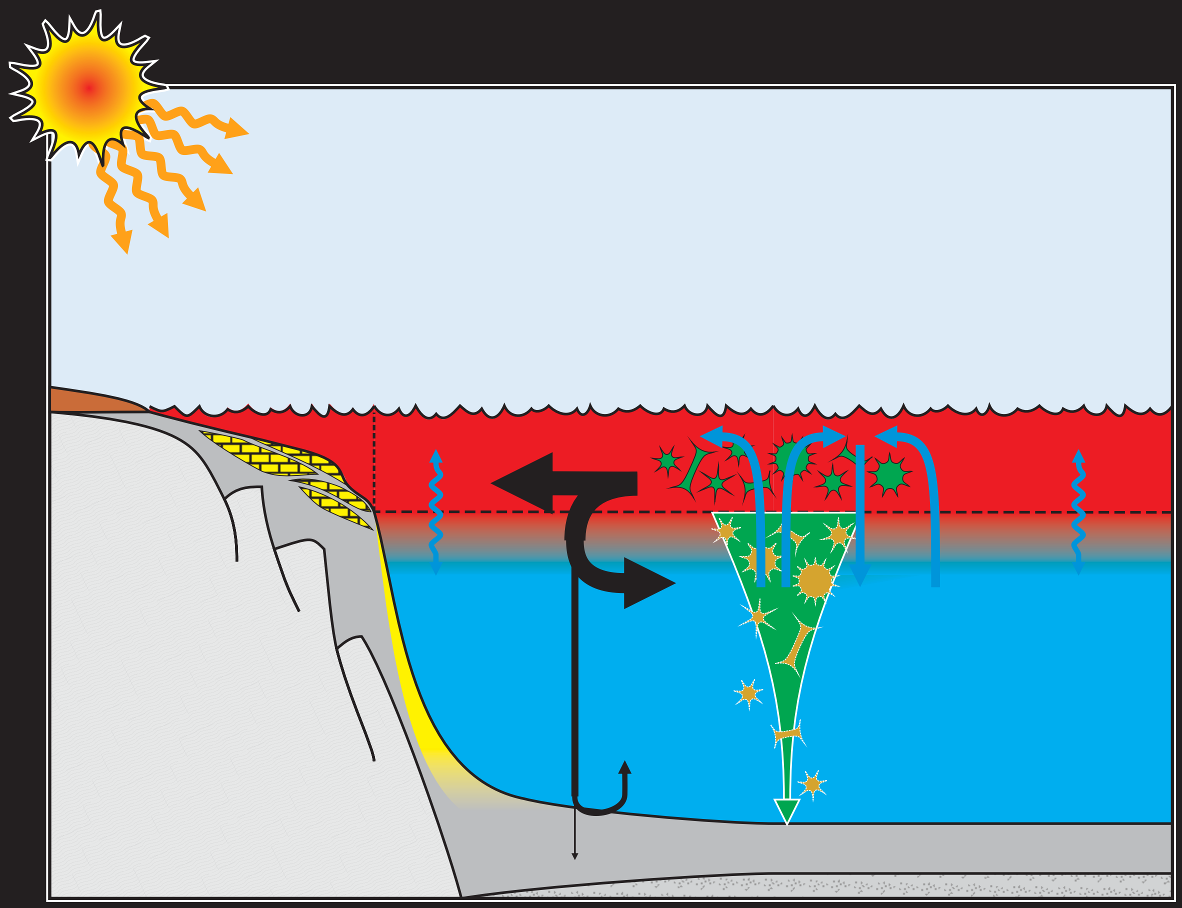
(warm == stratified) && (stratified == anoxic) == .true.

???

('stratified' || 'sluggish' || 'stagnant')



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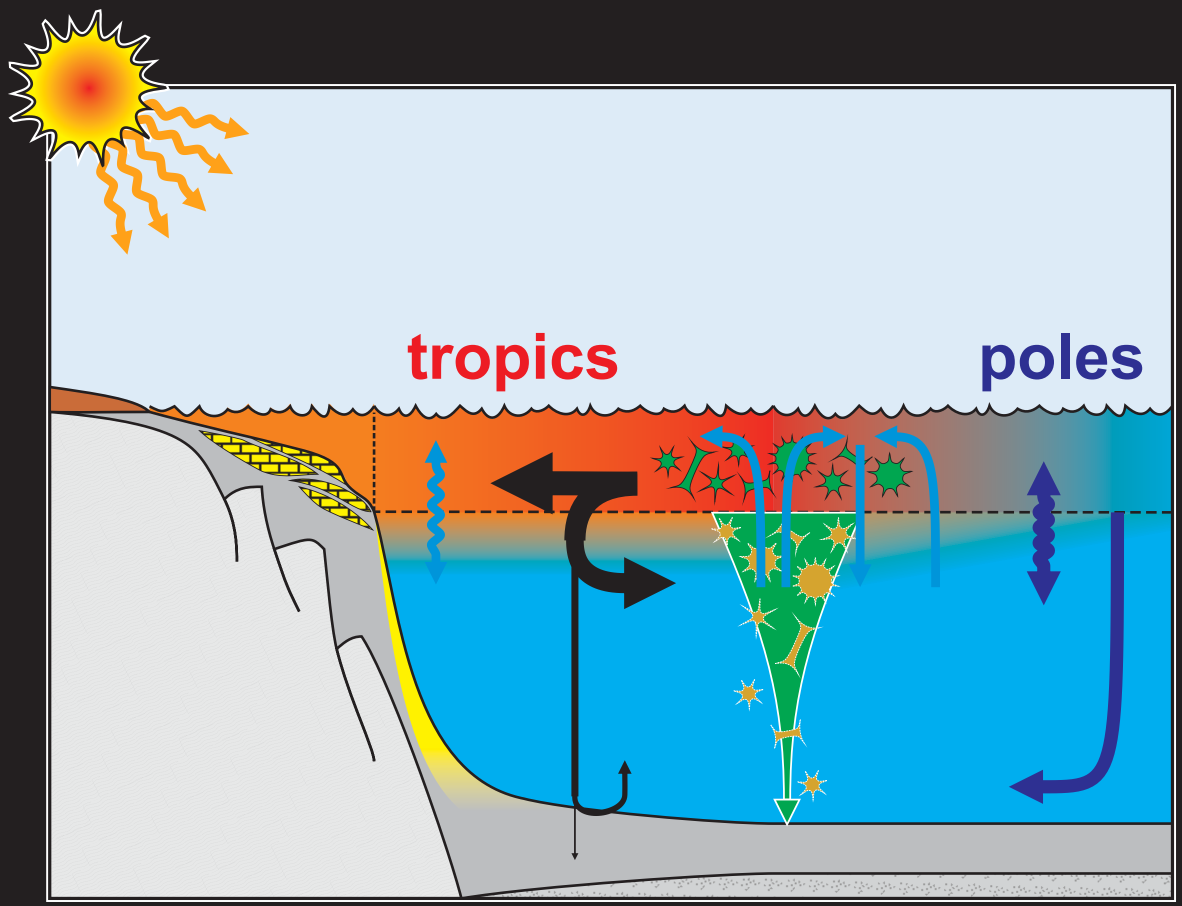
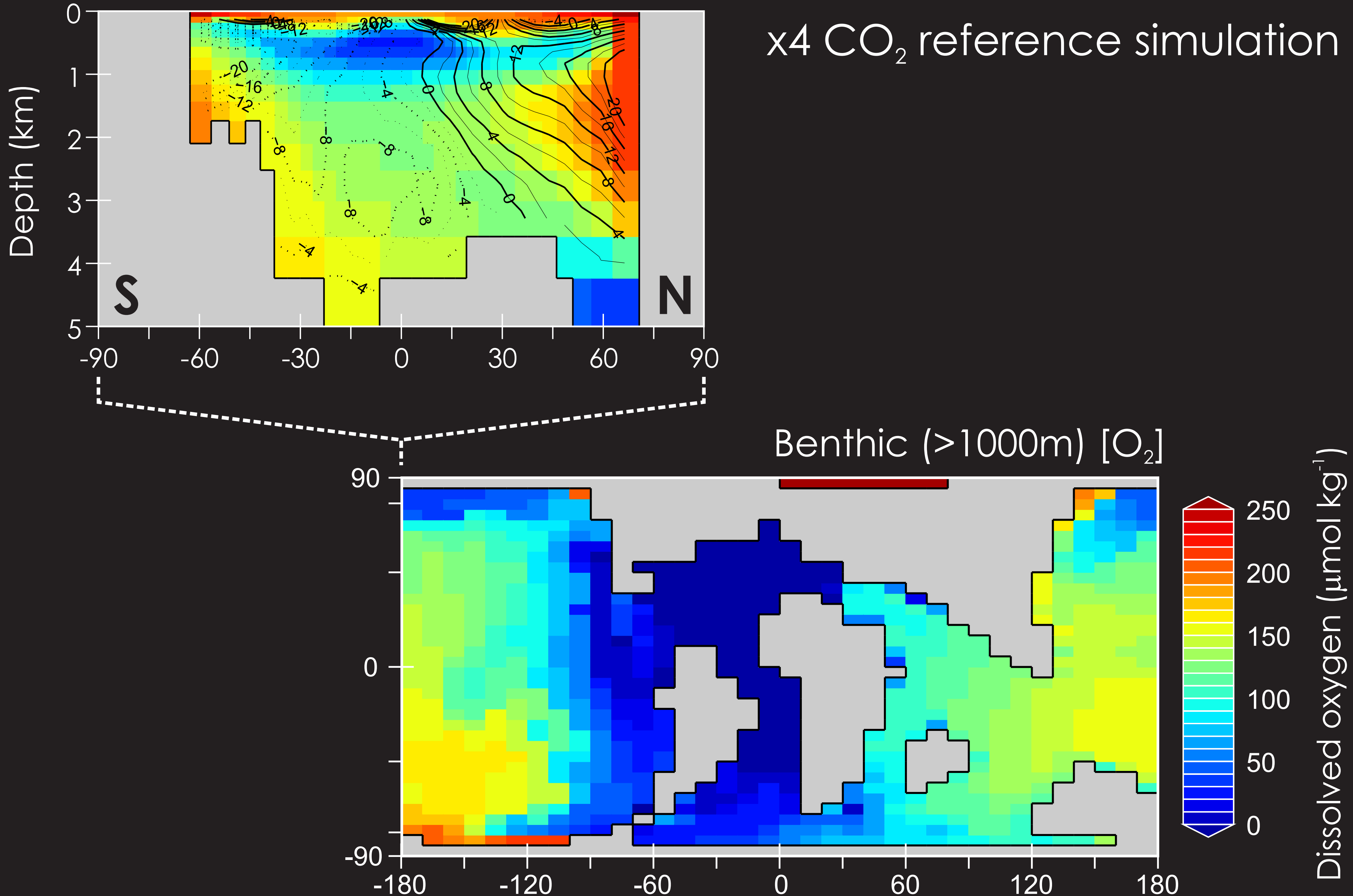


Is either view at all applicable?
Are we missing key physics in models and/or critical insights into ways in which the Cretaceous climate system might have operated differently?
(We already know that coupled GCMs tend not to obtain adequate warm poles.)

What do we know about ... ocean circulation (in a warm climate)?

x4 CO_2 reference simulation



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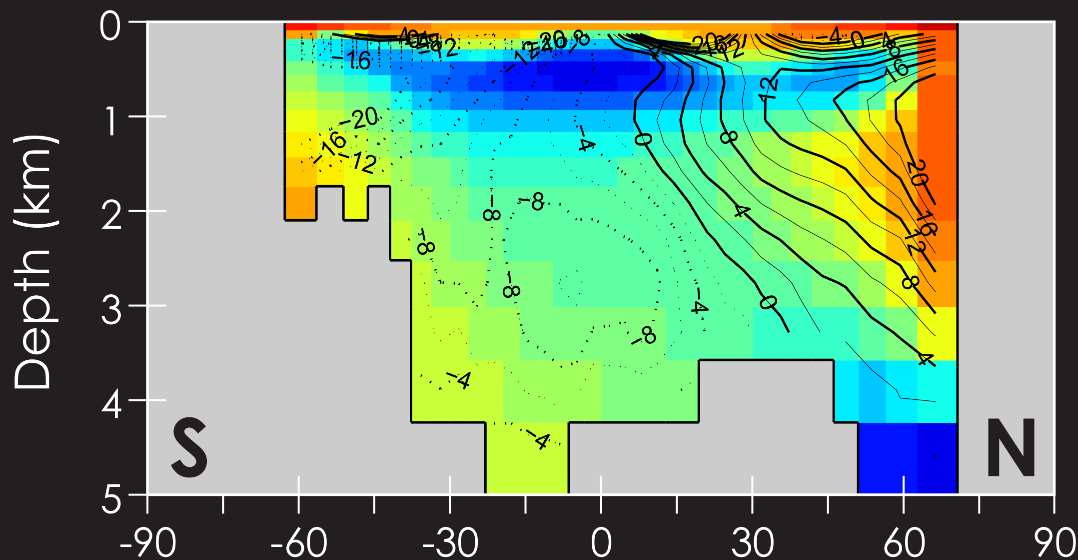
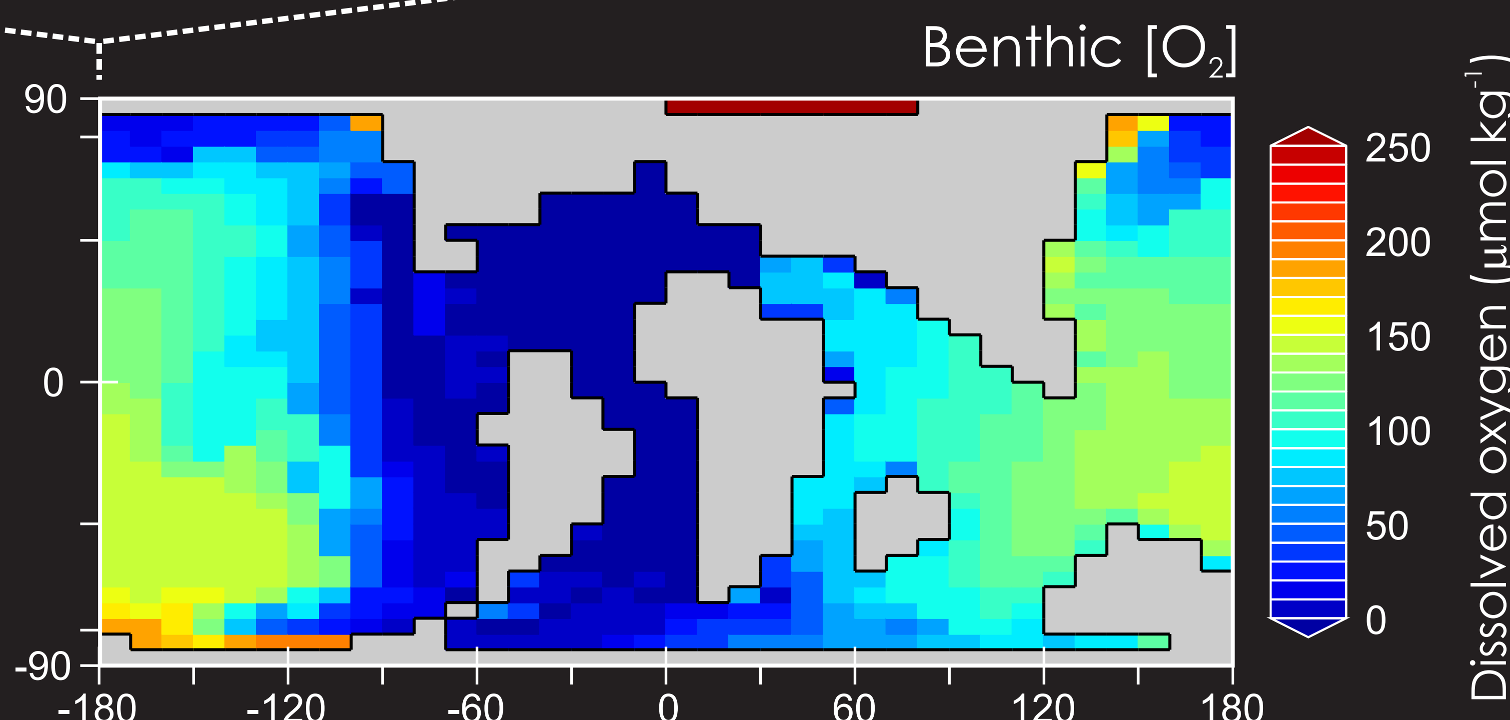


x8 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)



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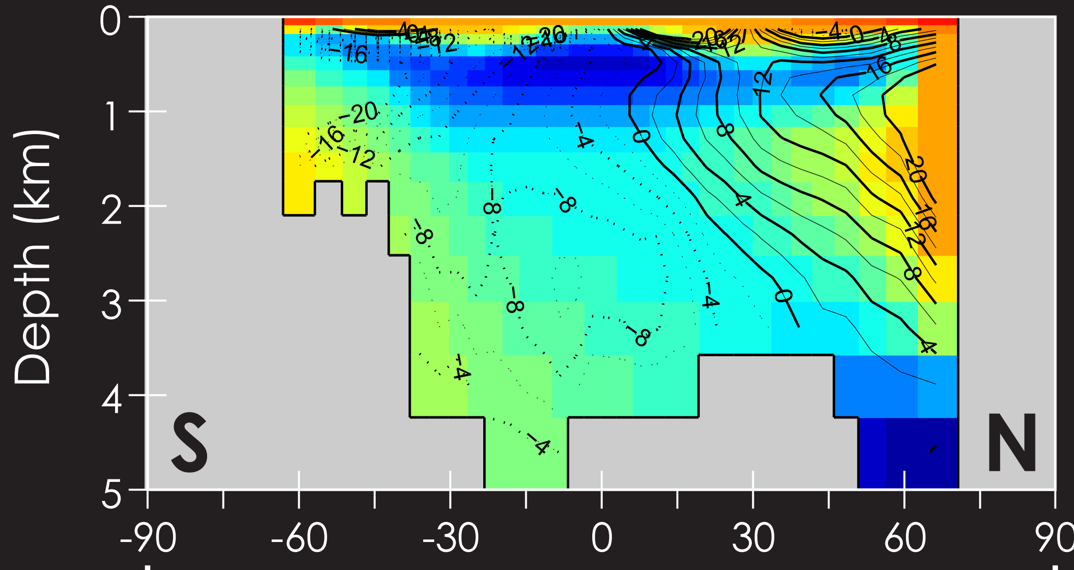
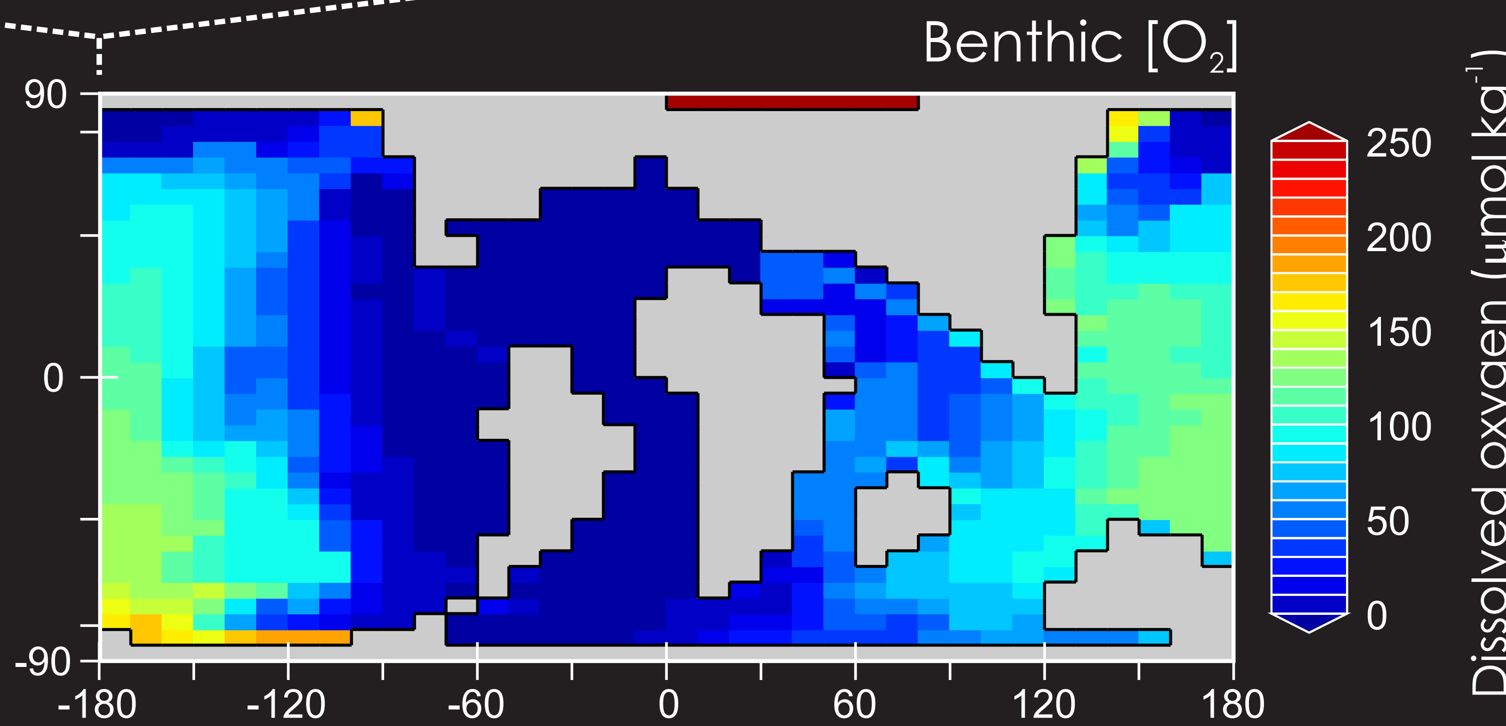
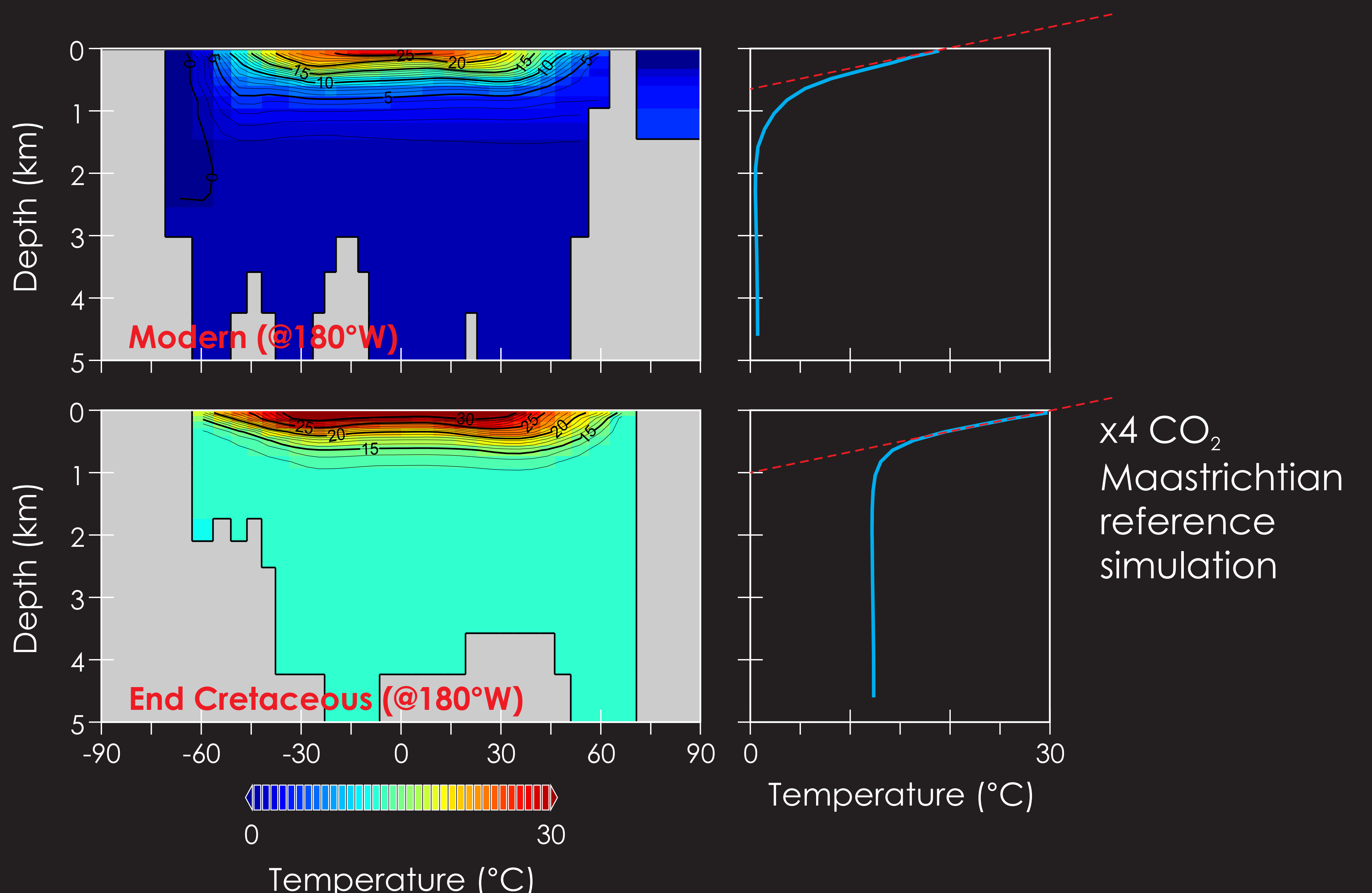


x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)



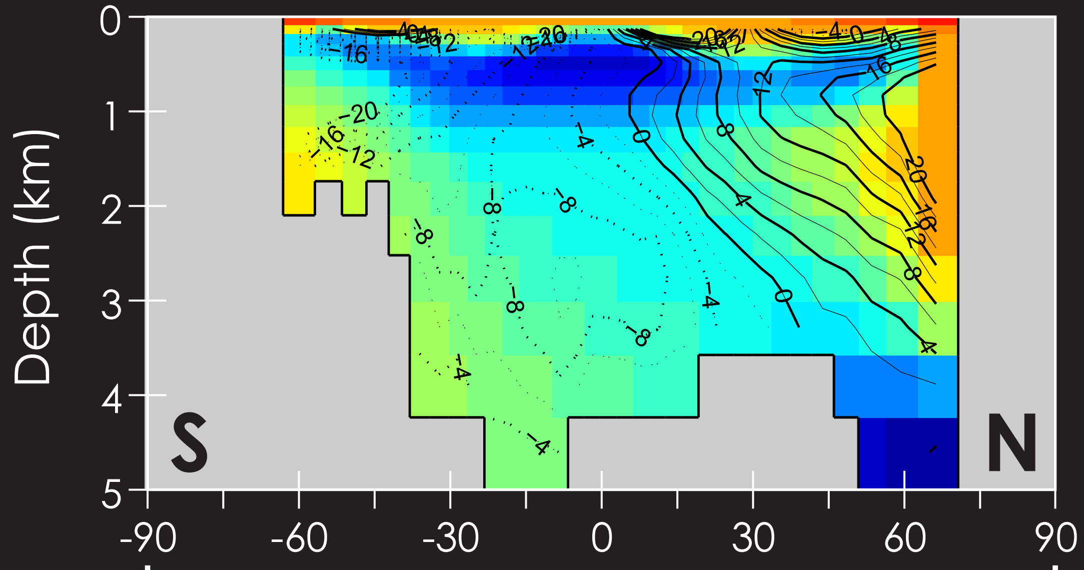
What do we know about ... ocean circulation (in a warm climate)?

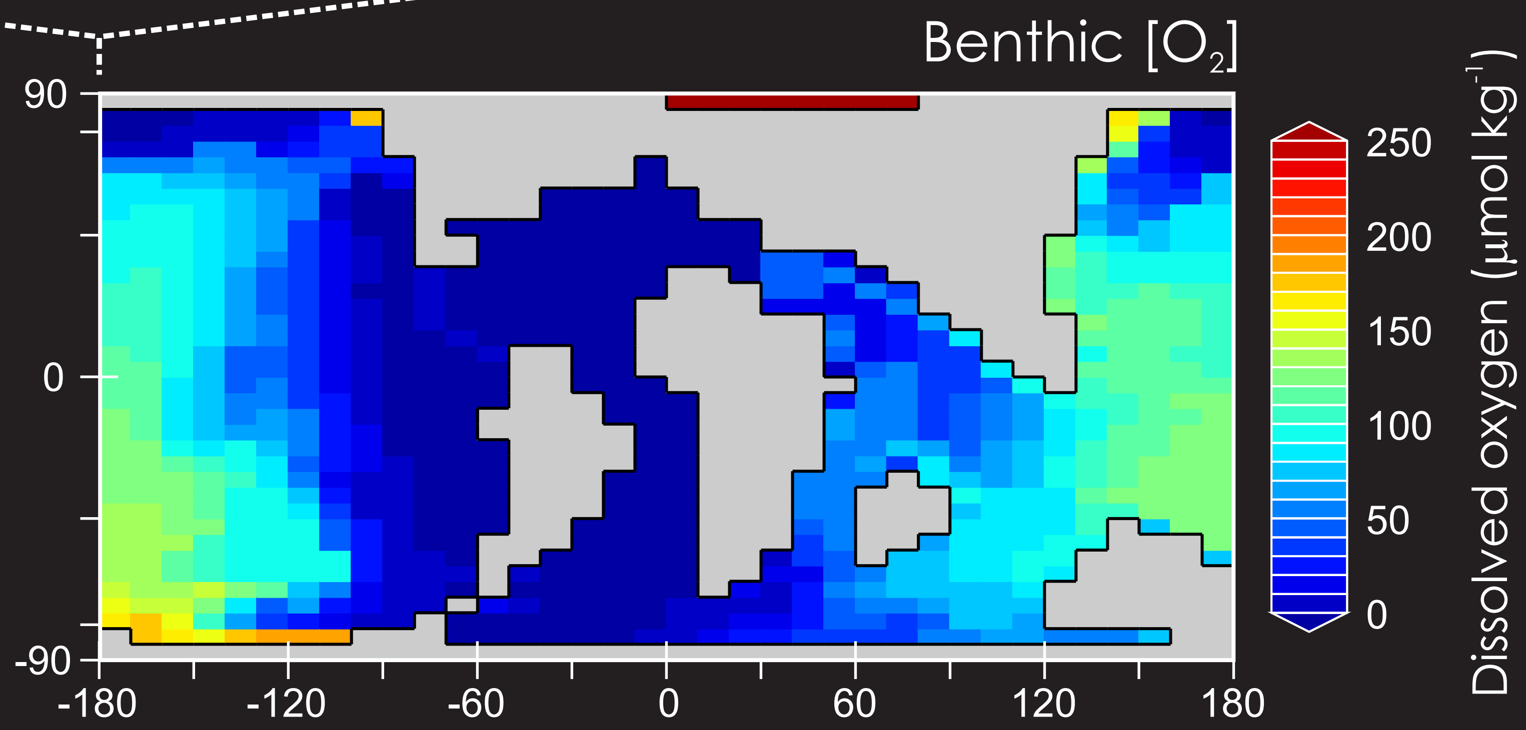


What do we know about ... ocean circulation (in a warm climate)?

x16 CO_2 @ 10,000 yrs

(started from end of the x4 simulation)





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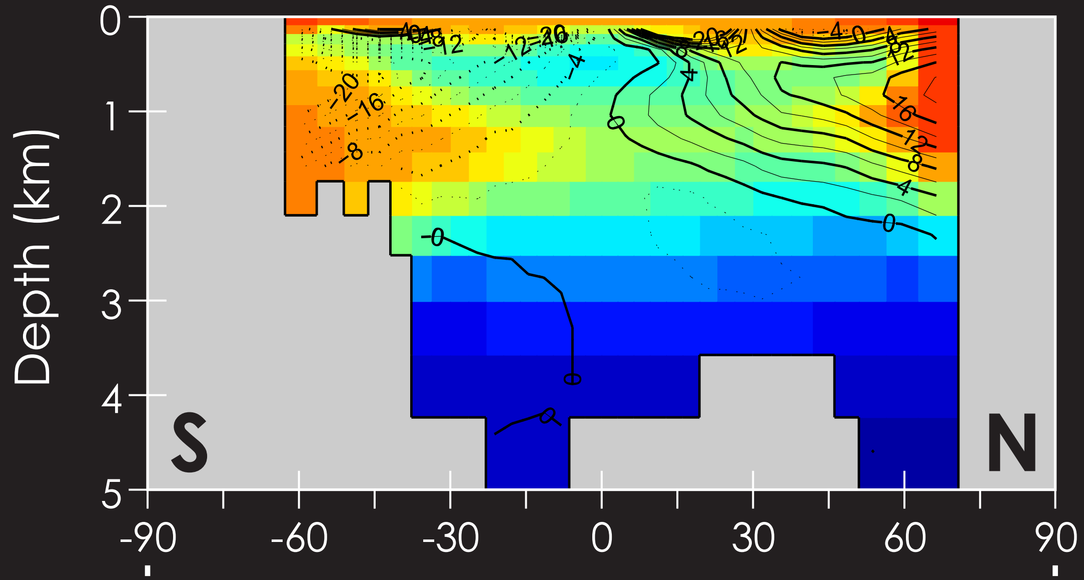
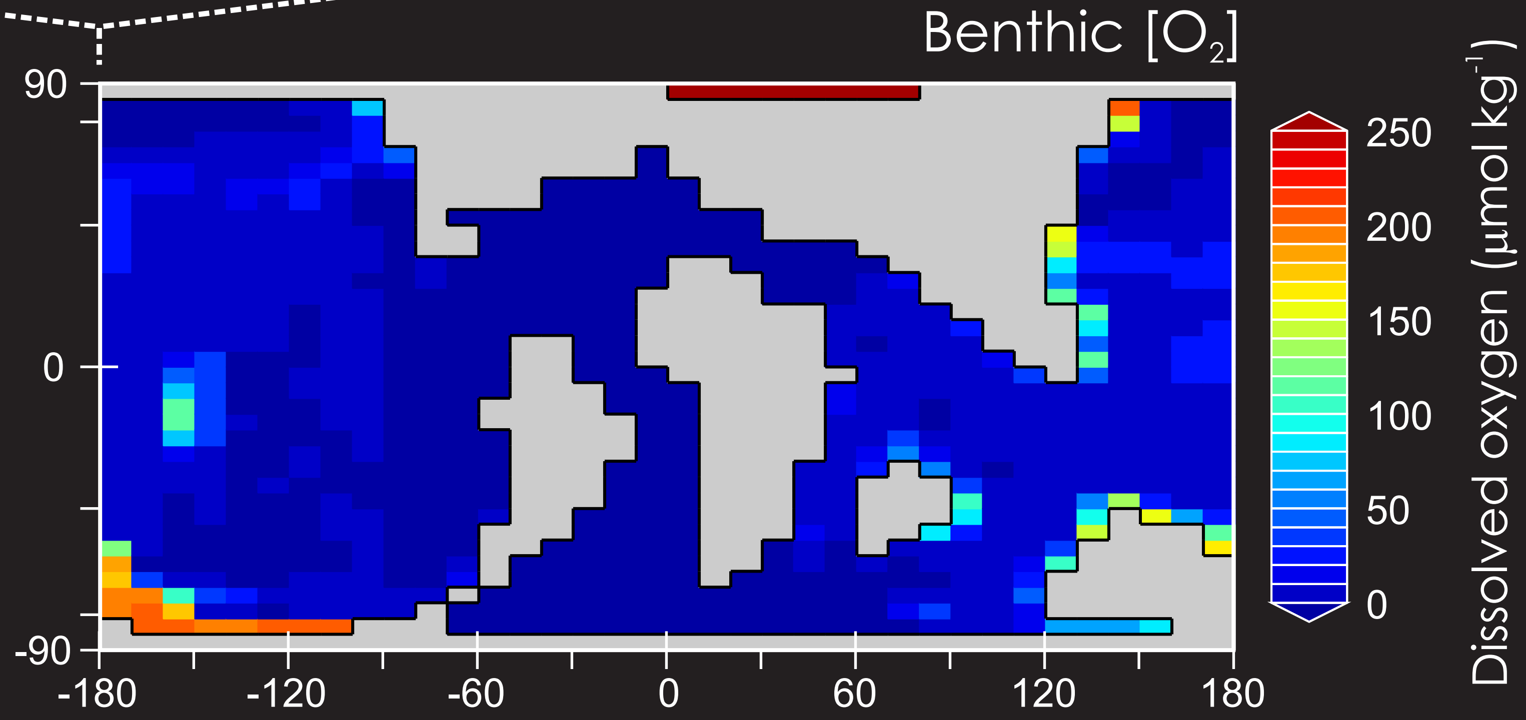


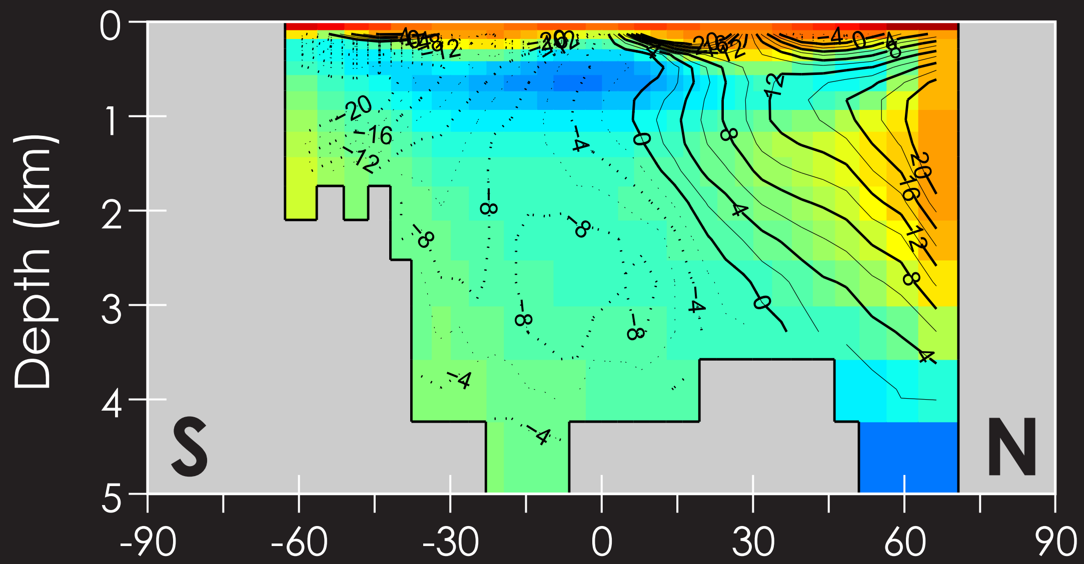
x16 CO_2 @ 2,000 yrs

transient state
(incomplete adjustment to
increased radiative forcing)



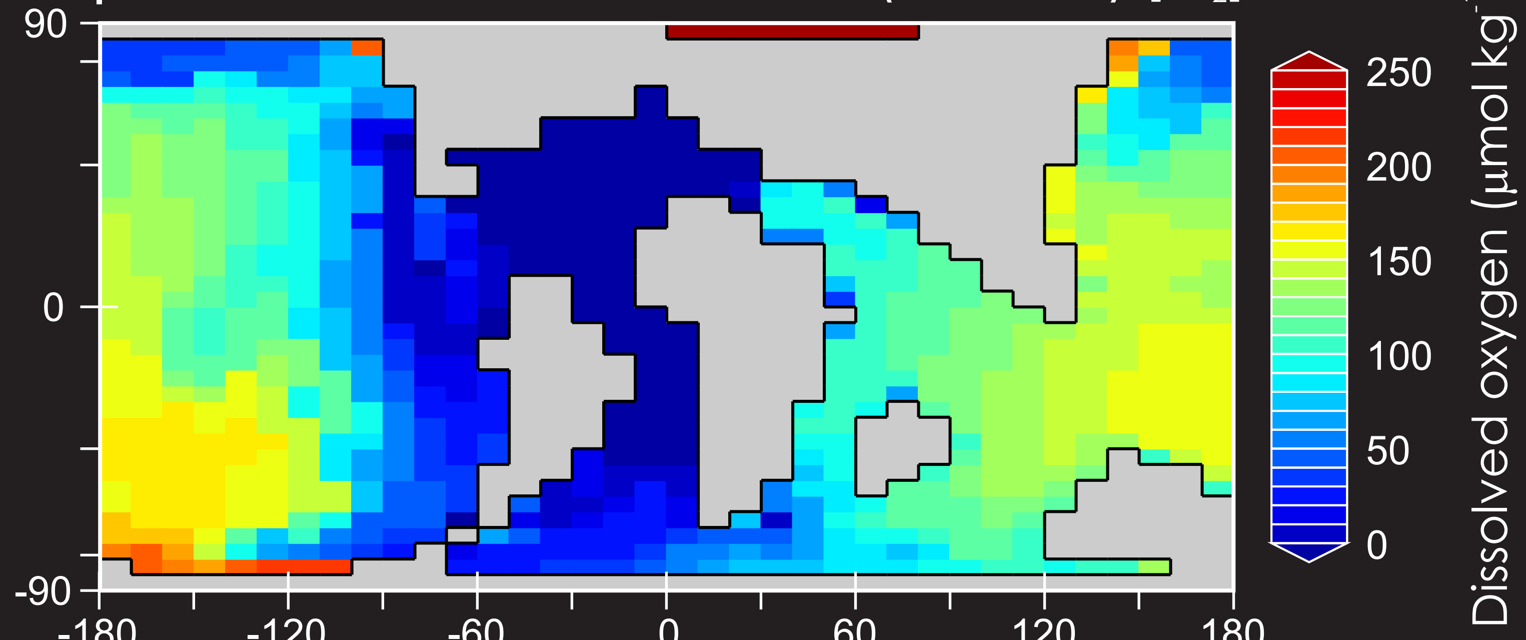
Can we (numerically) afford always to run our 'best' models to steady state?
Are all the phenomena of interest necessarily with respect to steady state ocean circulations?

What do we know about ... data constraints on circulation?



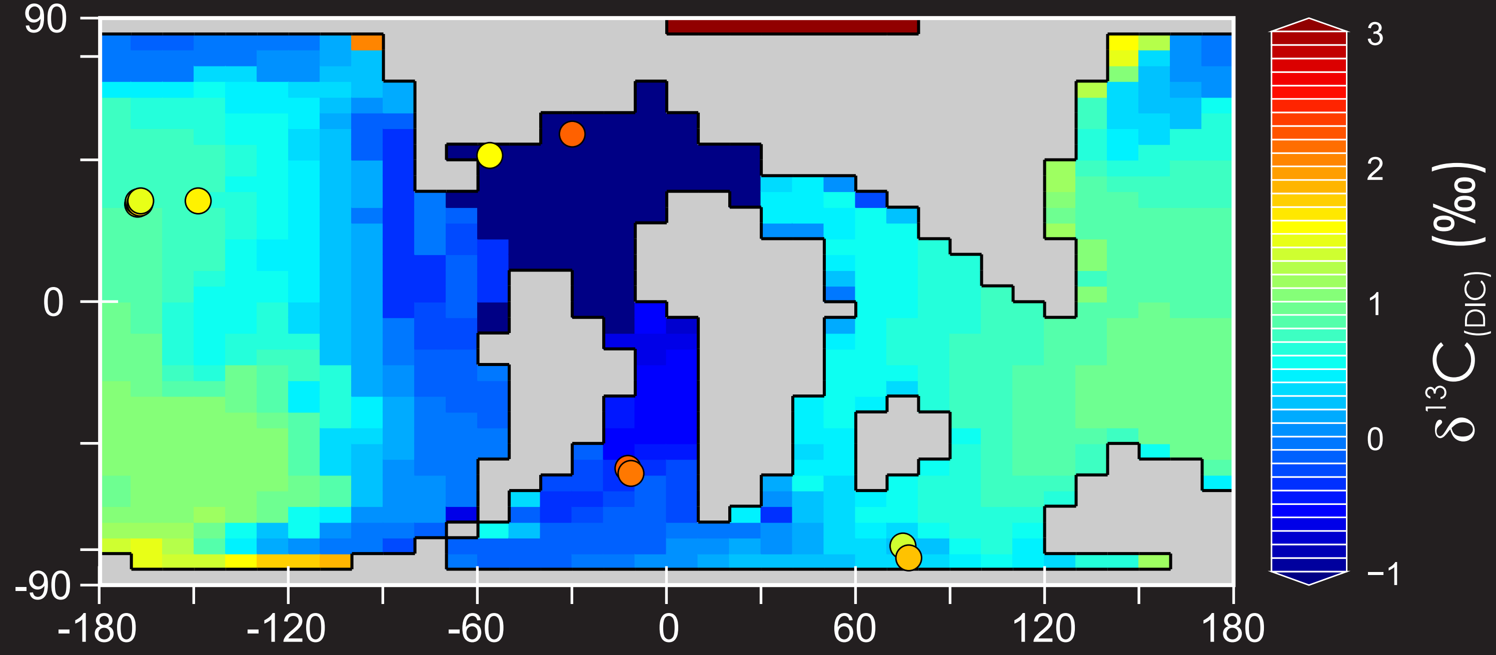
x4 CO_2 reference simulation; latest Maastrichtian

Benthic (>1000m) $[O_2]$



What do we know about ... data constraints on circulation?

Model bottom-water $\delta^{13}C$ with benthic foraminiferal $\delta^{13}C$ overlain (Cramer '09)



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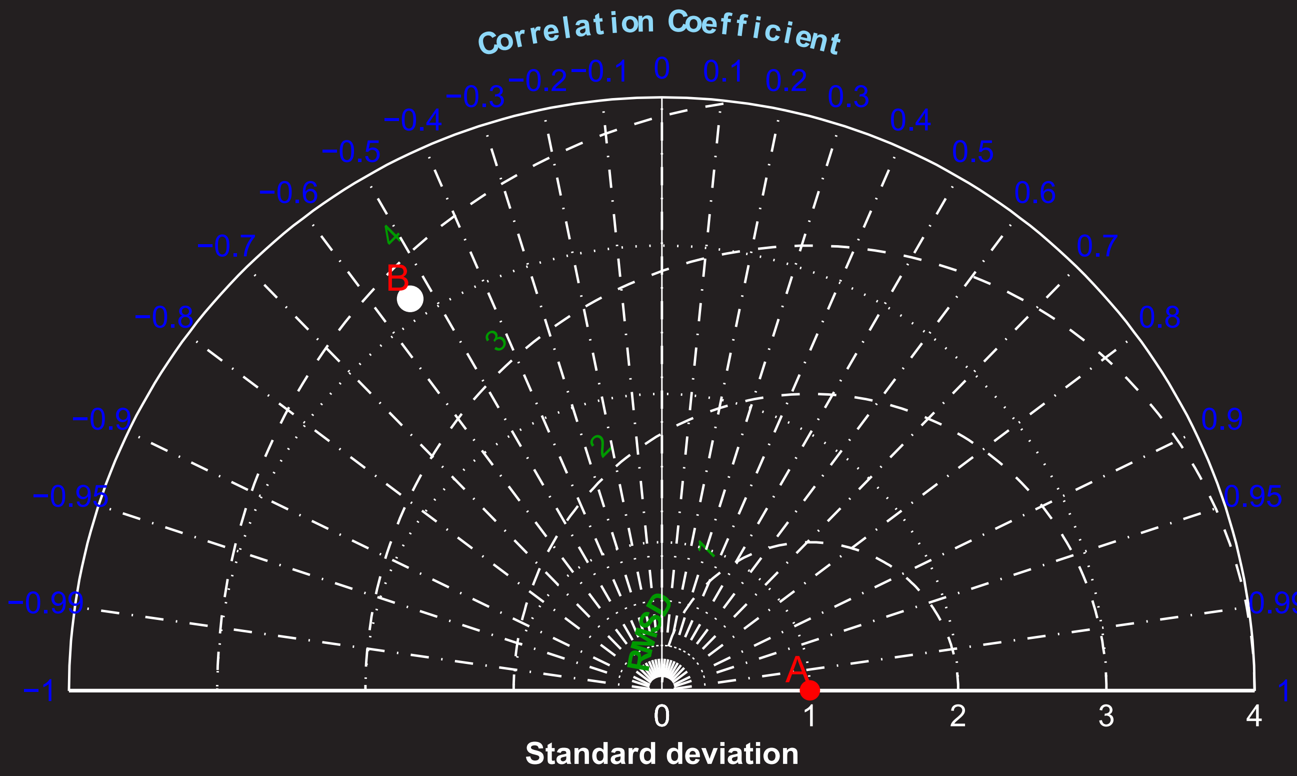

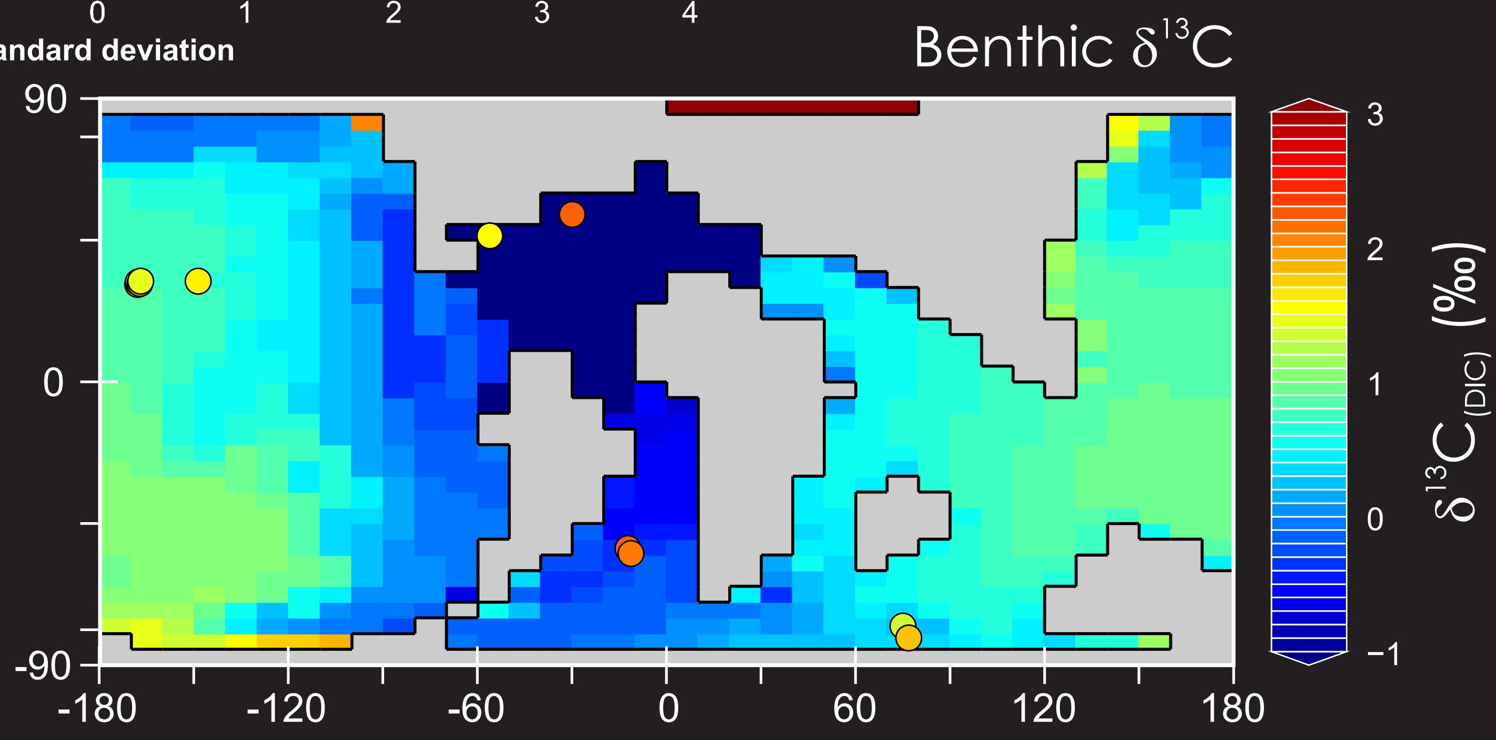

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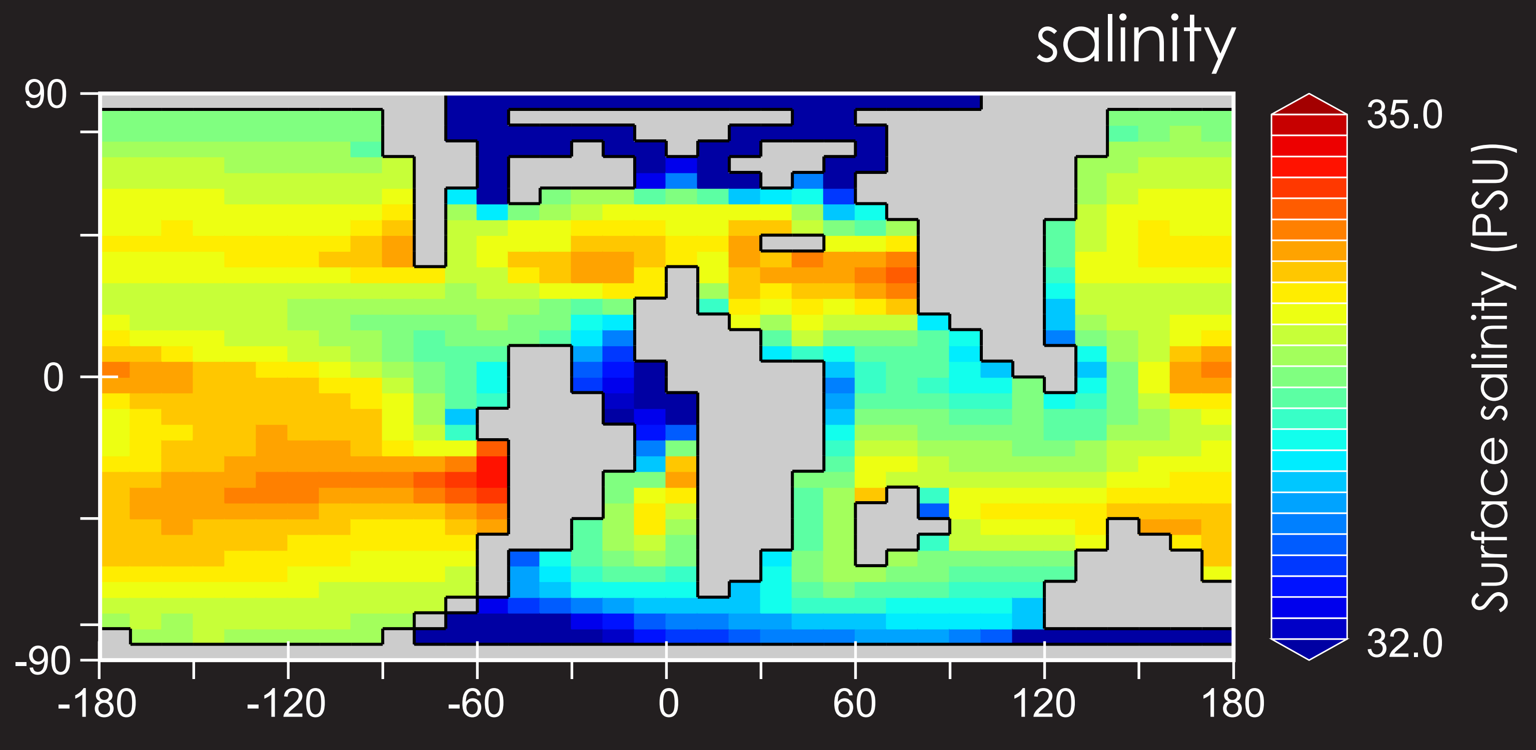

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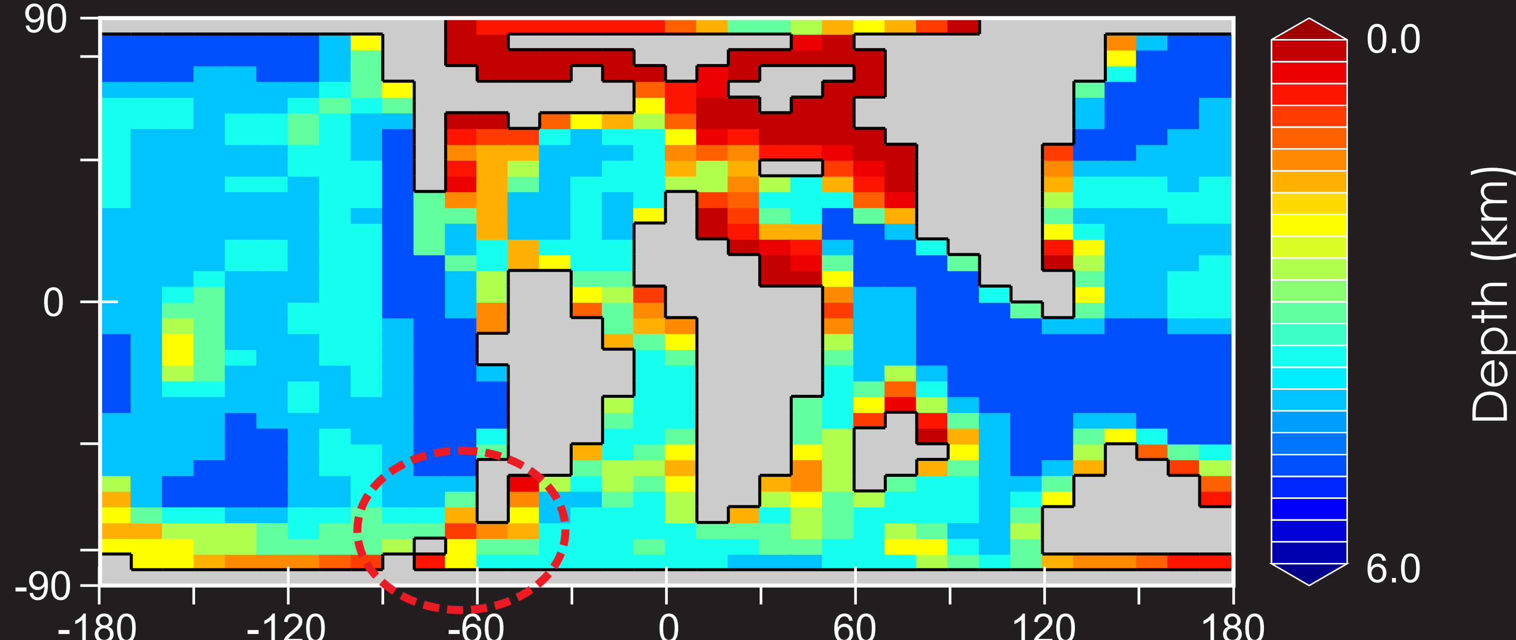

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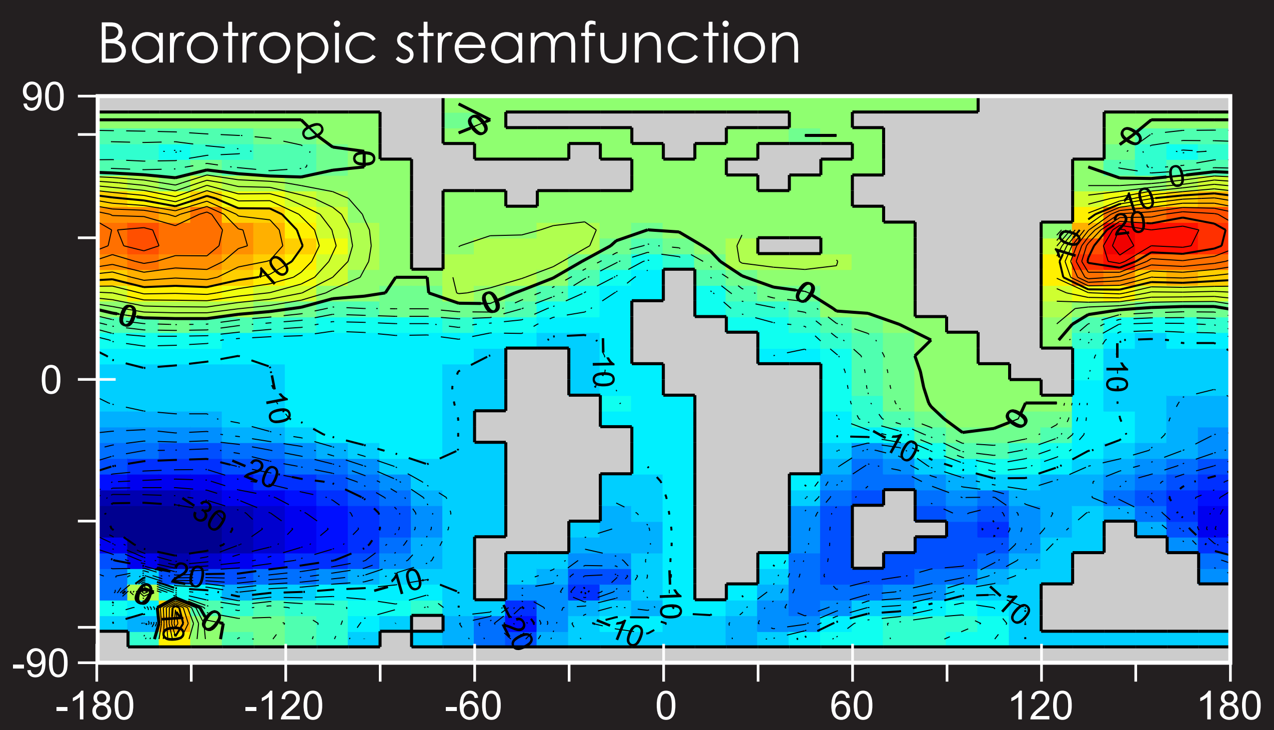

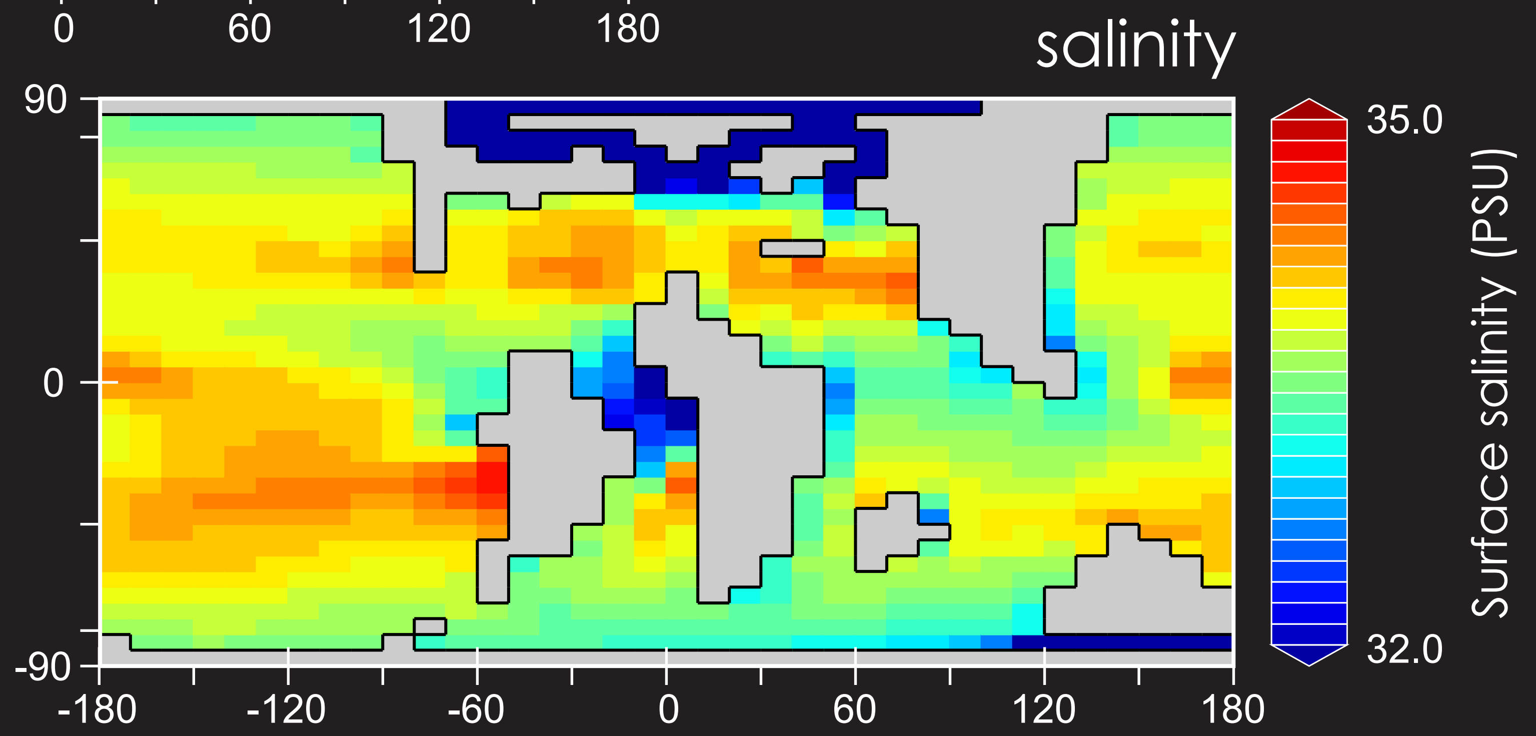

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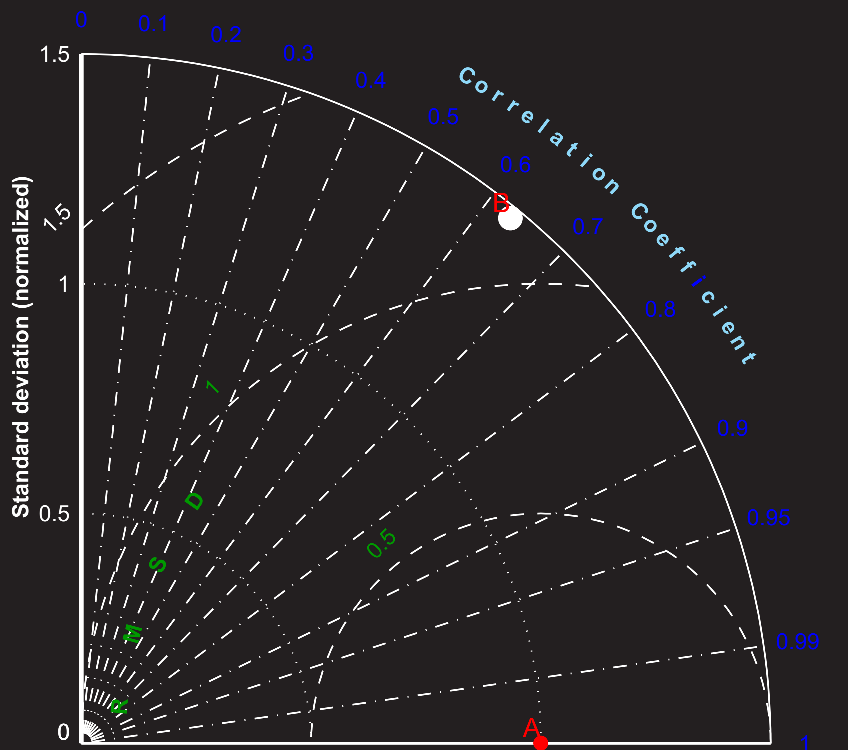

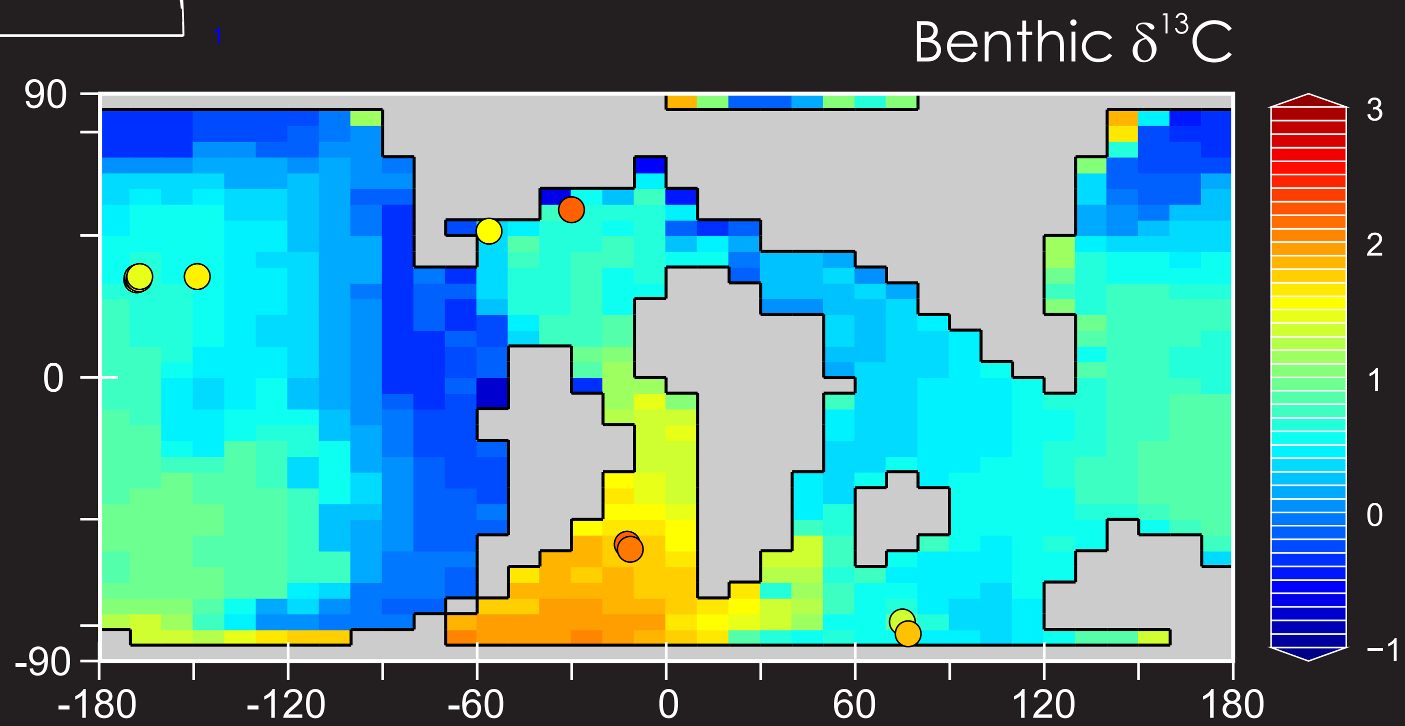

Can we make better use of existing but less 'sexy' data such as $\delta^{13}C$?
Are there key ocean locations that can be drilled/sampled for e.g. Nd that might decide between competing hypotheses?

What do we know about ... carbonate chemistry (and dynamics)?

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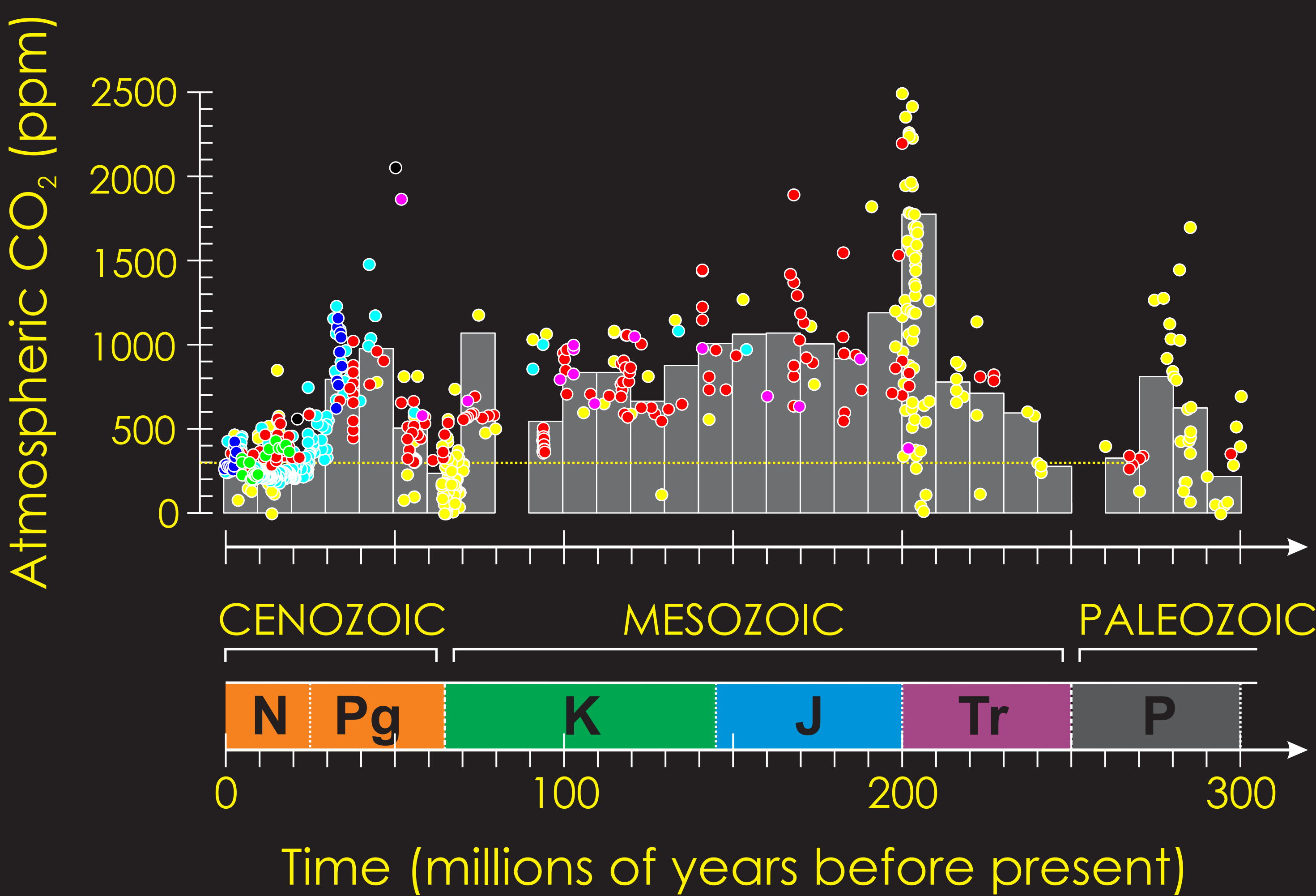
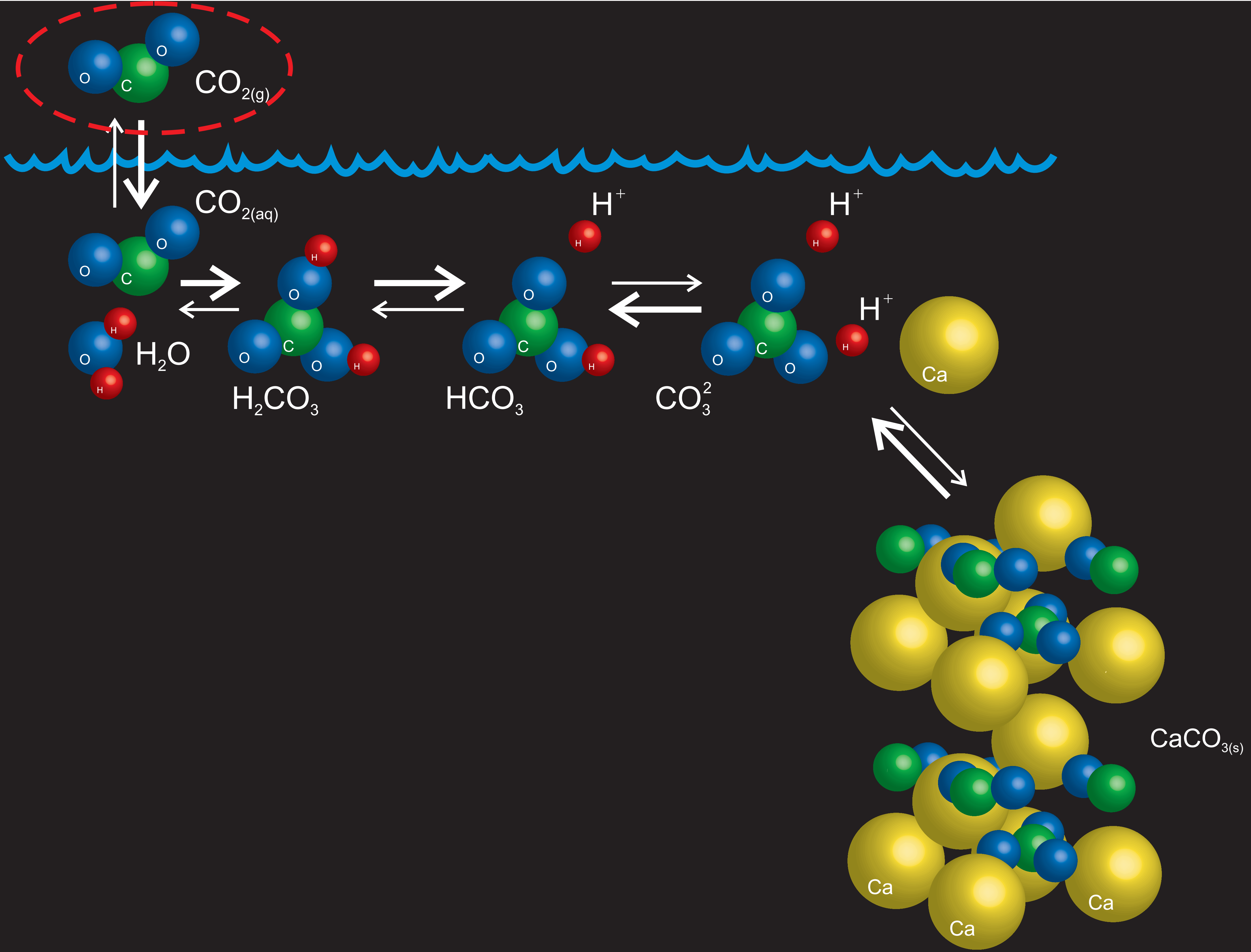
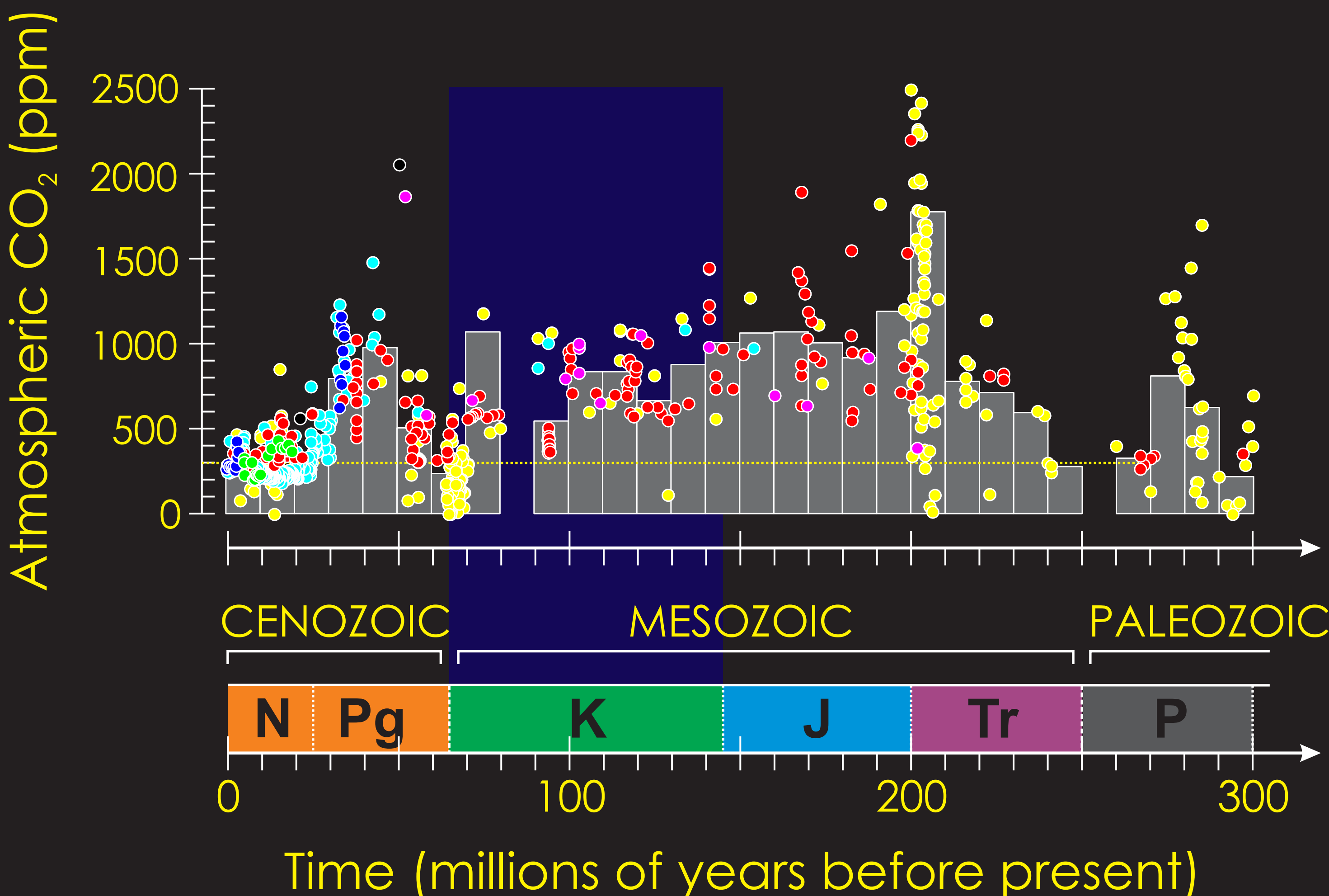


From: *Hönisch et al.* [2012]



$CO_{2(g)}$
$CO_{2(aq)}$
H_2O
H_2CO_3
HCO_3
CO_3^2
H^+
H^+
H^+
Ca
$CaCO_{3(s)}$
Ca
Ca
Ca

What do we know about ... carbonate chemistry (and dynamics)?



MailOnline

Rising carbon emissions could wipeout marine species with oceans acidifying at fastest rate

By Daily Mail Reporter

Last updated at 12:10 PM on 2nd March 2012

How can anyone believe any thing these proven Liers have to say..just look at globle warming not one shread of Real proof that people have any thing to do with it..and now this...
If they want to keep there jobs that badly ,Do some real work...before starting to make up scare stores

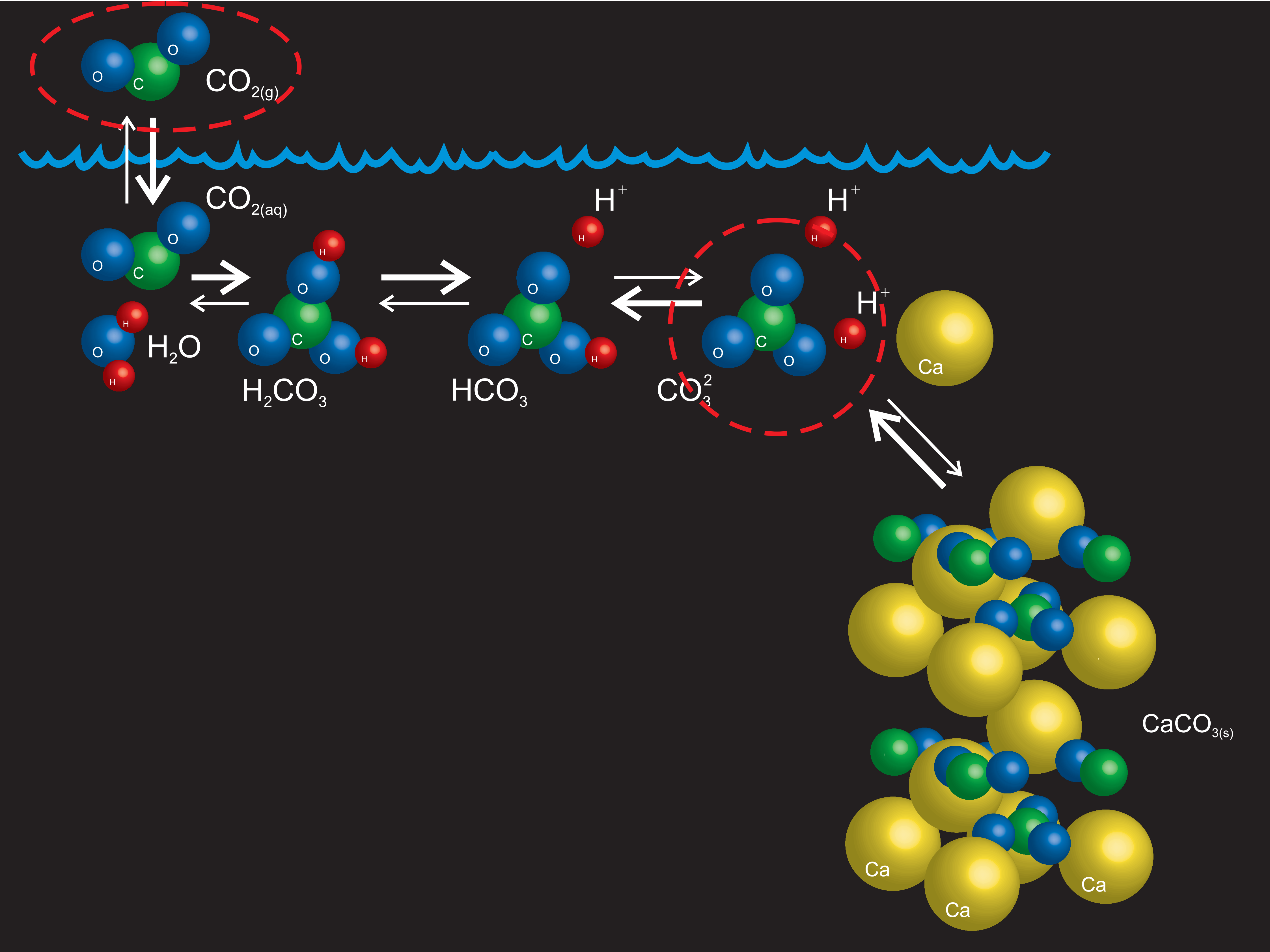
green_hackle, LONDON/ENGLAND, 03/3/2012 12:41

Alarmist garbage.
This is all just guesses made from tiny samples of imperfect information by people v
they want to find.
None of them have any real evidence for what happened 300 years ago, never r
finest. They also always fail to mention that the causes of mass extinctions in prehis
that those extinctions took place over millions of years.
Any sense of any kind of impending disaster is just Hollywood hyperbole and fundr
they say is true, there won't be any serious impact for the human race for millions c
plenty of engineering and technological solutions before then.

dave, Dystopia, UK, 1/3/2012 23:54

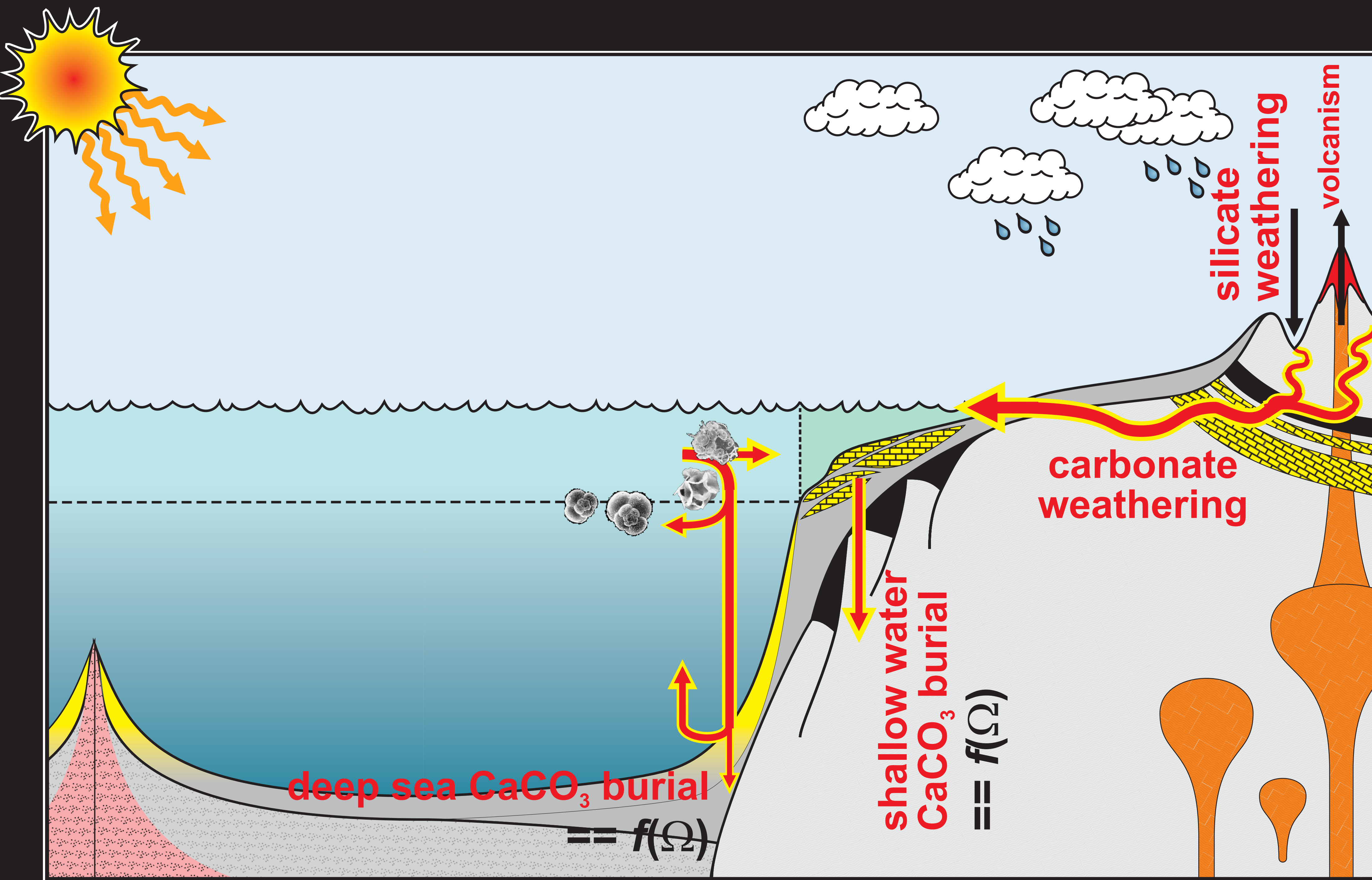
More dodgy science, all the records show that CO2 levels in the Atmosphere follow temperature not the other way round, CO2 is only soluble in water at lower temperatures so as the temperature rises more is released to the air. To prove it to yourself take some cold fizzy drink from the fridge and pour it into a mug, heat a spoon in hot water and put it in the mug. You will see bubbles of Carbon dioxide released as the spoon heats the liquid. That is why we all like cold soft drinks and beer they do not go flat as quickly. So the myth of more temperature causing acidification cannot happen because there would be less CO2 in the ocean not more.

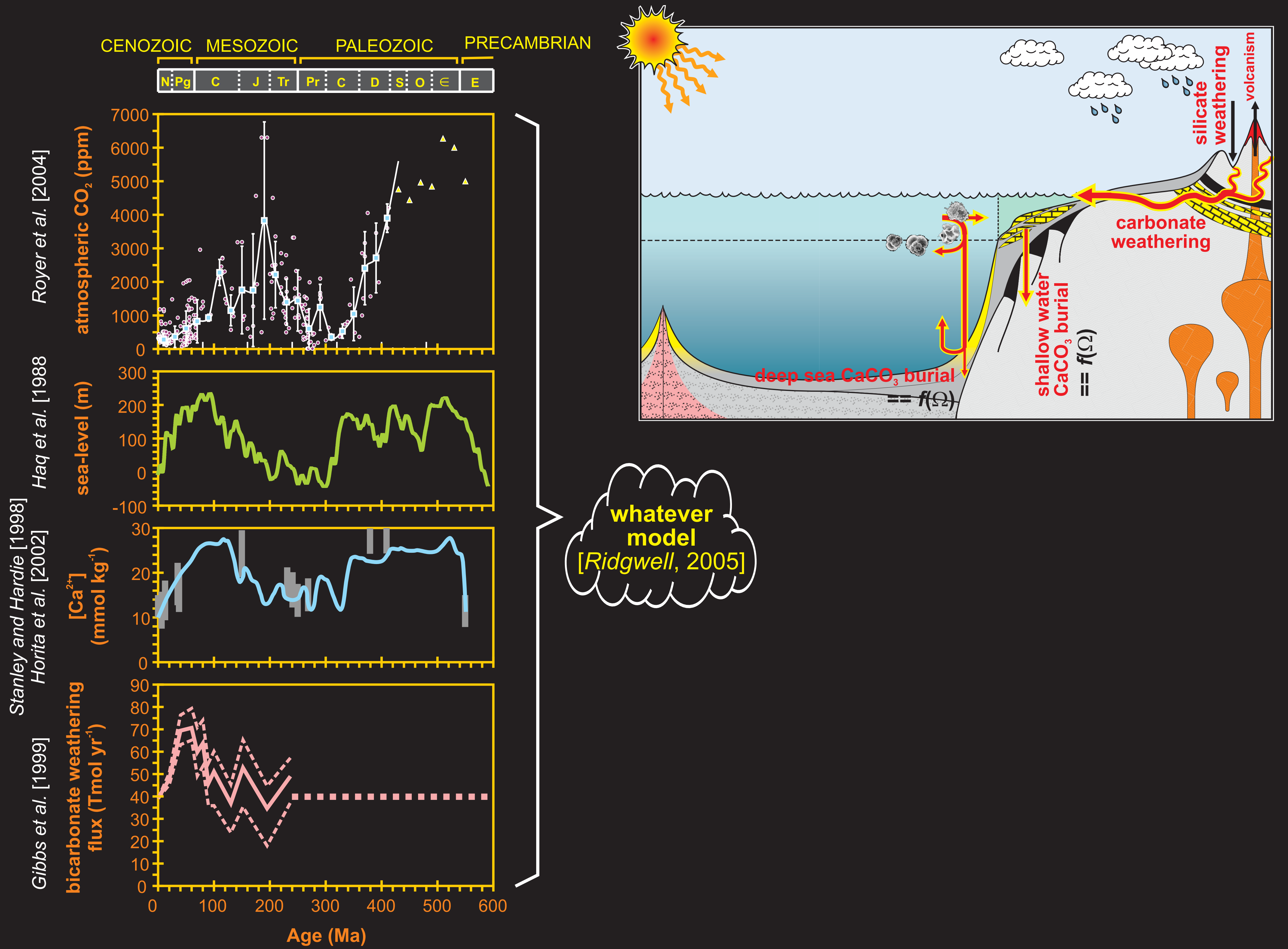
ChrisM, Ashford, England, 2/3/2012 12:07



O
C
O
CO2(g)
CO2(aq)
O
C
O
H
O
H
H2O
H
O
C
O
H
H2CO3
H
O
C
O
H
HCO3
H+
O
C
O
CO3 2
H+
H
H+
H
Ca
CaCO3(s)
Ca
Ca
Ca

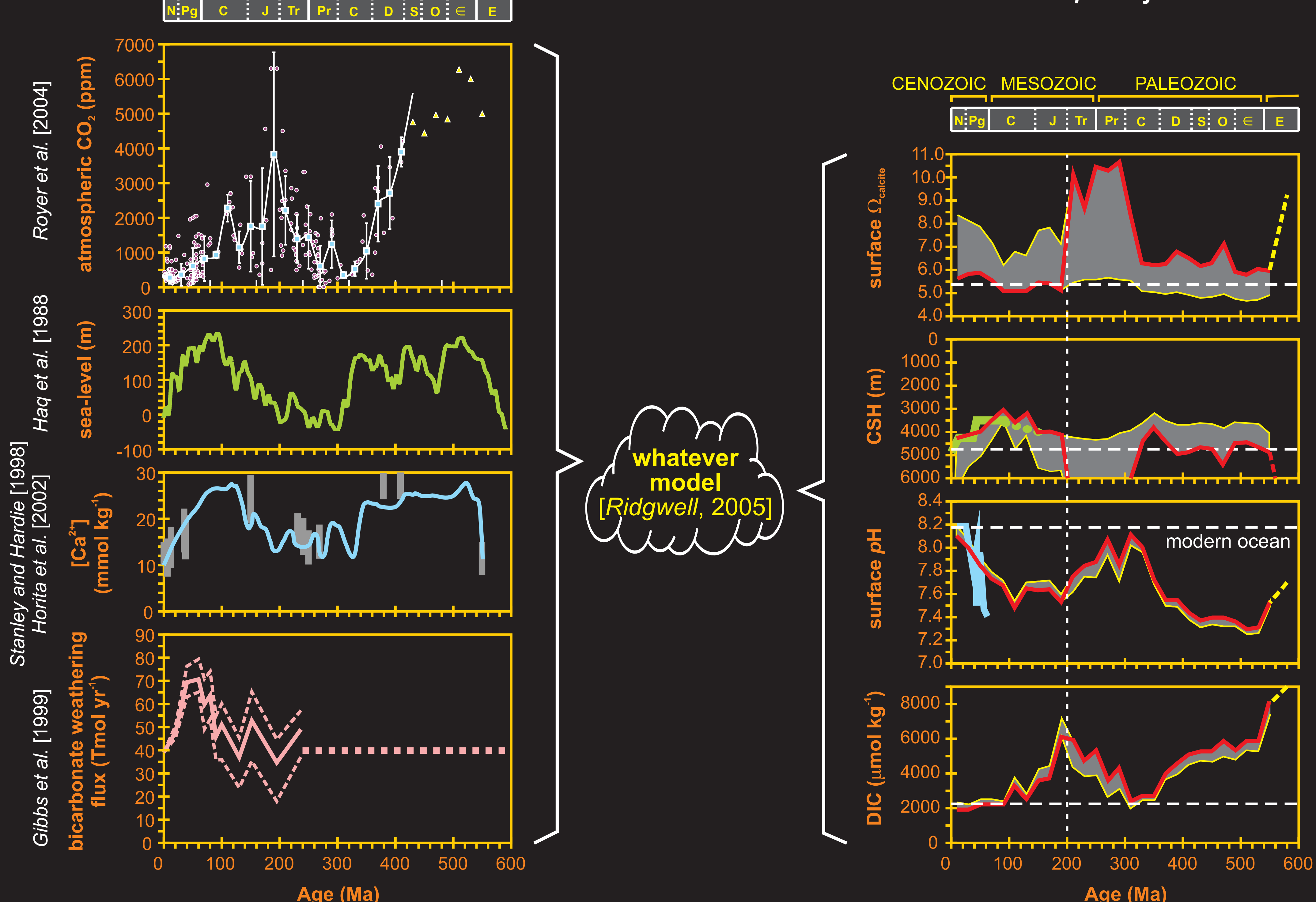
What do we know about ... carbonate chemistry (and dynamics)?



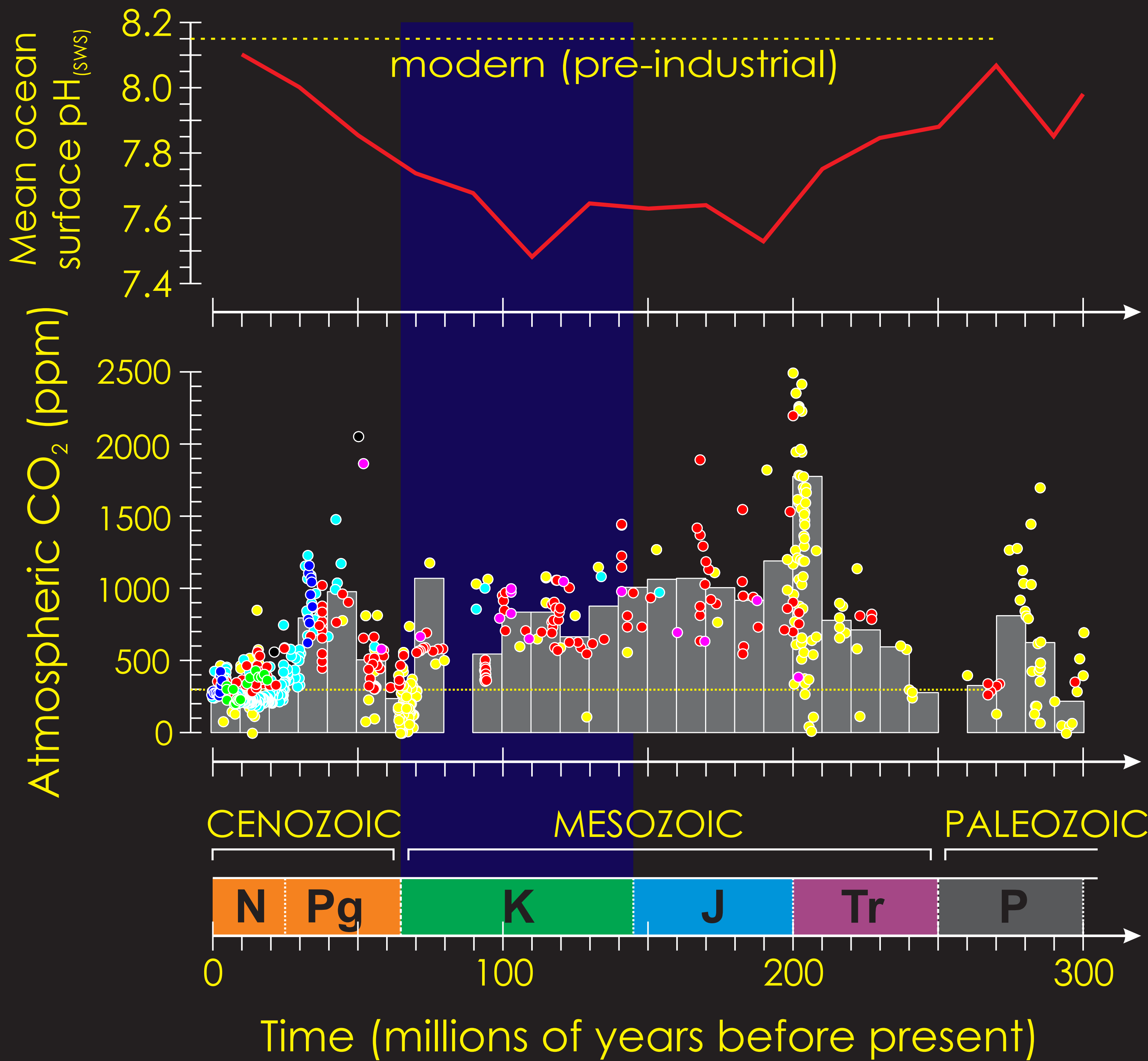


CENOZOIC
MESOZOIC
PALEOZOIC
PRECAMBRIAN
N Pg C J Tr Pr C D S O ∈ E
Royer et al. [2004]
atmospheric CO2 (ppm)
7000
6000
5000
4000
3000
2000
1000
0
Haq et al. [1988
sea-level (m)
300
200
100
0
-100
Stanley and Hardie [1998]
Horita et al. [2002]
[Ca2+] (mmol kg-1)
30
20
10
0
Gibbs et al. [1999]
bicarbonate weathering flux (Tmol yr-1)
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
Age (Ma)
whatever model
[Ridgwell, 2005]
volcanism
silicate weathering
carbonate weathering
shallow water CaCO3 burial
== f(Ω)
deep sea CaCO3 burial
== f(Ω)

Model projections



What do we know about ... carbonate chemistry (and dynamics)?



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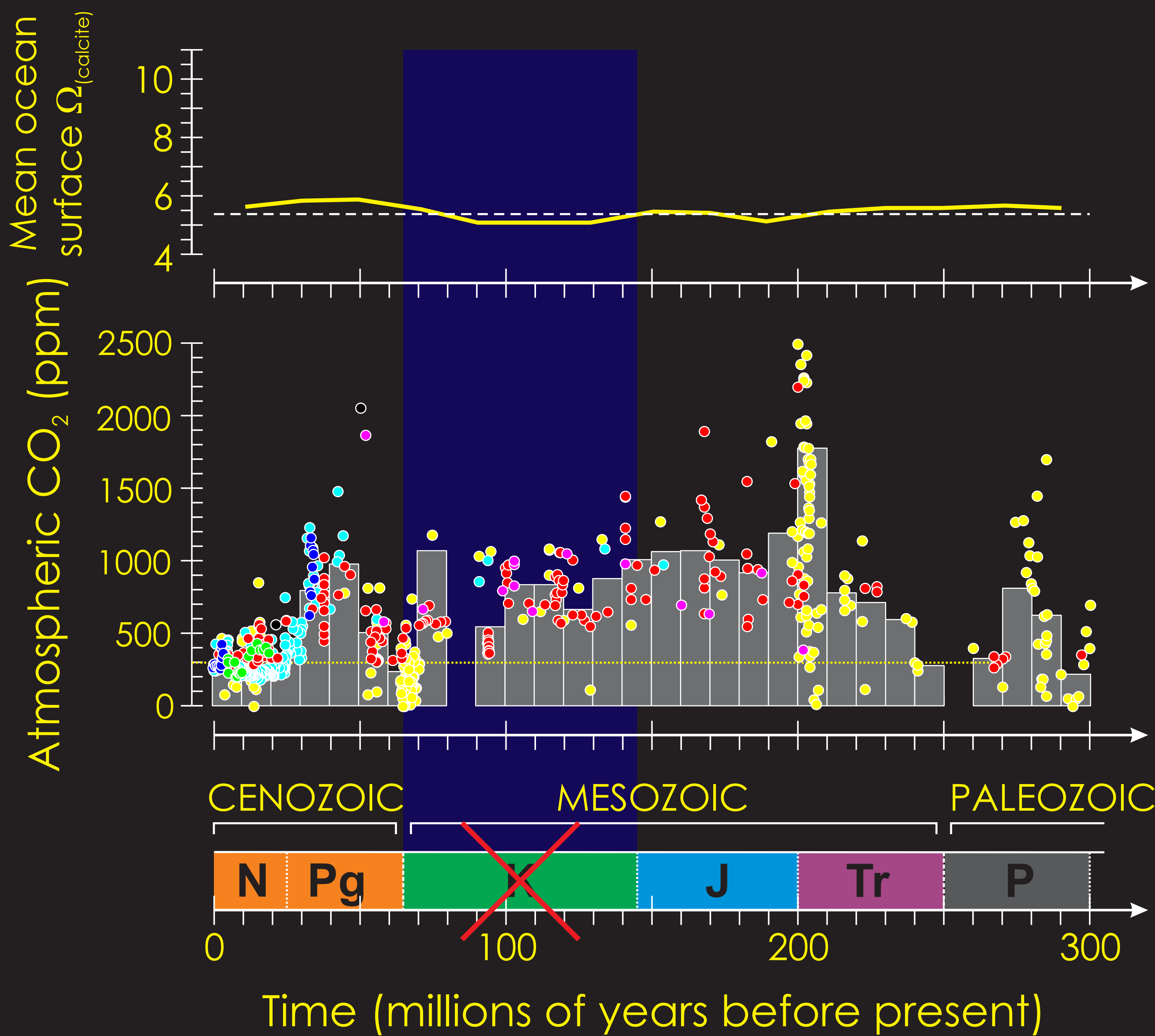

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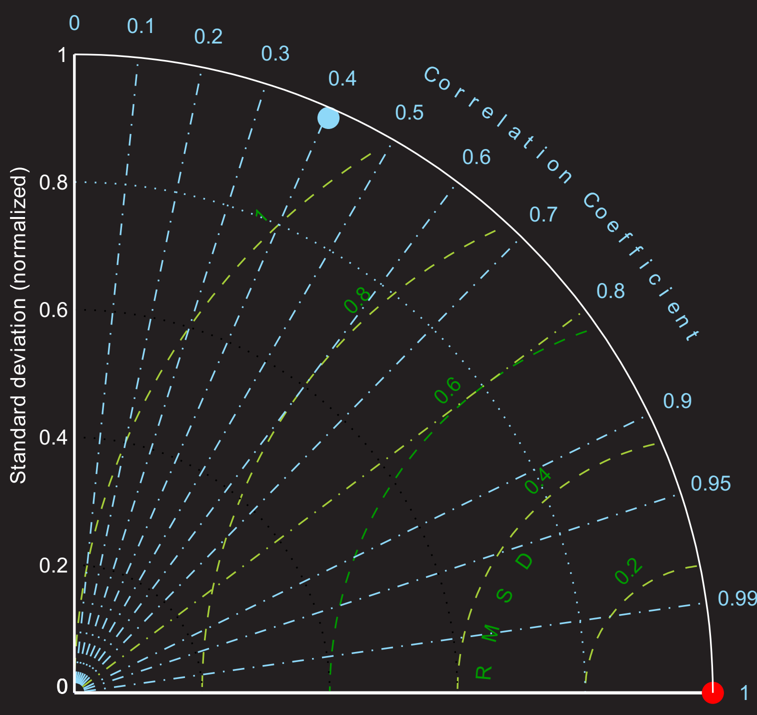
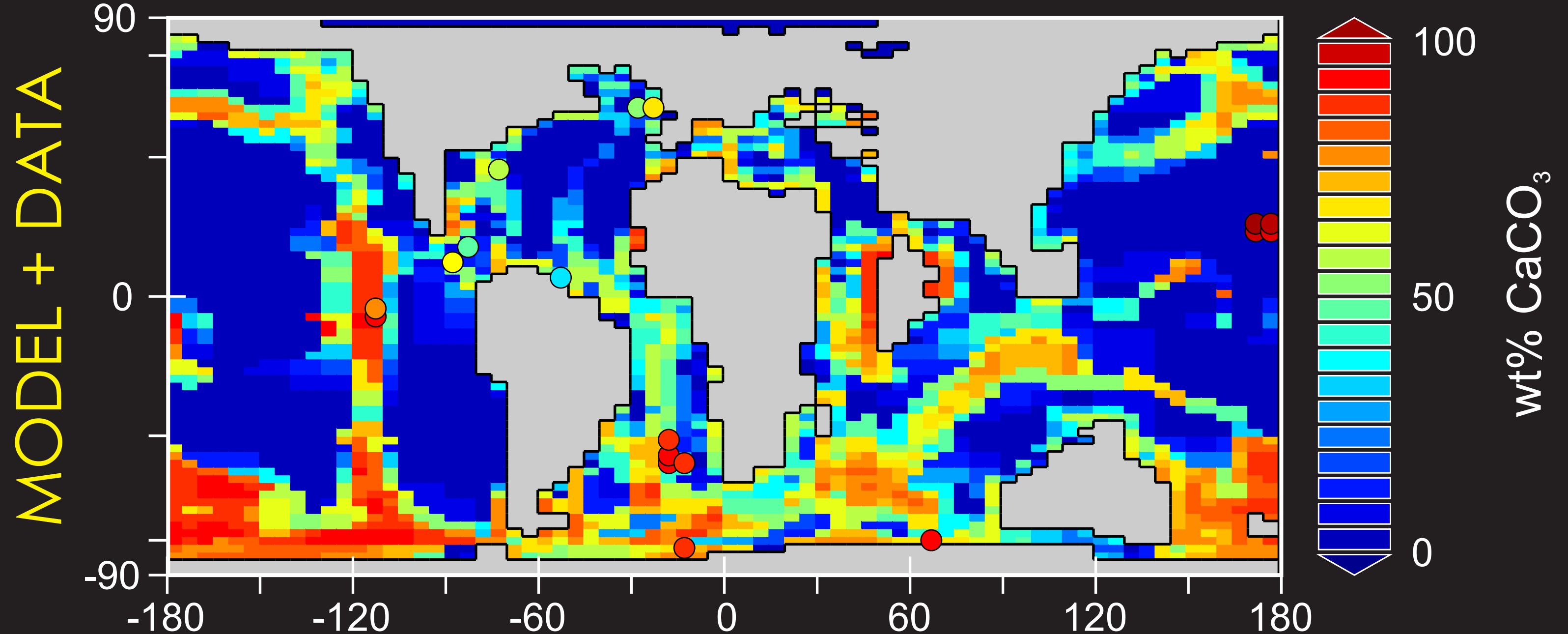
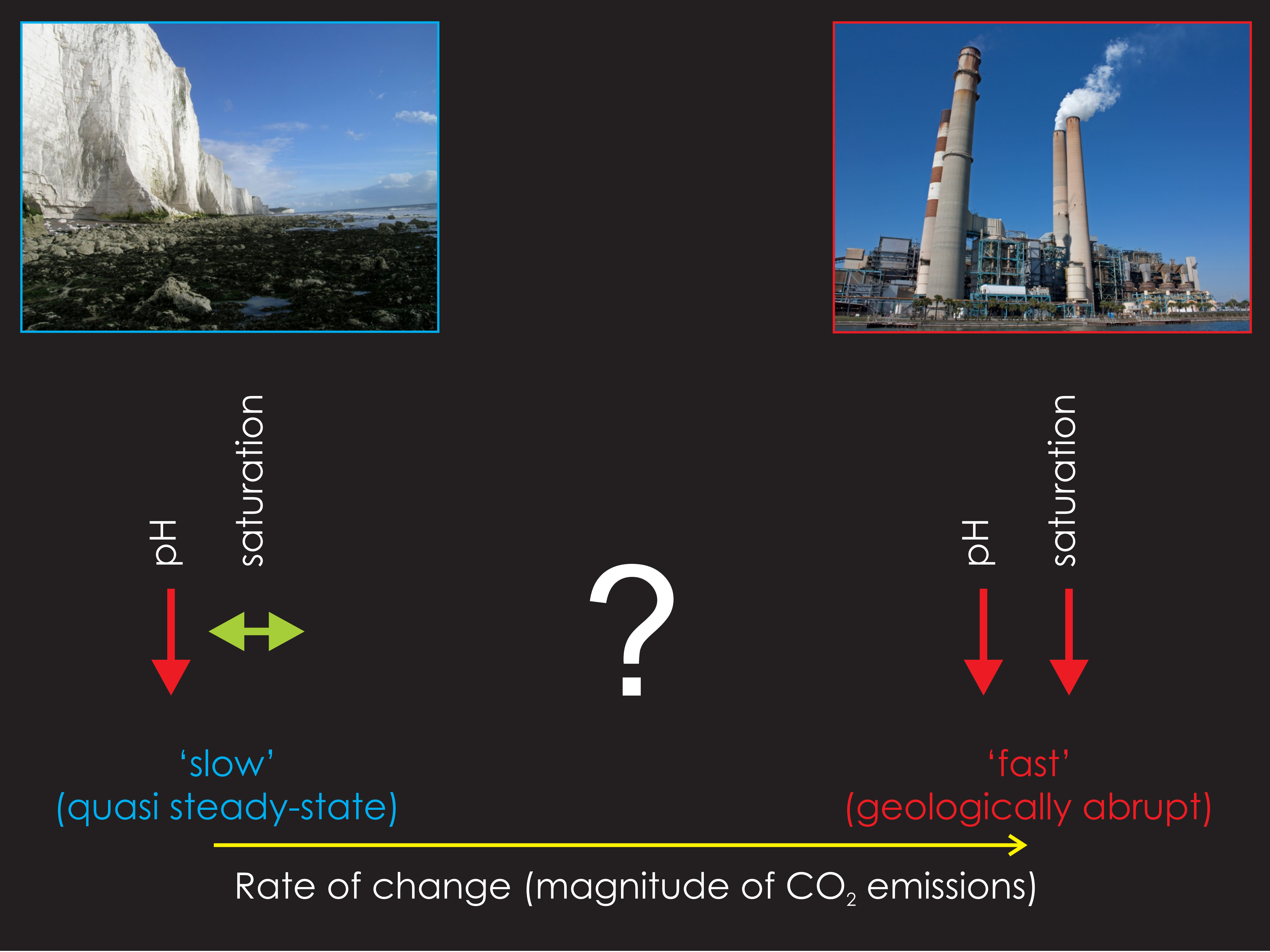
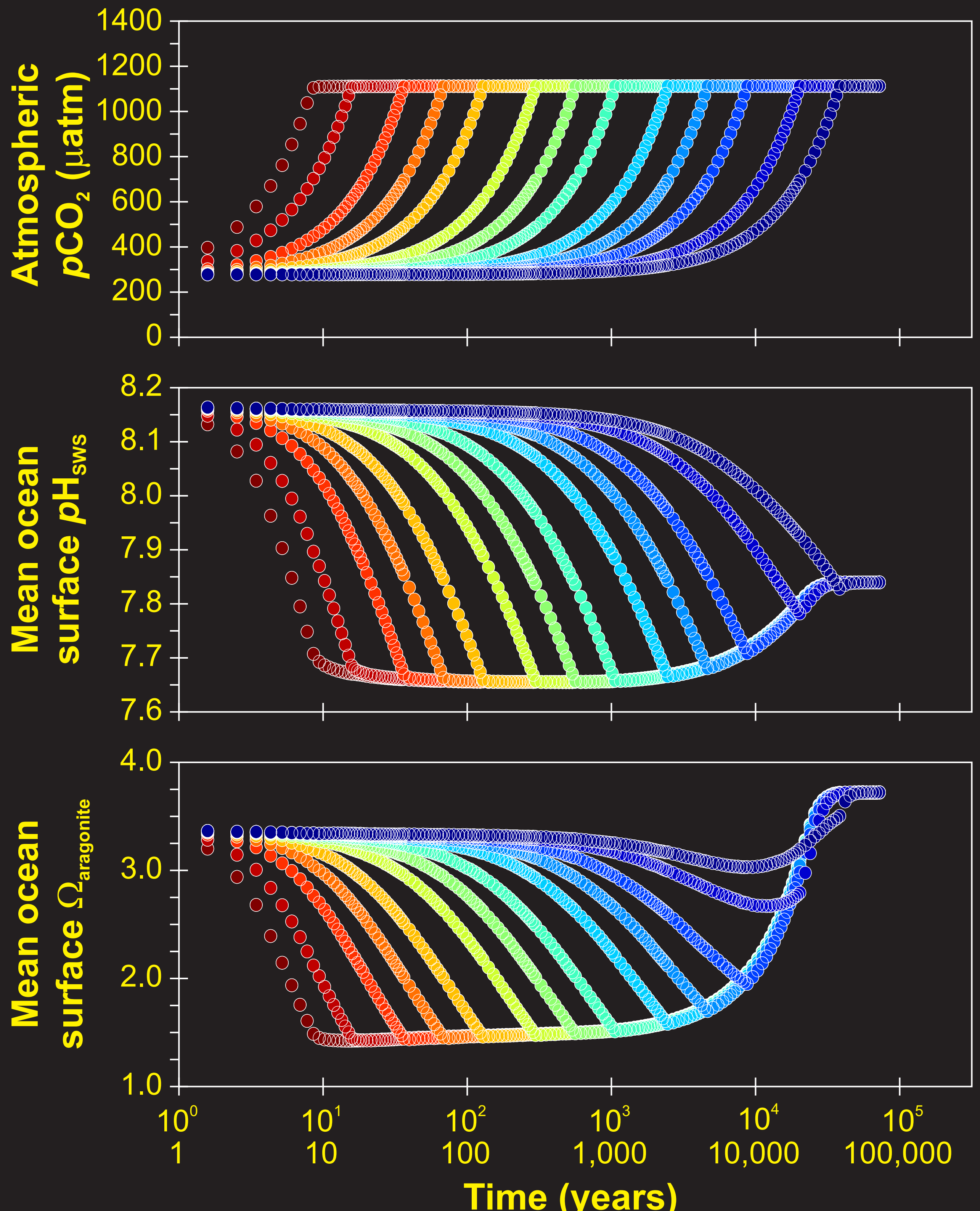




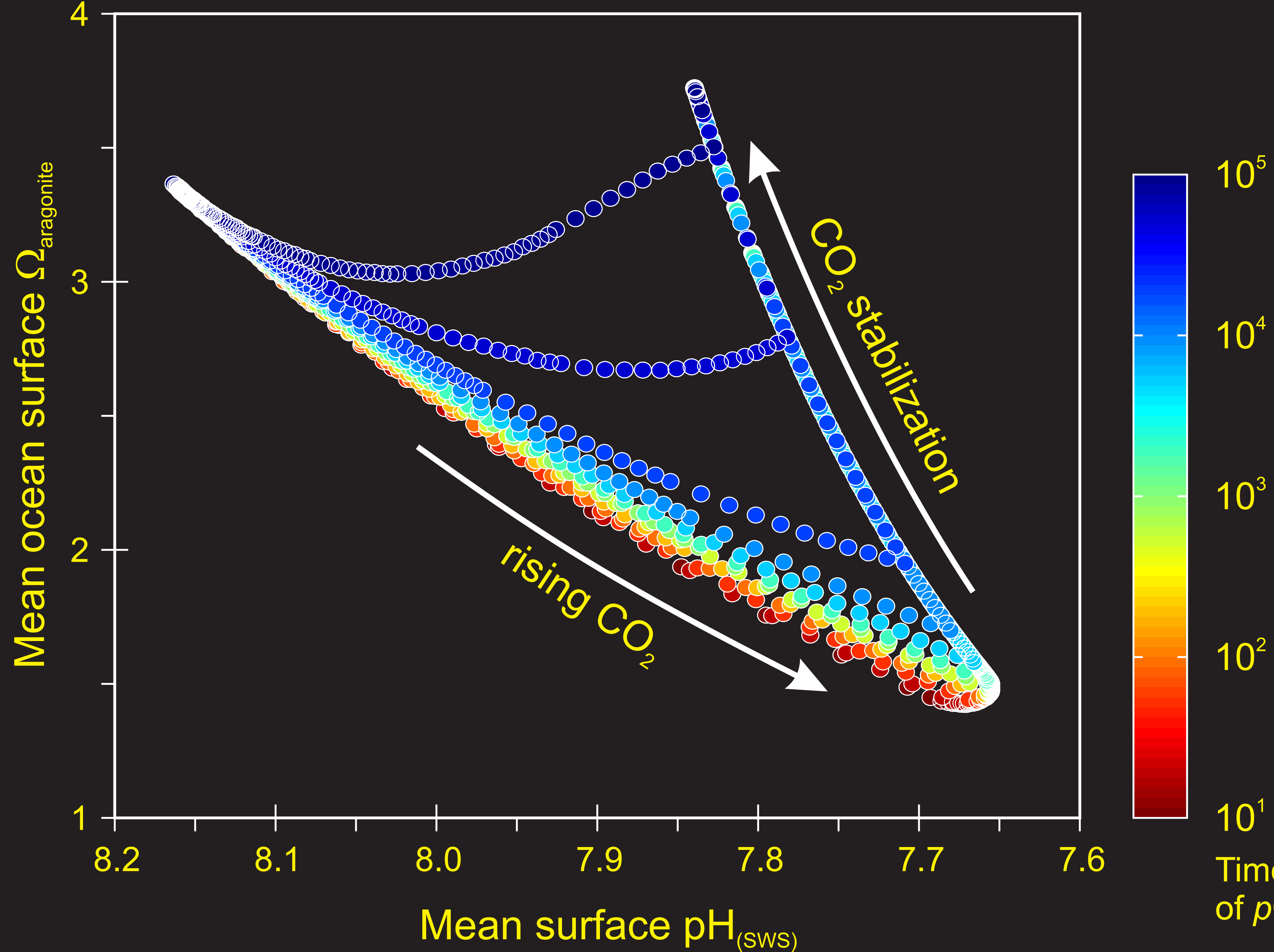


pH
saturation
?
pH
saturation
'slow'
(quasi steady-state)
'fast'
(geologically abrupt)
Rate of change (magnitude of CO_2 emissions)



From: Hönisch *et al.* [2012]

What do we know about ... carbonate chemistry (and dynamics)?



From: *Hönisch et al.* [2012]

Can we adequately constrain the bulk chemistry of the ocean (e.g. DIC, ALK, Ca^{2+}, Mg^{2+}) and hence carbonate chemistry (e.g. pH)? Alternatively: constrain global carbonate deposition and the CCD? Also: the <u>time-scale of change</u>.

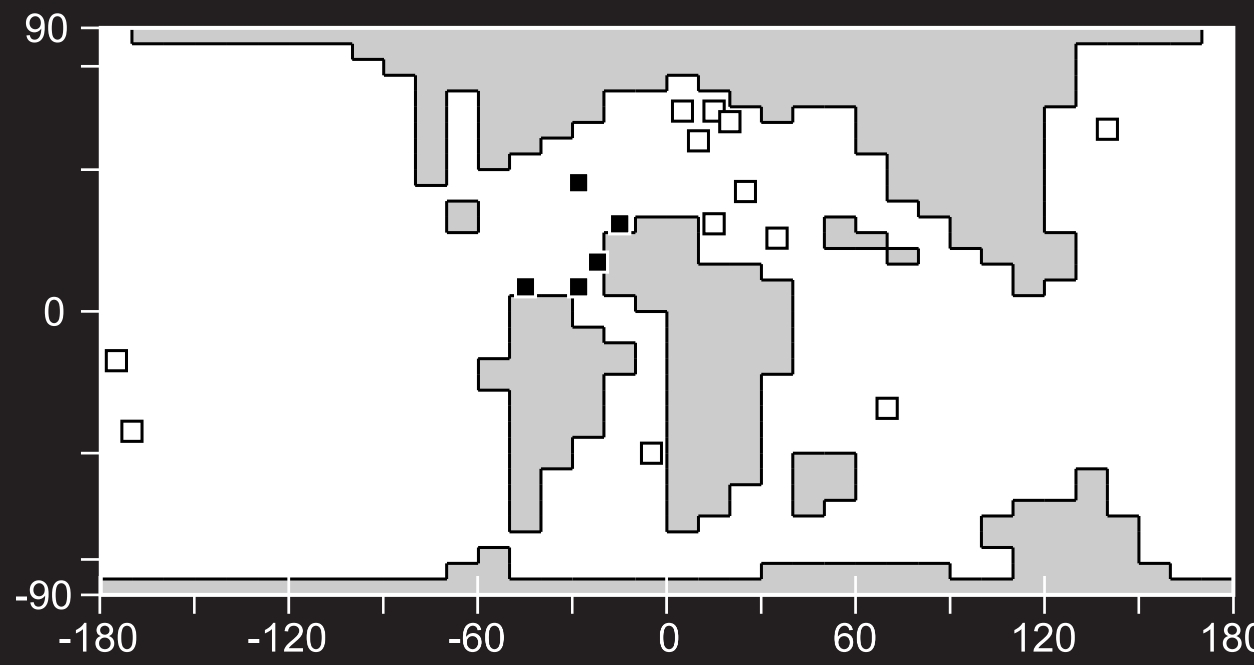
What do we know about ... ocean oxygenation?

What do we know about ... ocean oxygenation?

filled symbols: >1 wt% TOC

empty symbols: <1 wt% TOC

(caveats as per reference)



pre-OAE2

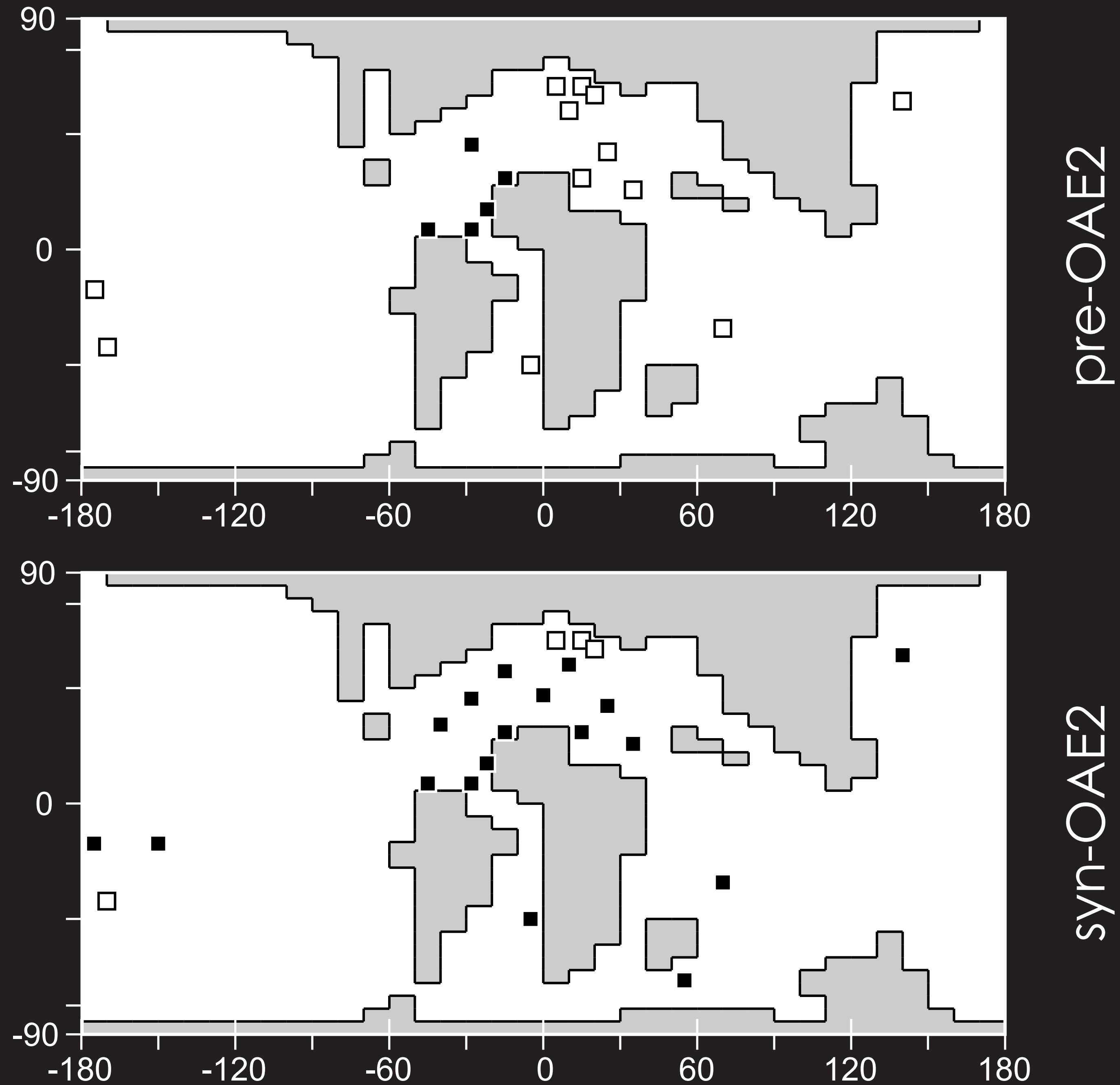
Monteiro et al [2012]

What do we know about ... ocean oxygenation?

filled symbols: >1 wt% TOC

empty symbols: <1 wt% TOC

(caveats as per reference)



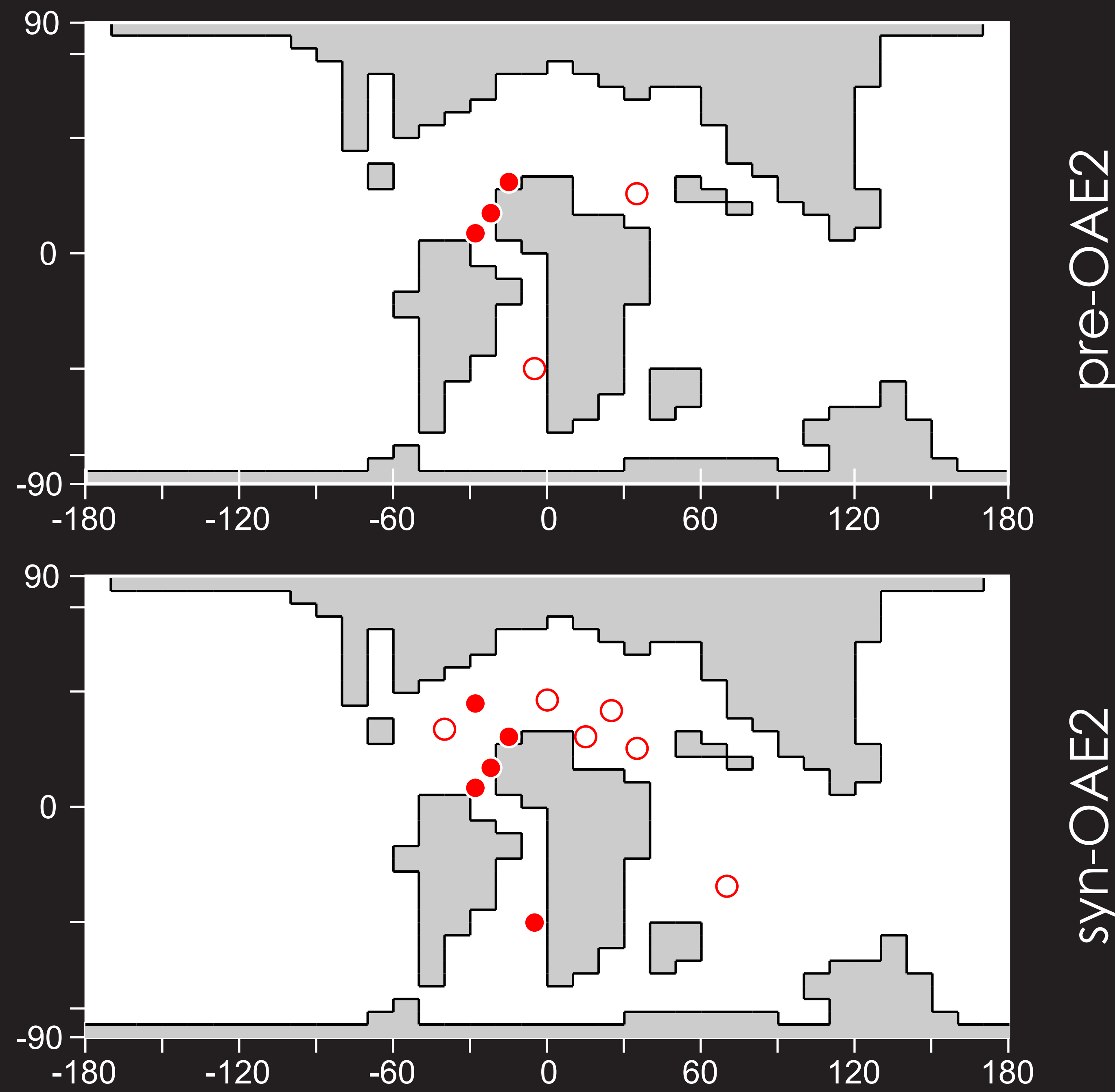
Monteiro et al [2012]

What do we know about ... ocean oxygenation?

filled symbols: biomarker evidence for photic zone euxinia

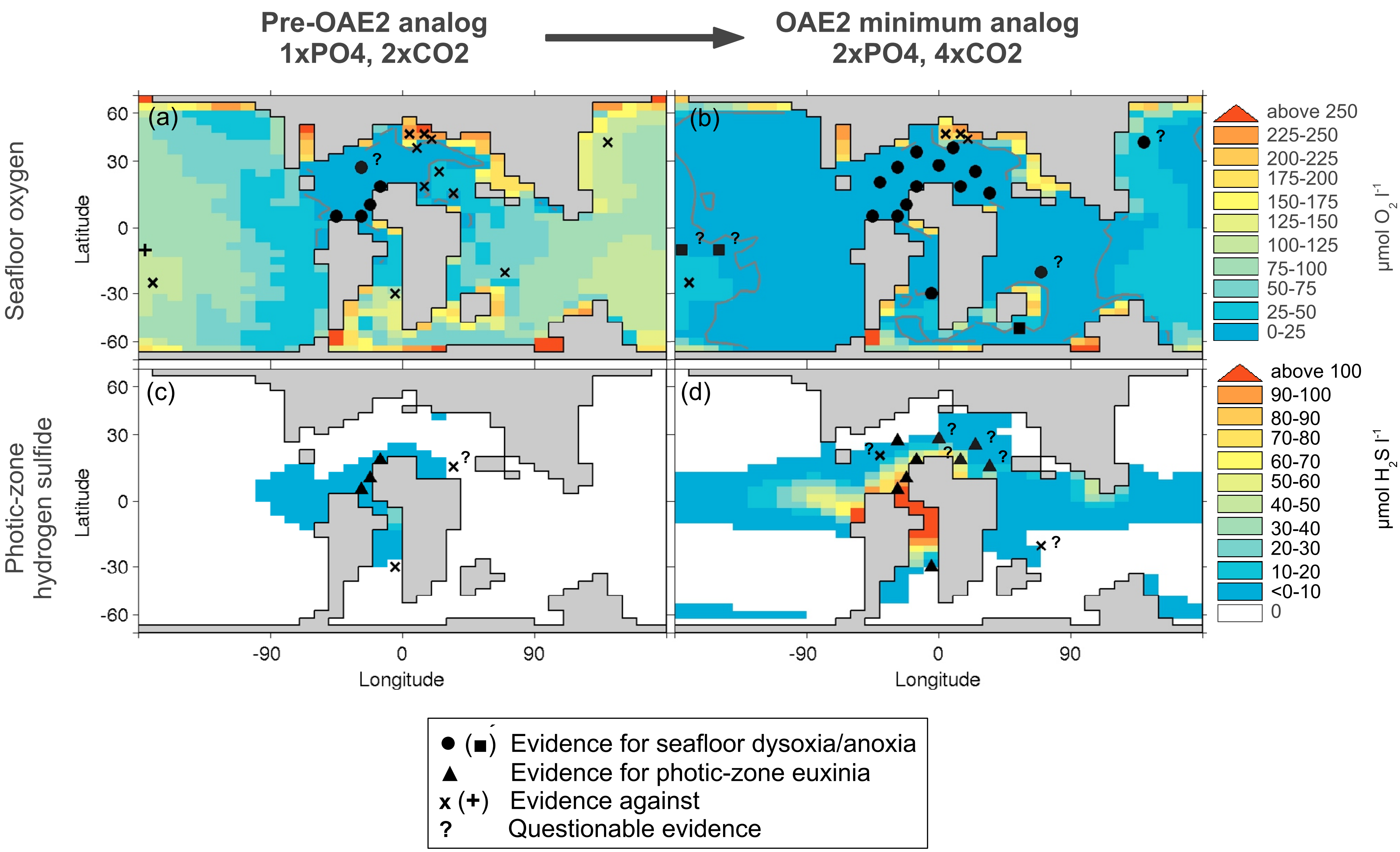
empty symbols: no evidence for PZE

(caveats as per reference)



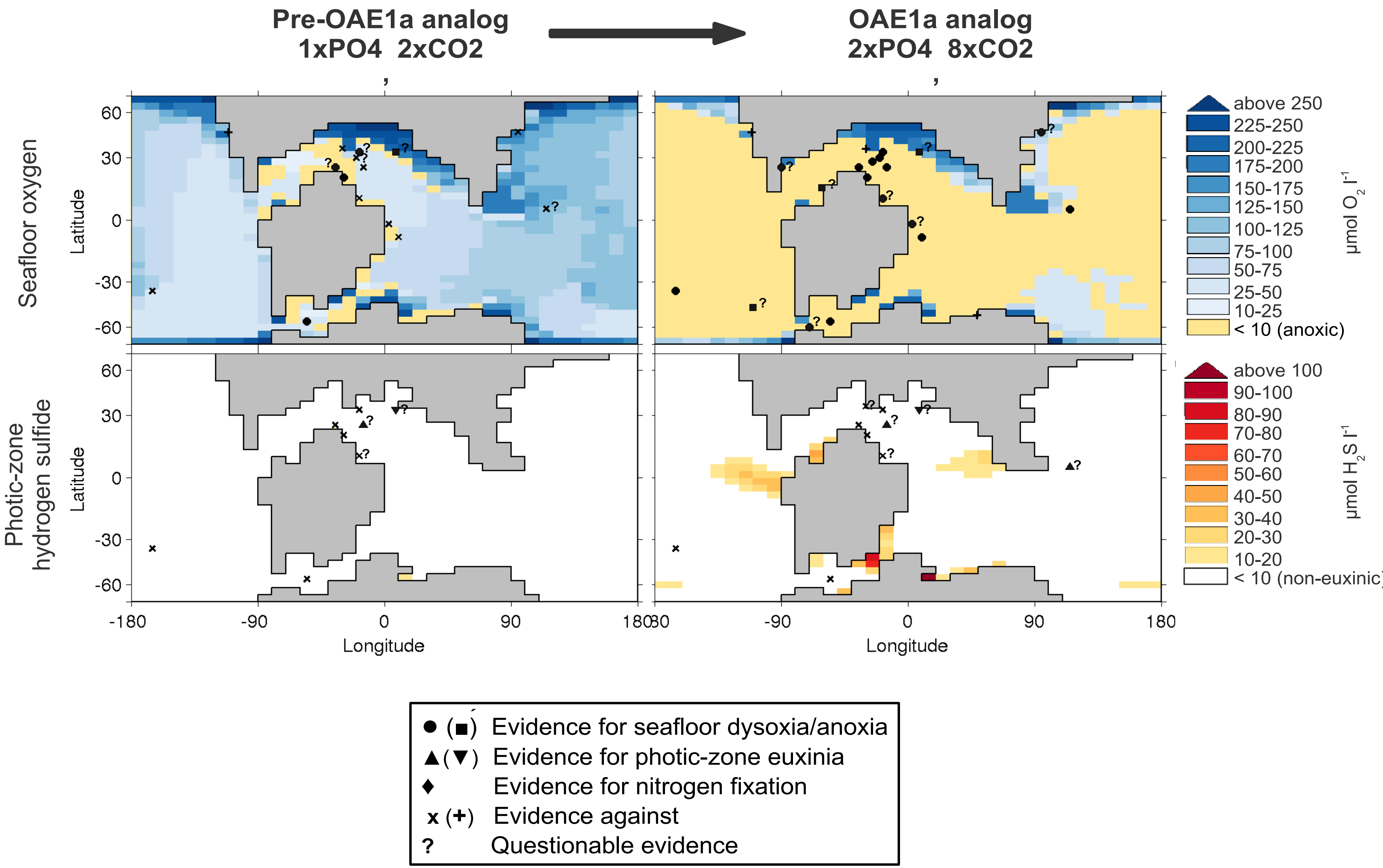
Monteiro et al [2012]

What do we know about ... ocean oxygenation?



Monteiro et al [2012]

What do we know about ... ocean oxygenation?



Naafs et al [in prep]

Sub-challenges:

- Mechanistically modelling wt% Corg in marine sediments.

(Or identifying an appropriate biologically limiting concentration of H_2S.)

- Accounting for sub-gridscale topography, e.g. many e.g. IODP cores tend to be on topographic features rather on the seafloor *per se* ...
- Improved statistical techniques for presence-absence, and incorporating fuzziness(?)
- Simultaneously addressing other forms of uncertainty including alternative possible states of ocean circulation (and constraints thereon).

What do we know about ... ocean oxygenation?

Adding further proxies: here I/Ca in biogenic carbonates

2 species: iodide (reduced) and iodate (oxidized)

iodate is the only form incorporated into the carbonate lattice, and it reduced in dysoxic/anoxic conditions

iodide is kinetically-limited in its re-oxidation back to iodate, hence providing a tracer of the oxygenation statu of local/regional source waters

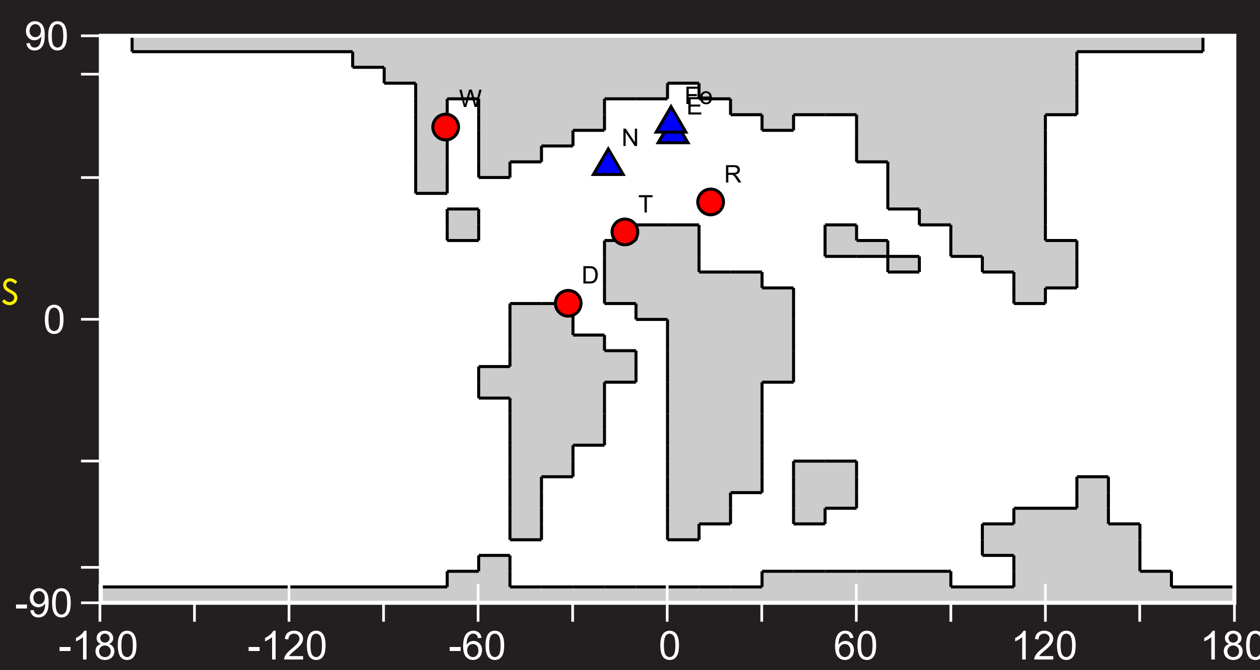
(there is also biological update and release of I ...)

blue symbols: high I/Ca

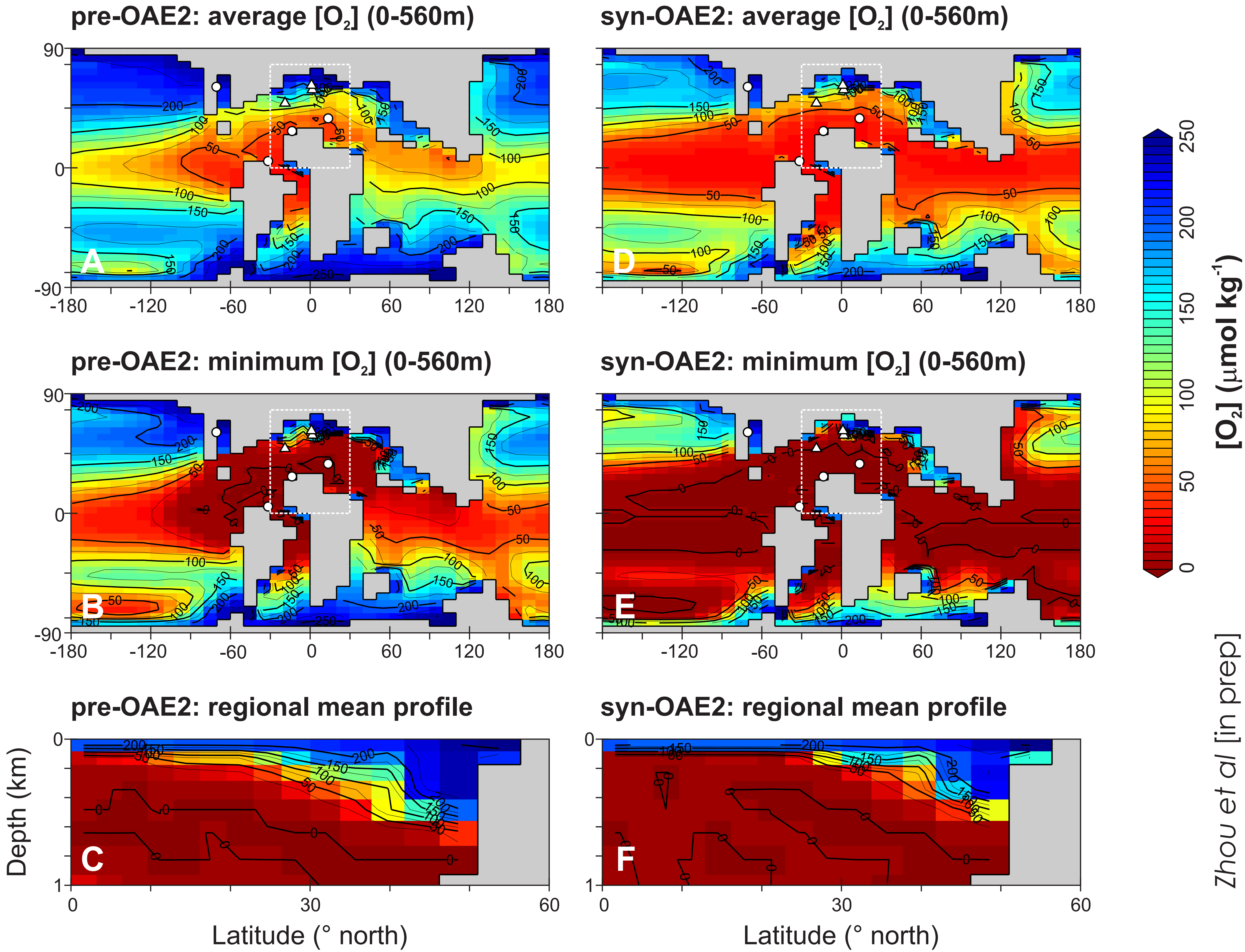
red: low I/Ca

variable I/Ca through OAE2 with a general decrease across most sites

northern proto-Atlantic sites retain high I/Ca



Zhou et al [in prep]



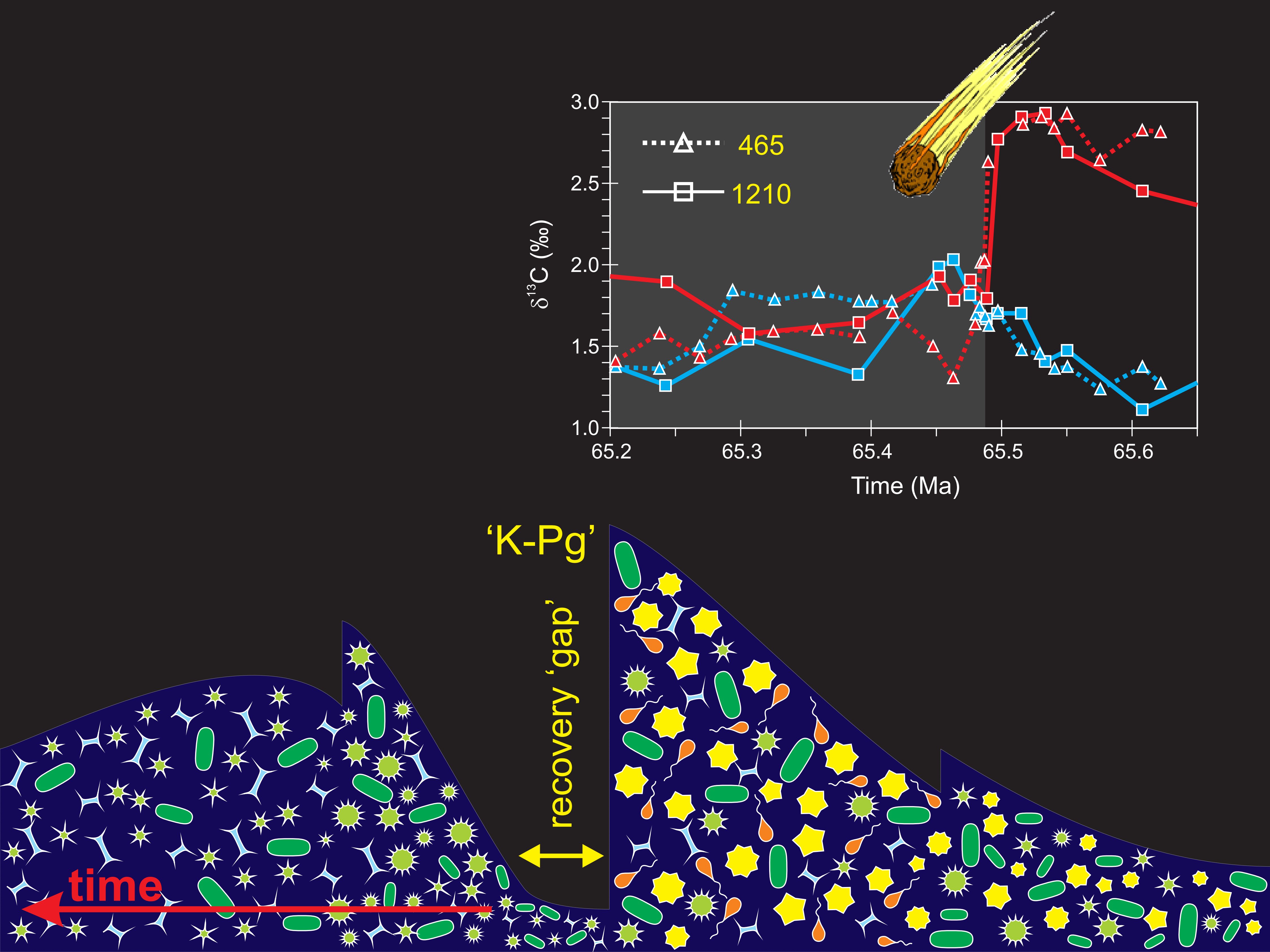
pre-OAE2: average [O2] (0-560m)
syn-OAE2: average [O2] (0-560m)
pre-OAE2: minimum [O2] (0-560m)
syn-OAE2: minimum [O2] (0-560m)
pre-OAE2: regional mean profile
syn-OAE2: regional mean profile
A
B
C
D
E
F
Depth (km)
Latitude (° north)
[O2] (µmol kg-1)
Zhou et al [in prep]

How can we constrain the changing patterns of ocean redox?

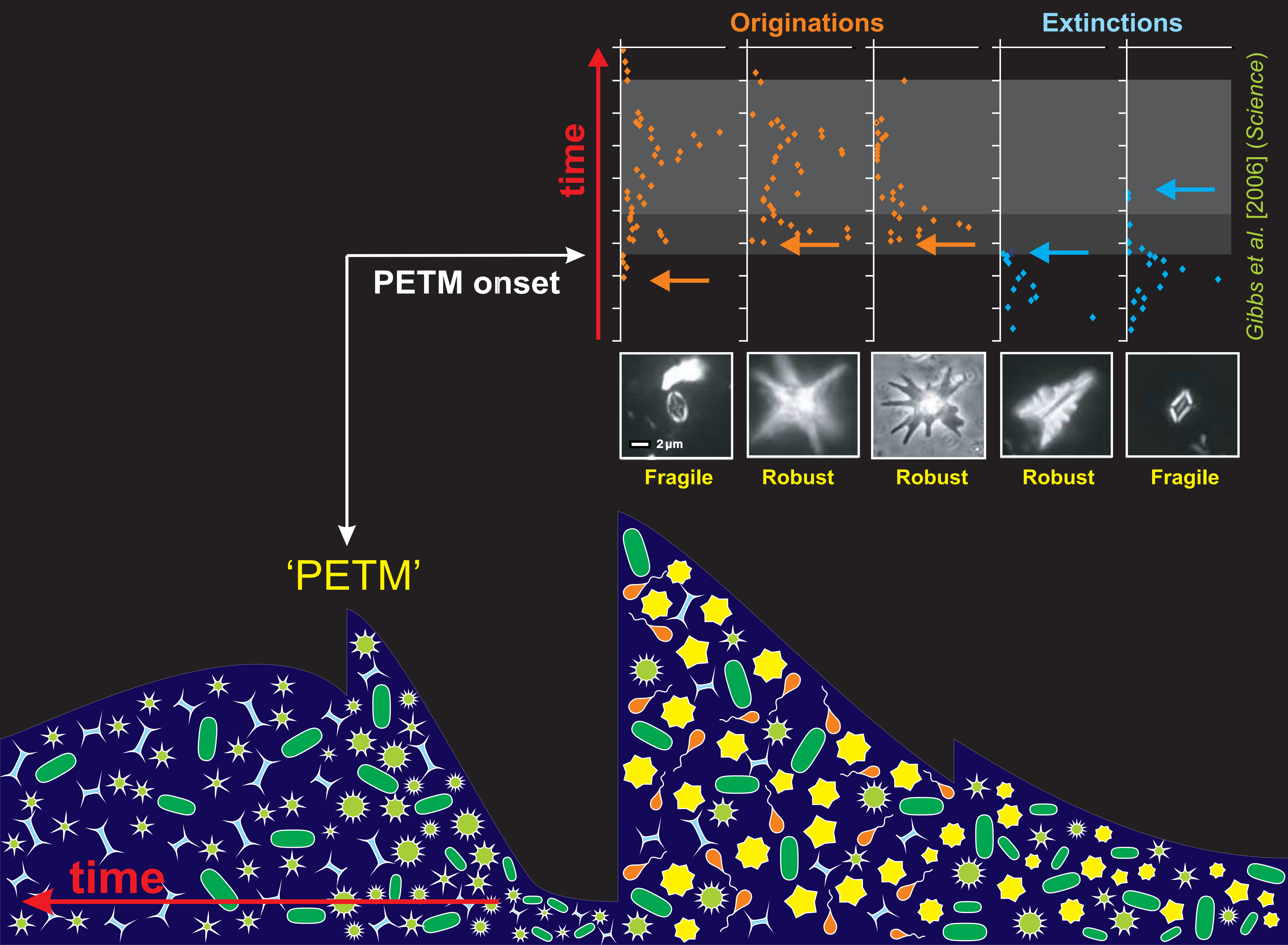
How can we distinguish different levels of suboxia and low oxygenation rather than e.g. extremes in euxinia?

Can we incorporate new proxies into models as and when they are developed such that mechanistic interpretation always goes hand-in-hand with the data?

What do we know about ... environmental sensitivities of ecosystems?

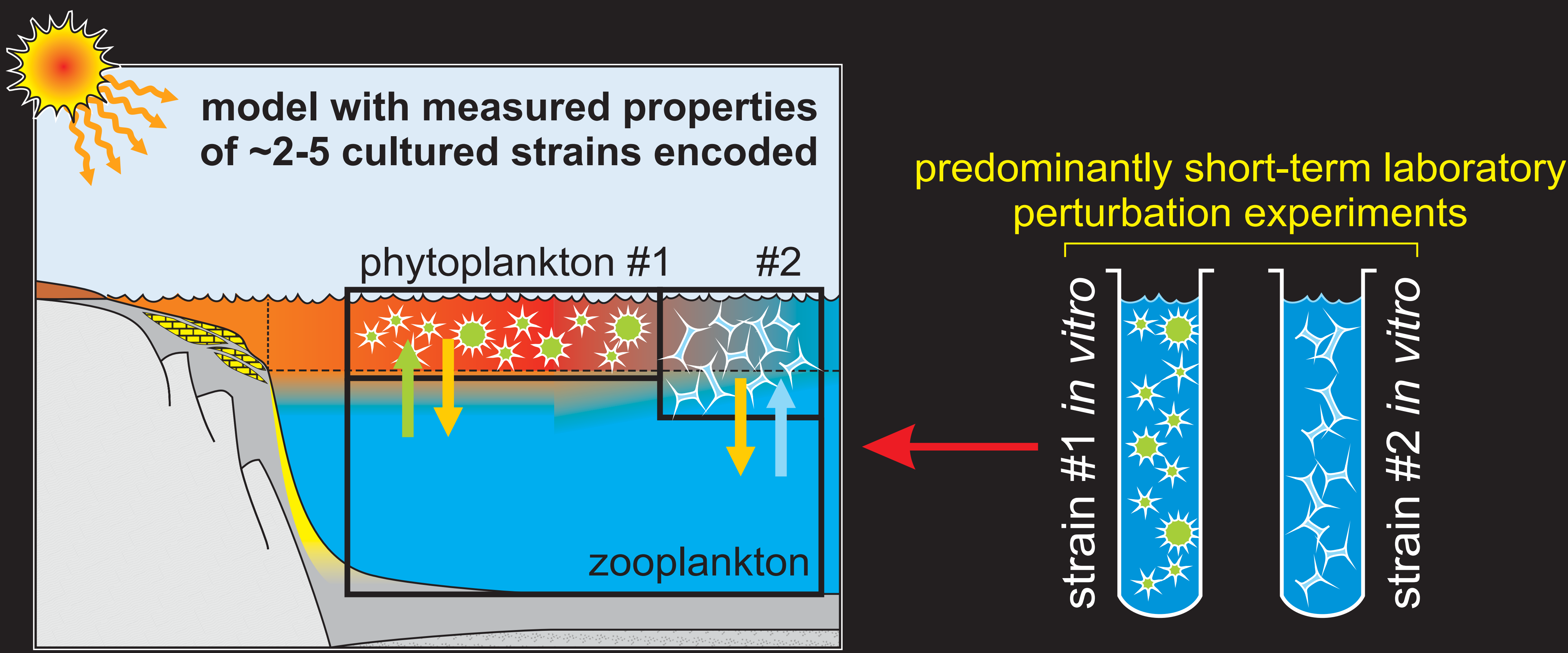


3.0
2.5
2.0
1.5
1.0
δ13C (‰)
465
1210
65.2
65.3
65.4
65.5
65.6
Time (Ma)
‘K-Pg’
recovery ‘gap’
time

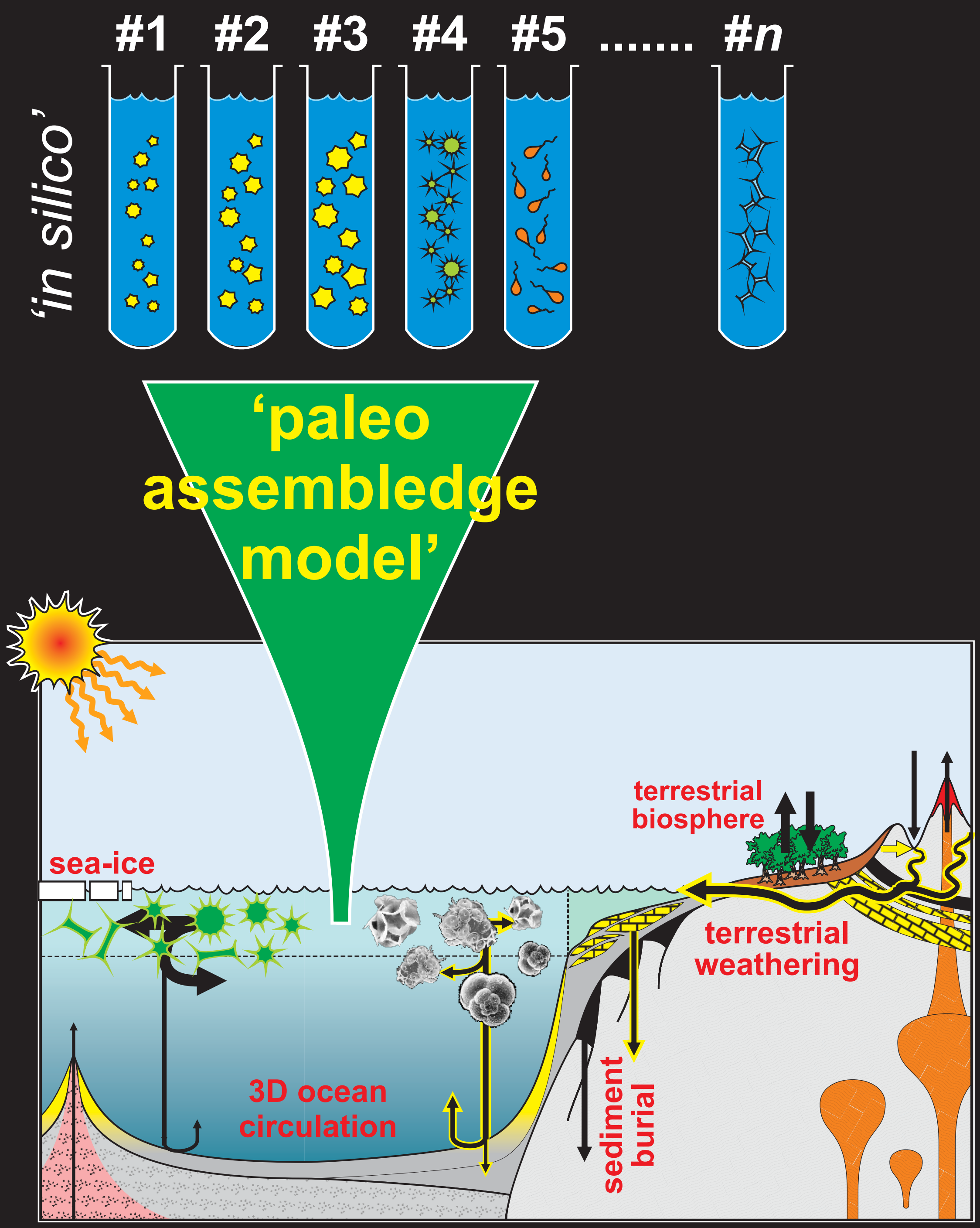

Originations
Extinctions
time
PETM onset
Gibbs et al. [2006] (Science)
2 μm
Fragile
Robust
Robust
Robust
Fragile
'PETM'
time

Can we use (ecosystem) models to help interpret the micropaleotological record and deduce species and ecosystem sensitivities to environmental change?

What do we know about ... environmental sensitivities of ecosystems?



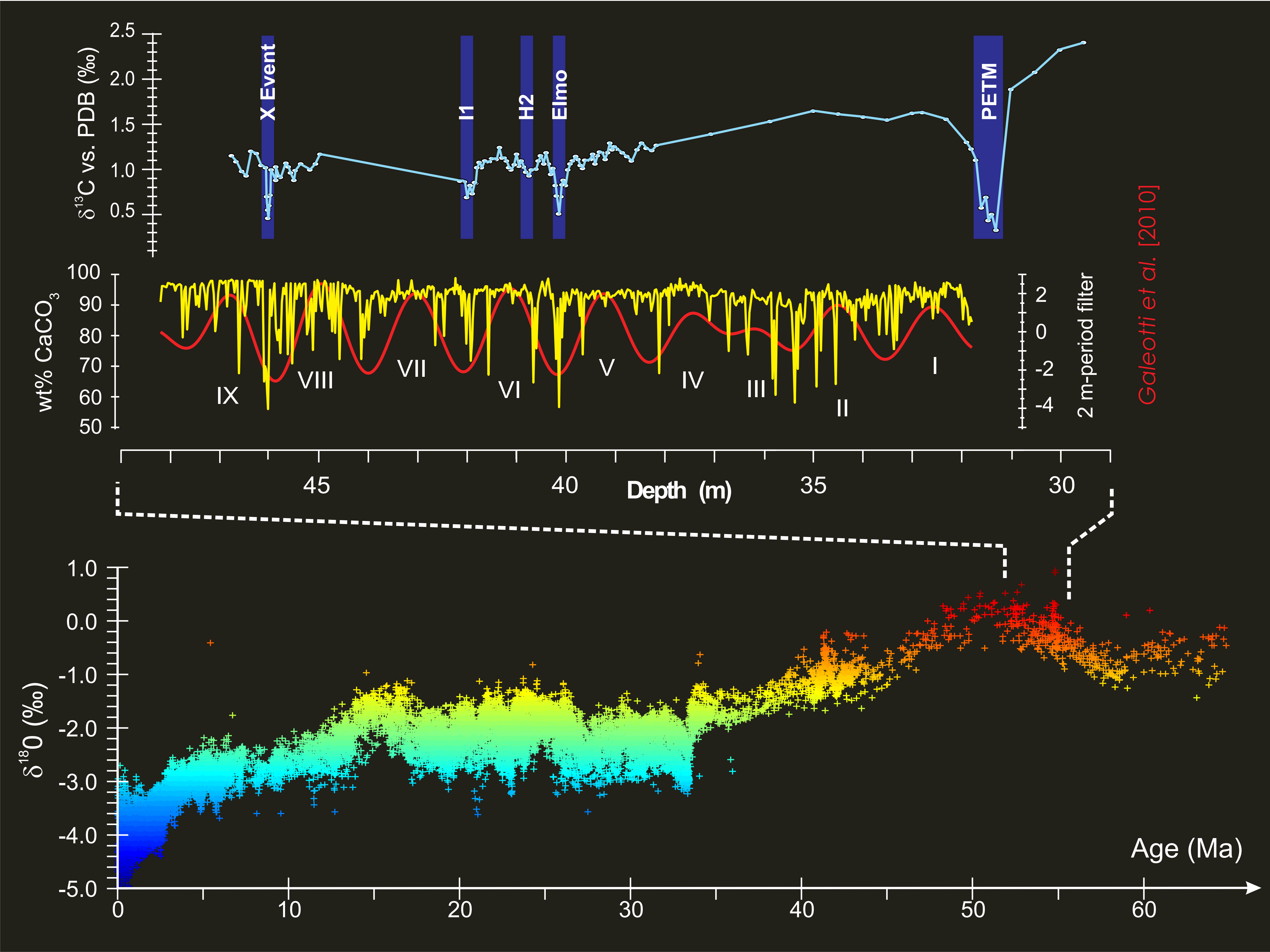
‘PALEOGENiE’



Marine ecosystems *in silico*:

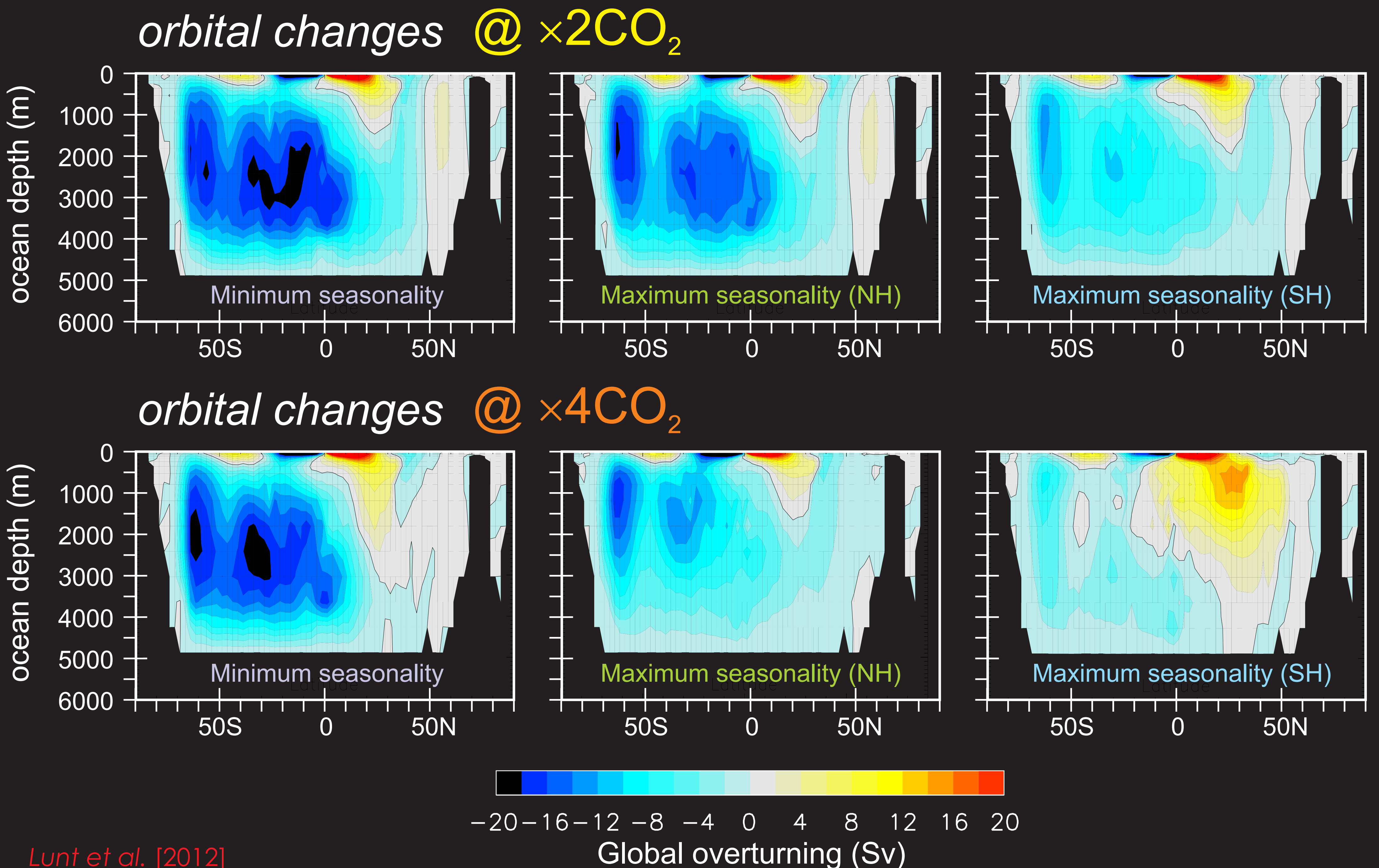
- *n* = 1,000-10,000 randomly-generated trait vectors (’plankton’).
- Plankton trait vectors set according to physiological ‘rules’, e.g. larger cells have a higher nutrient limitation threshold, the ability to fixed N_2 comes at the expense of reduced growth rate, etc.
- Plankton compete and the ecosystem is an **emergent** rather than prescribed property.
  But ...
  ... *the geochemical environment and climate co-evolves as global nutrient cycles are modified*.
- At very high resolved diversity, we can explore questions of **adaptation** and rates of **evolutionary change** by spawning new plankton with perturbed characteristics.

What do we know about ... paleo-wiggles?

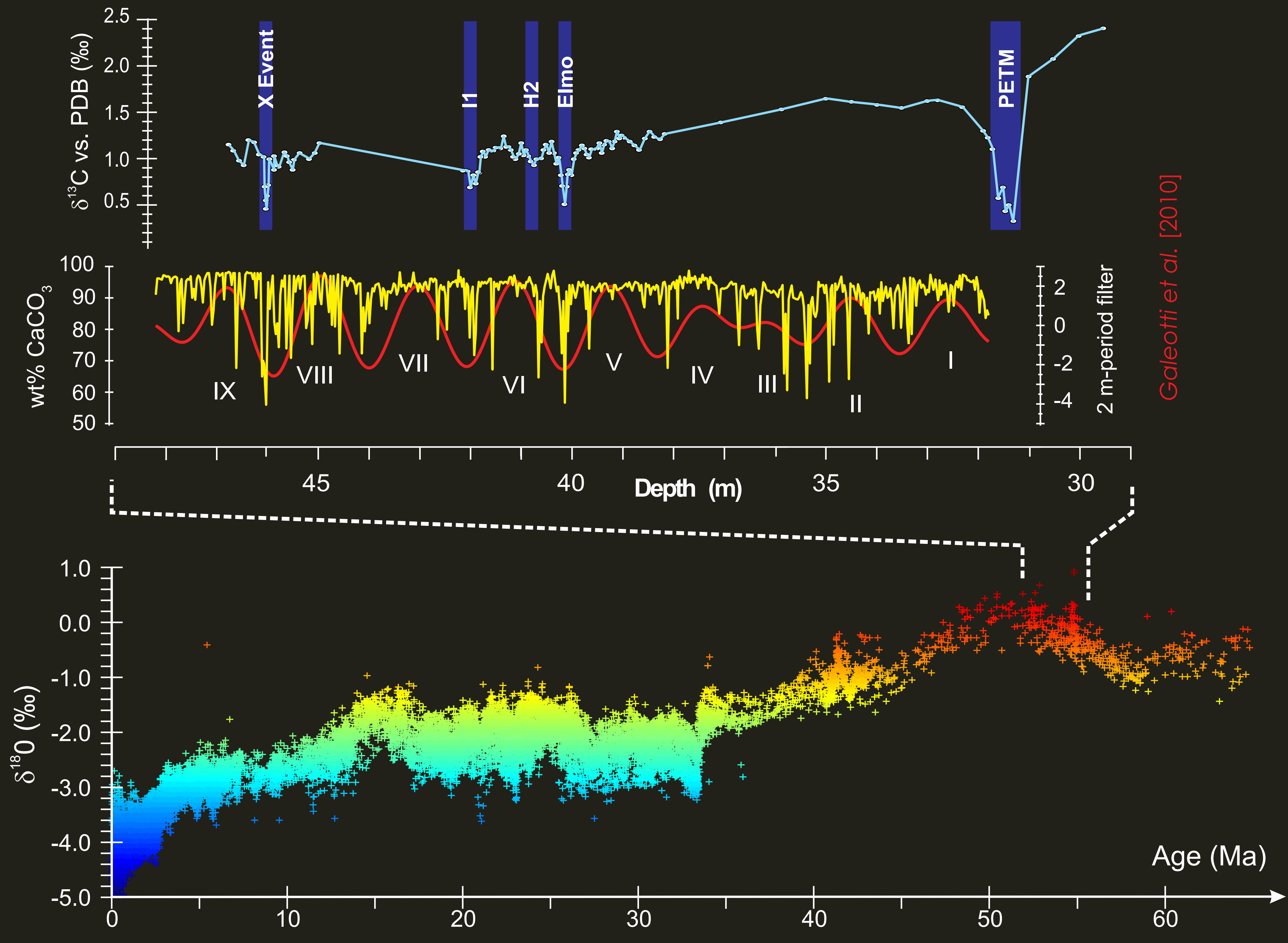


δ13C vs. PDB (‰)
X Event
I1
H2
Elmo
PETM
wt% CaCO3
IX
VIII
VII
VI
V
IV
III
II
I
2 m-period filter
Galeotti et al. [2010]
Depth (m)
δ18O (‰)
Age (Ma)

What do we know about ... paleo-wiggles?



Lunt et al. [2012]



δ^{13}C vs. PDB (‰)
X Event
I1
H2
Elmo
PETM
wt% CaCO$_3$
IX
VIII
VII
VI
V
IV
III
II
I
2 m-period filter
Galeotti et al. [2010]
Depth (m)
45
40
35
30
δ^{18}O (‰)
Age (Ma)

Can we use (biogeochemical-climate) models to understanding the mechanistic driver of observed orbital-scale variability?

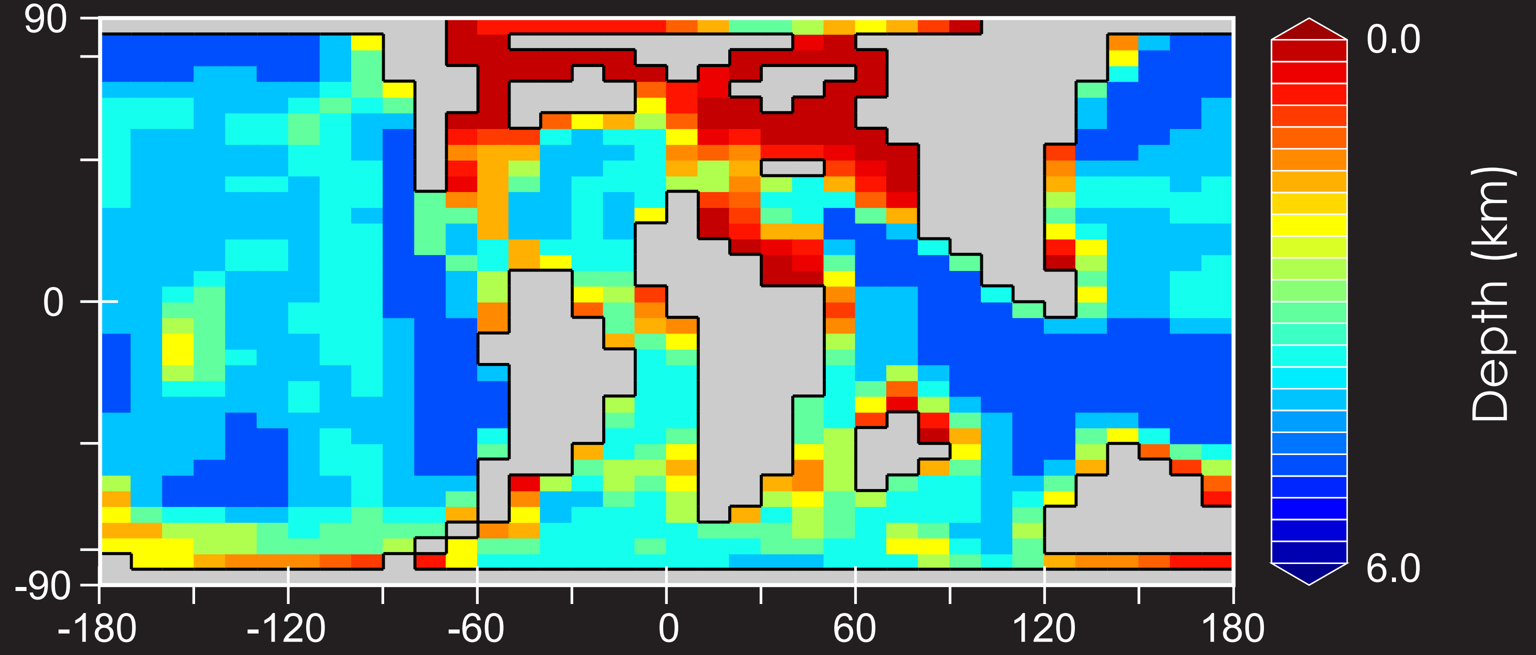
(The challenge partly being running a sufficient model for >1 Myr ...)

What do we know about ... using numerical models?

What do YOU know about using models?
Why are numerical models not more widely used to test hypotheses, as a device to explore plausibilities (within physical constraints), and treated as 'just another' piece of analytical instrumentation?

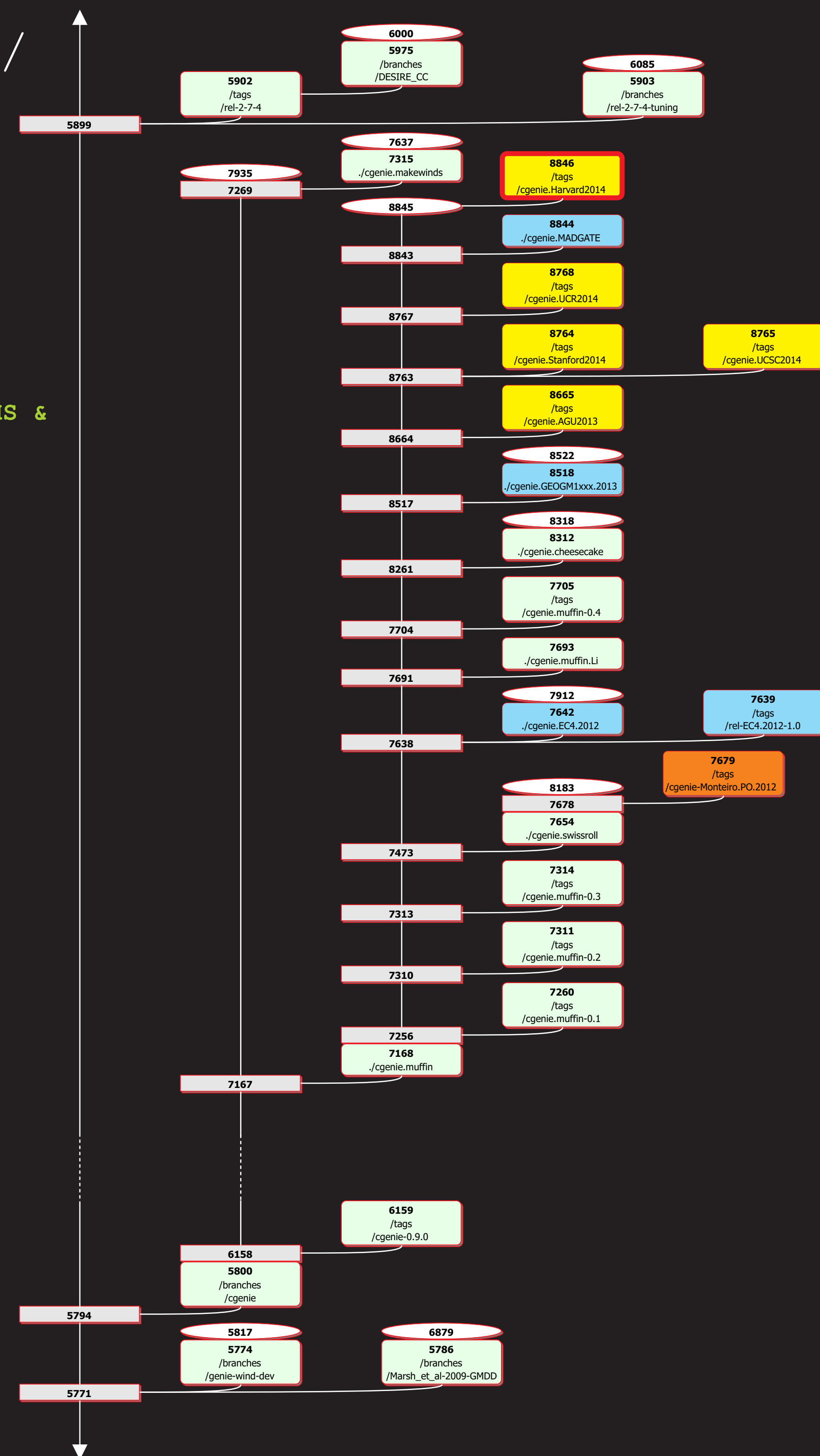
What do we know about ... using numerical models?

‘cGENIE’ Earth system model re-grided for the latest Maastrichtian following simulations from the HadCM3L fully-coupled GCM.

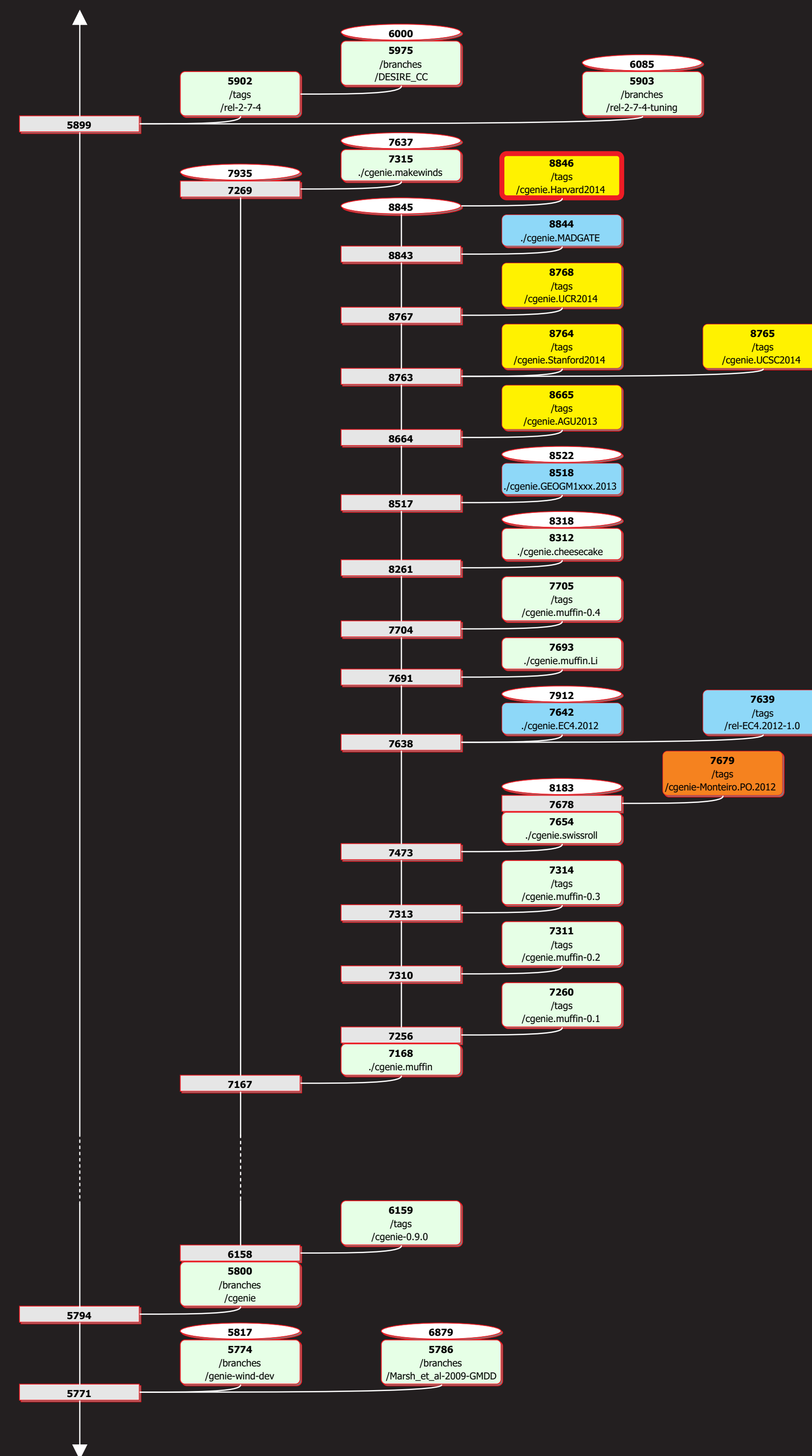


https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.Harvard2014

```
! calculate carbonate alkalinity
loc_ALK_DIC = dum_ALK &
& - loc_H4BO4 - loc_OH - loc_HPO4 - 2.0*loc_PO4 - loc_H3SiO4 - loc_NH3 - loc_HS &
& + loc_H + loc_HSO4 + loc_HF + loc_H3PO4
! estimate the partitioning between the aqueous carbonate species
loc_zed = ( &
&    (4.0*loc_ALK_DIC + dum_DIC*dum_carbconst(icc_k) -
loc_ALK_DIC*dum_carbconst(icc_k))**2 + &
&    4.0*(dum_carbconst(icc_k) - 4.0)*loc_ALK_DIC**2 &
& )**0.5        loc_conc_HCO3 = (dum_DIC*dum_carbconst(icc_k) -
loc_zed)/(dum_carbconst(icc_k) - 4.0)
loc_conc_CO3 = &
& ( &
&    loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
&    4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))
loc_conc_CO2 = dum_DIC - loc_ALK_DIC + &
& ( &
&    loc_ALK_DIC*dum_carbconst(icc_k) - dum_DIC*dum_carbconst(icc_k) - &
&    4.0*loc_ALK_DIC + loc_zed &
& ) &
& /(2.0*(dum_carbconst(icc_k) - 4.0))
loc_H1 = dum_carbconst(icc_k1)*loc_conc_CO2/loc_conc_HCO3
loc_H2 = dum_carbconst(icc_k2)*loc_conc_HCO3/loc_conc_CO3
```



www.seao2.info/misc_harvard2014.html



cGENIE ClimaTea 2014 version: README

Andy Ridgwell

April 23, 2014

1. To get an exact (read-only) copy of the ('muffin' development branch) cGENIE source code used for the ClimaTea presentation – in linux, (ideally from your home directory) type:
   svn co https://svn.ggy.bris.ac.uk/subversion/genie/tags/cgenie.Harvard2014 --username=genie-user cgenie.muffin
   NOTE: All this must be typed continuously on ONE LINE, with a S P A C E before '--username', and before 'cgenie'. You will be asked for a password – it isg3n1e-user.
2. You need to set a couple of environment variables – the compiler name, netCDF library name, and netCDF path. These are specified in the file user.mak (genie-main directory). If the cgenie code tree (cgenie.muffin) and output directory (cgenie_output) are installed anywhere other than in your account HOME directory, paths specifying this will have to be edited in: user.mak and user.sh (genie-main directory). Installing the model code under the default directory name (cgenie.muffin) in your HOME directory is hence by far the simplest and avoids incurring additional/unnecessary pain (configuration complexity) ...
   You will also need to have installed or linked to an appropriate FORTRAN compiler and netCDF library (built with the same FORTRAN compiler). The GNU FORTRAN compiler (gfort) version 4.4.4 or later is recommended. The netCDF version needs to be 4.0 (more recent versions require a little work-around, not documented here ...).
3. To test the code installation – change directory to cgenie.muffin/genie-main and type:
   make testbiogem
   This compiles a carbon cycle enabled configuration of cGENIE and runs a short test, comparing the results against those of a pre-run experiment (also downloaded alongside the model source code). It serves to check that you have the software environment correctly configured. If you are unsuccessful here ... double-check the software and directory environment settings in user.mak (or user.sh) and for a netCDF error, check the value of the NETCDF DIR environment variable. (Refer to the User Manual for addition fault-finding tips.) If environment variables are changed: before re-trying the test, you will need to type:
   make cleanall

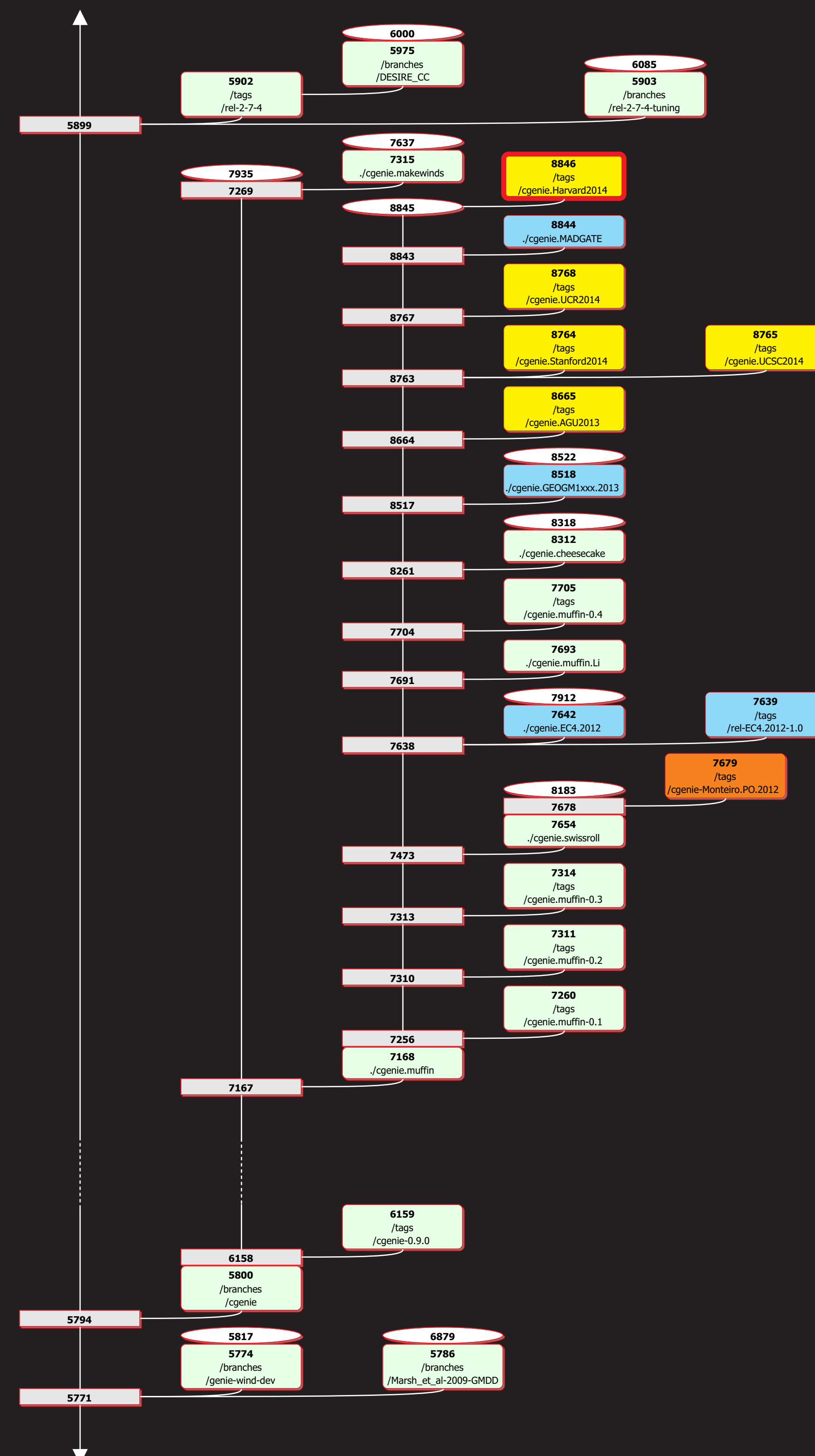
That is is for the basic installation. To run the model it is a simple matter of calling the 'runmuffin.sh' shell script from genie-main and supplying a couple of parameter values, e.g.:

./runmuffin.sh cgenie.eb_go_gs_ac_bg.worjh2.ANTH / EXAMPLE.worjh2.Caoetal2009.SPIN 10000

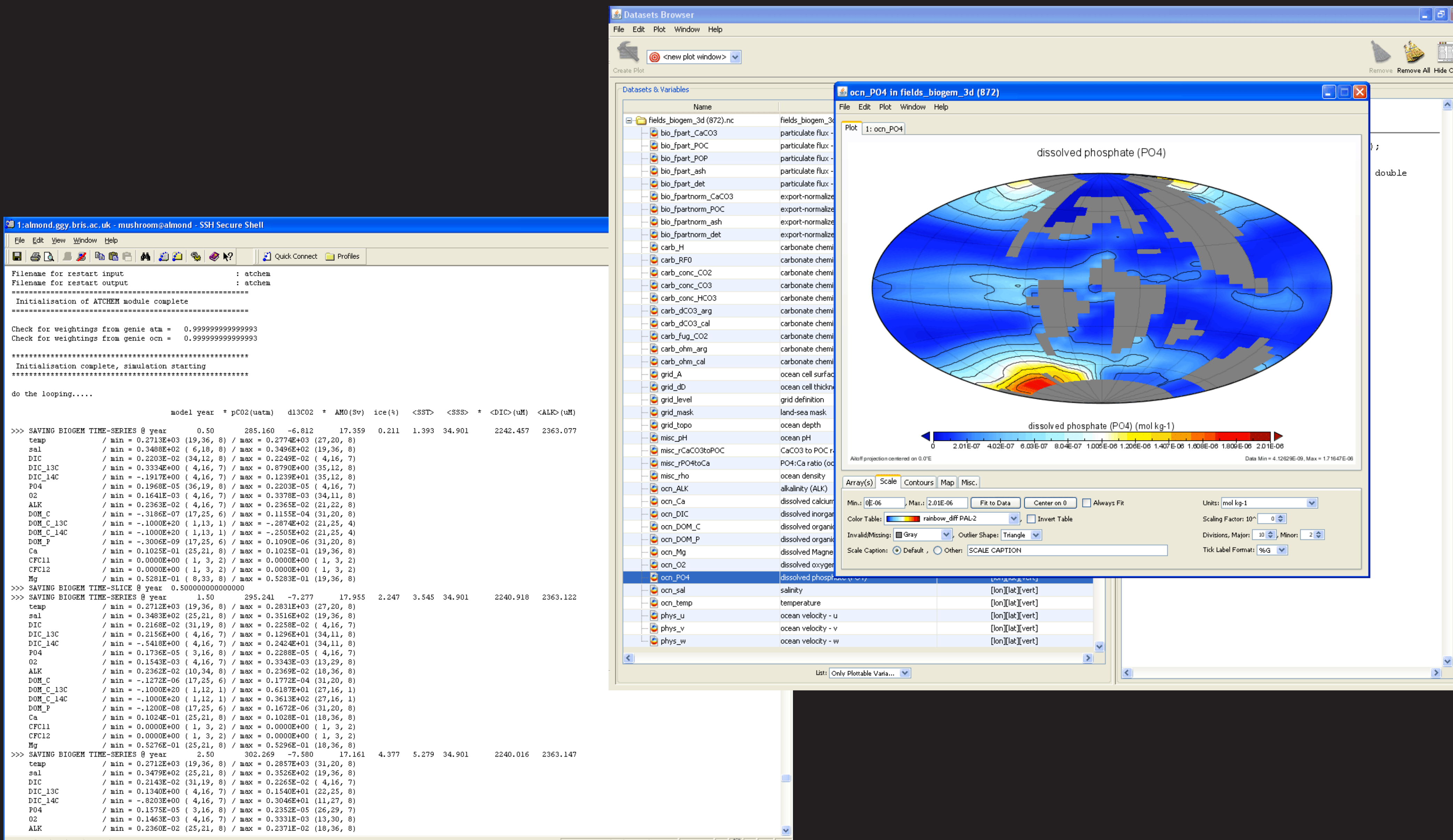
Refer to the cGENIE User manual for more information regarding installing, running, and analyzing model output, and cGENIE Examples for more information on this specific example.[1] Also read the cGENIE README
Highly recommended ... is in order to have a working appreciation of the structure of the model and output, plus the format of the model output and how to visualize it – to read through:

http://www.seao2.info/cgenie/labs/EC4.2013/GEOGM1110andM1404.2013-14.cGENIE_LAB.0000.pdf

(which serves as a basic introduction to the model and how to use it).

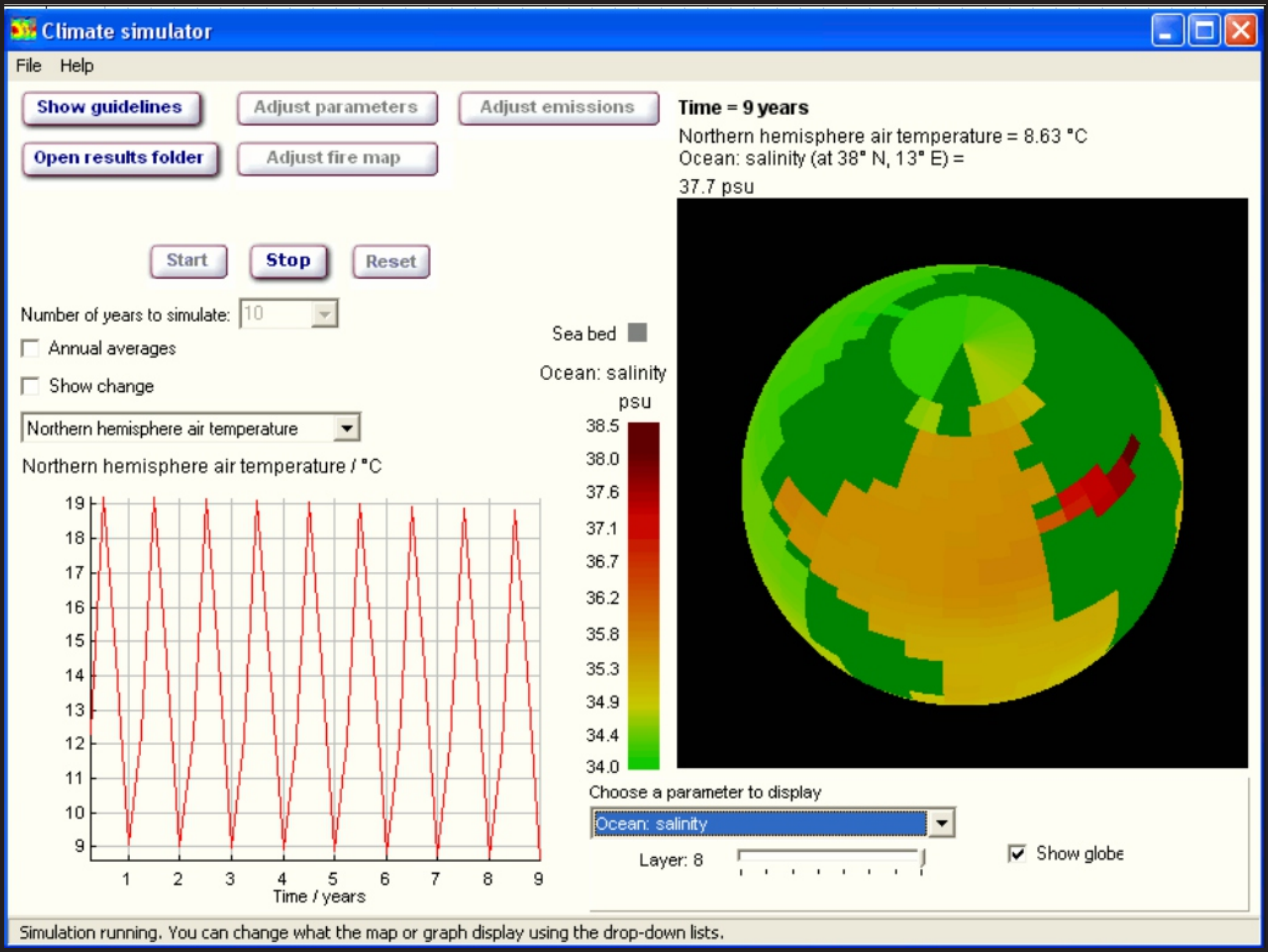


What do we know about … using numerical models?



The challenge now being to YOU – what would it take for (climate/Earth system) models to be used more widely and become a more commonplace and standard methodology?

What do we know about ... using numerical models?



Challenges (model world):

- Bringing model output and data sufficiently close together to allow for a correct interpretation.
- Cretaceous ocean circulation – how can we constrain it? (proxies, model physics/resolution)

And surface climate and lack of polar warmth in many GCMs, whilst we are about it ...

- Are we looking at steady states or dynamical transients and can we (numerically afford to) model either?
- Can we adequately constrain the bulk chemistry of the ocean (e.g. DIC, ALK, Ca^{2+}, Mg^{2+}) and hence carbonate chemistry (e.g. *p*H).

Also: time-scale of change.

- How finely can we resolve ocean redox? Can we do rather better than 'significant vs. no' euxinia?
- Can we (develop and) use models to help interpret the micropaleontological record?
- Where do the 'wiggles' (in $\delta^{13}C$ / $\delta^{18}O$ / wt% $CaCO_3$) come from? What do they 'mean?
- Who can drive models? Is a driving test necessary? Can it all be made much easier and models more accessible?