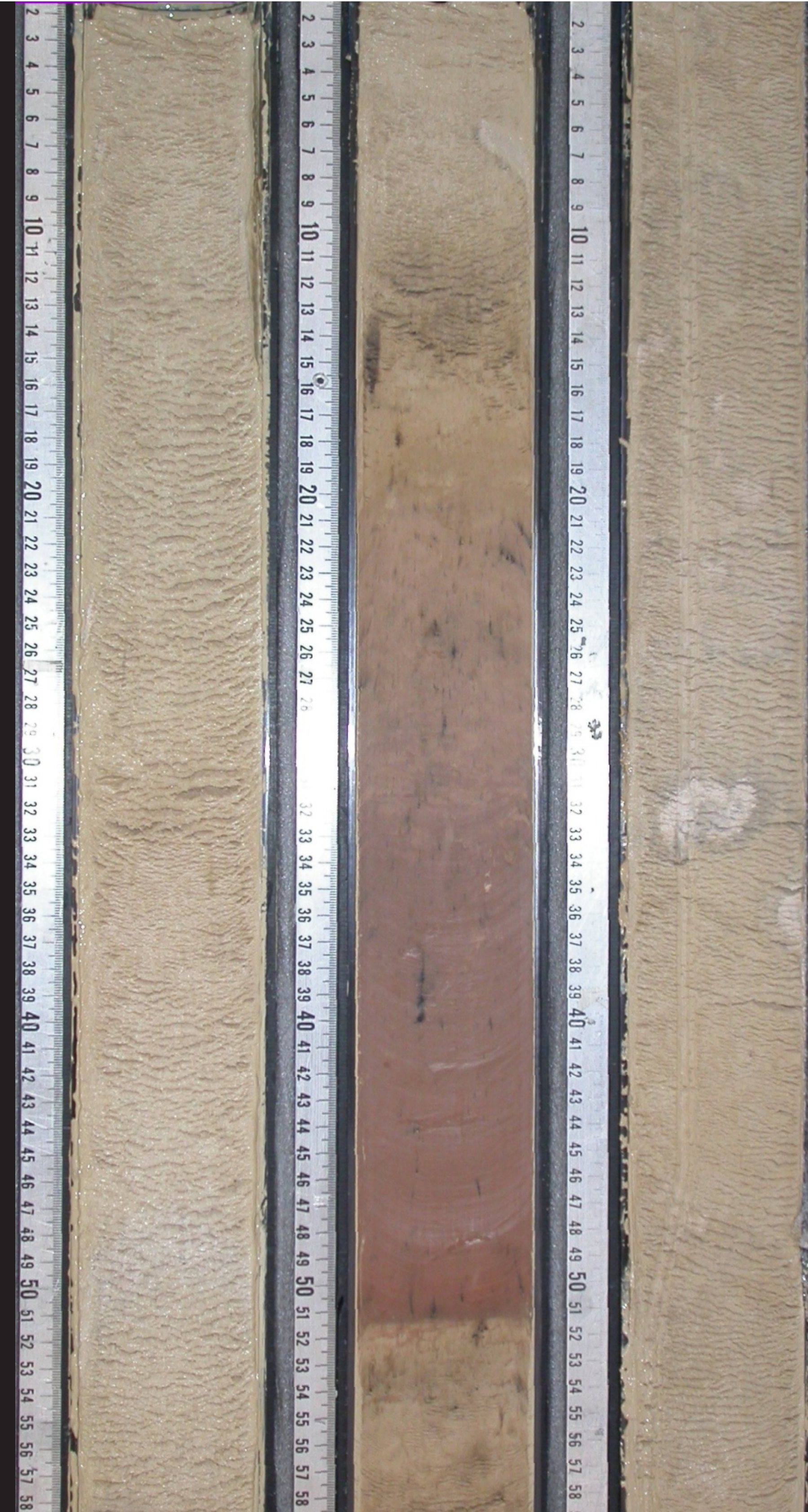
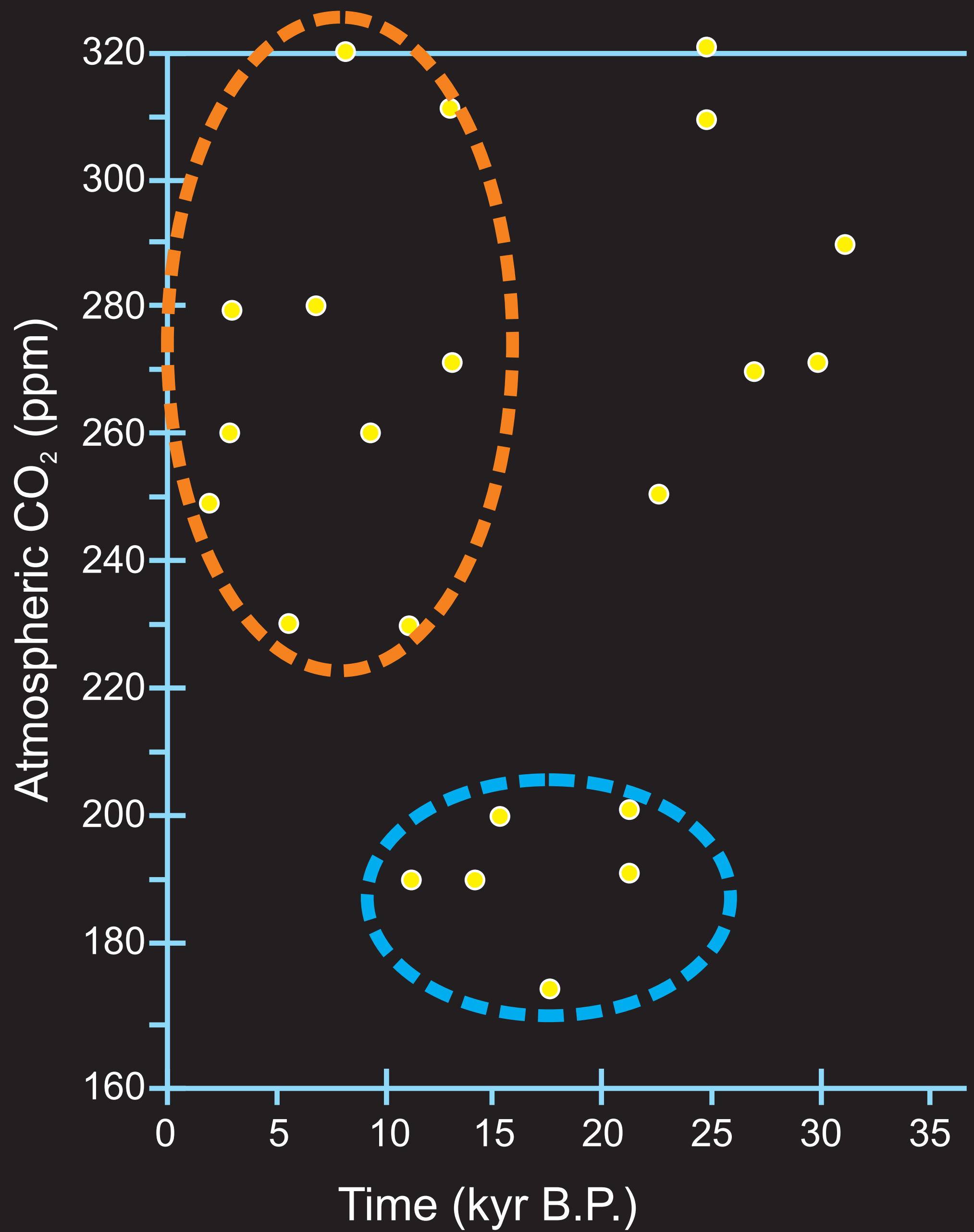
The global carbon cycle

Andy Ridgwell



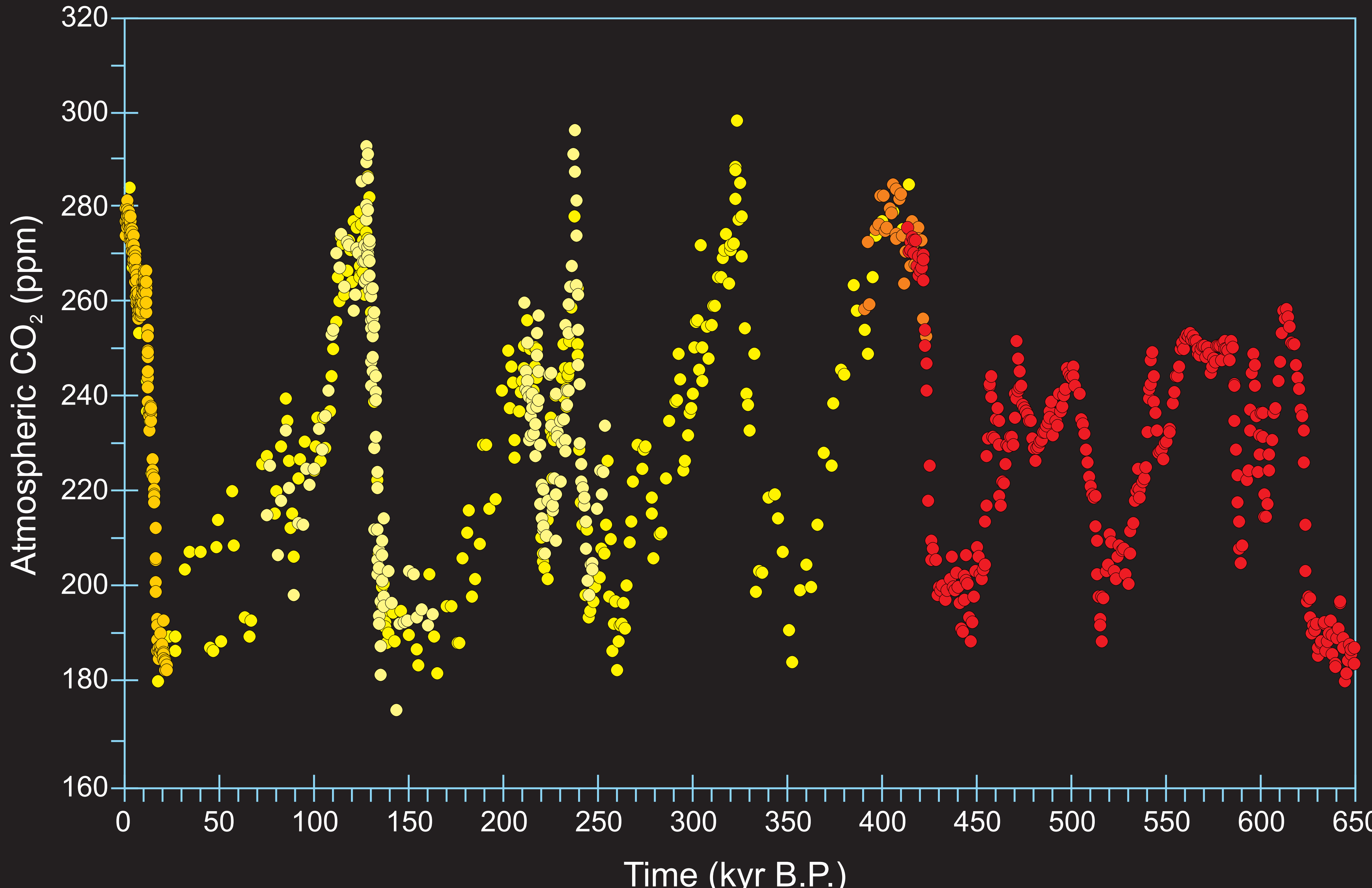
Classic CO_2 (and climate) problems



Extraction carried out by crushing (rather than melting) ice under vacuum eliminated previous contamination problems. This gave the first reliable evidence for a substantially (ca. 50%) lower glacial CO_2 concentration compared to the modern

Dome C ice core; Delmas et al. [1980] (Nature 284)

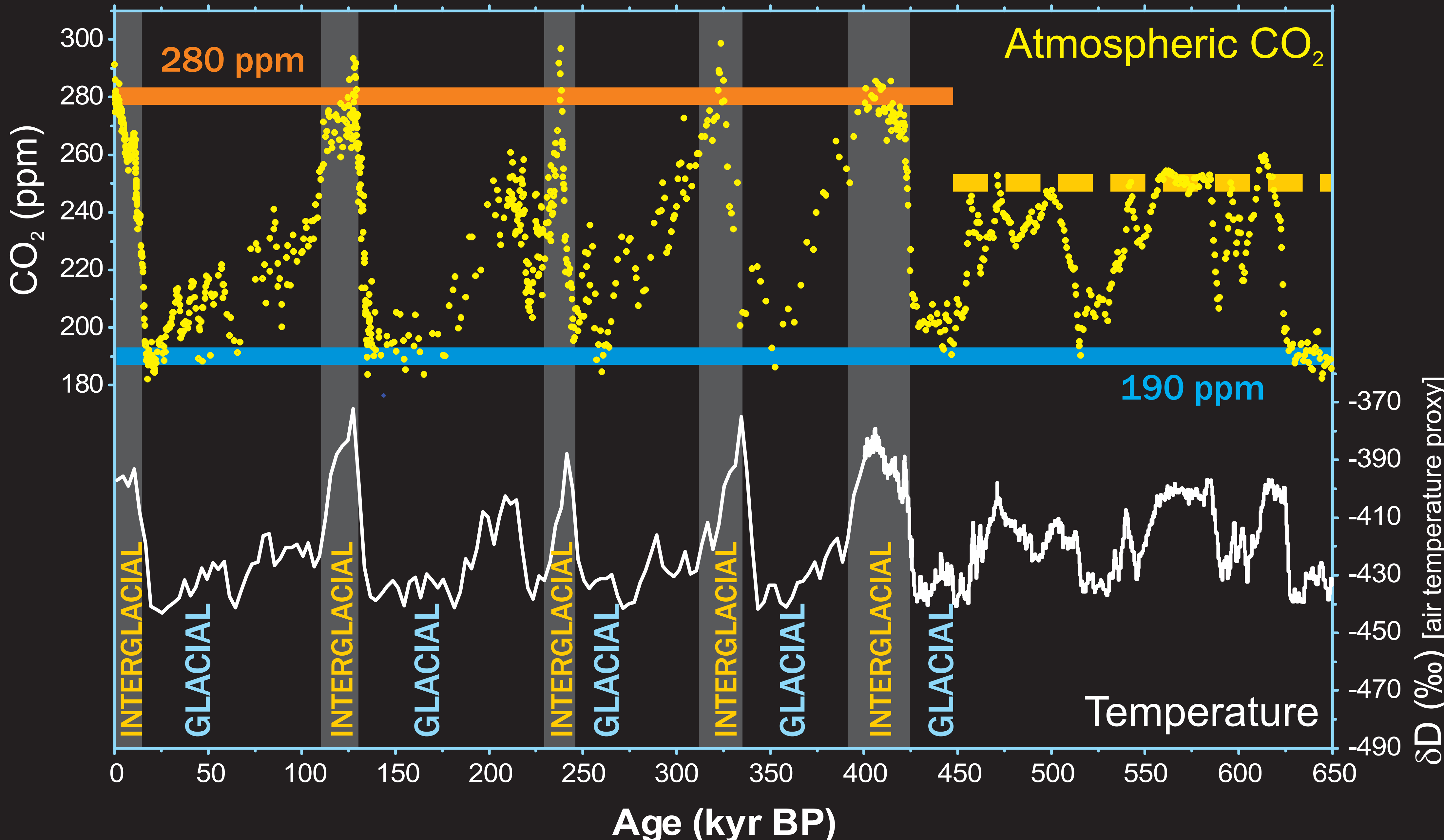
Classic CO_2 (and climate) problems

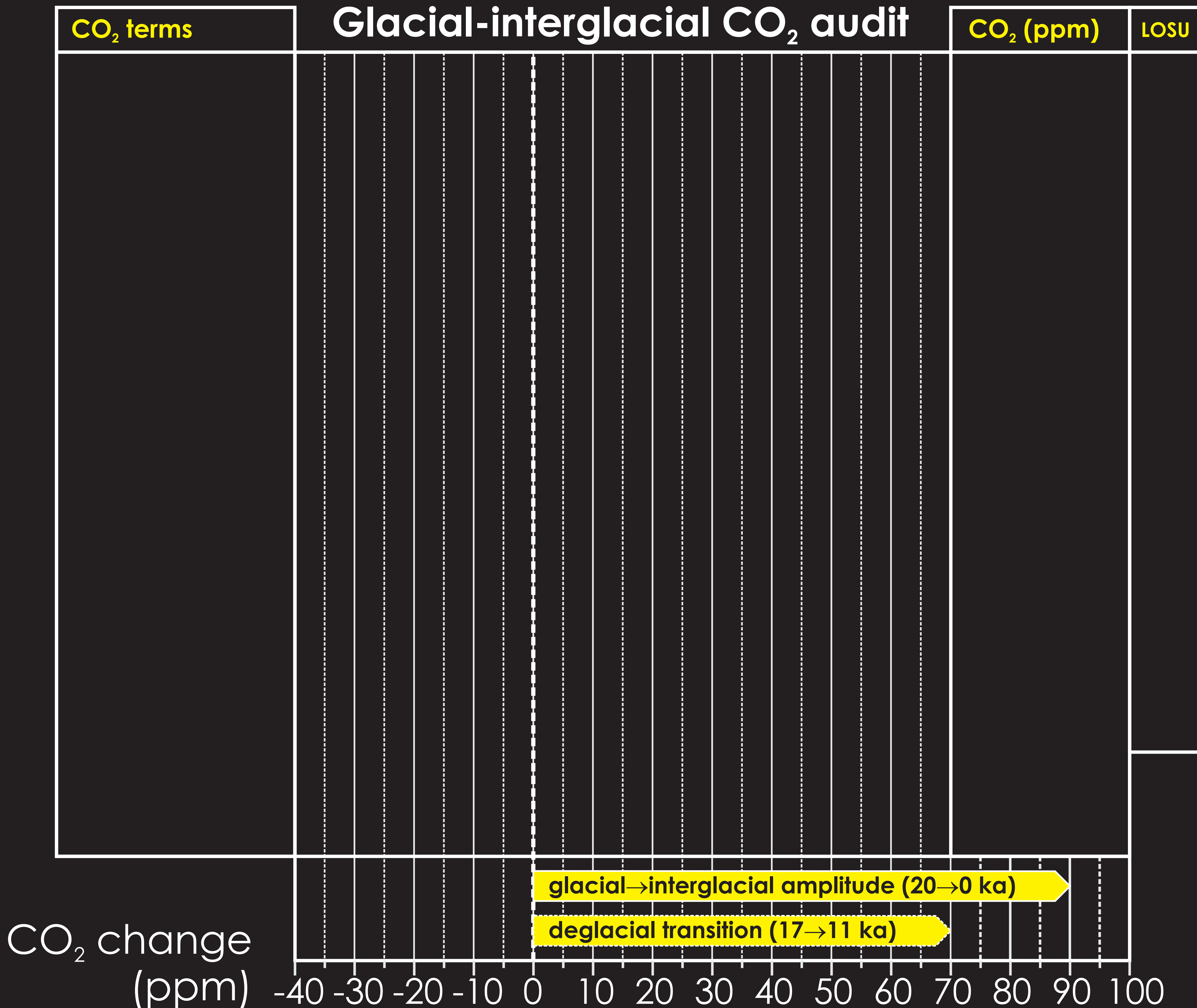


Combined Dome C and Vostok ice core data

Classic CO_2 (and climate) problems

Dome C and Vostok ice core data; *Siegenthaler et al.* [2005] (*Science* **310**)





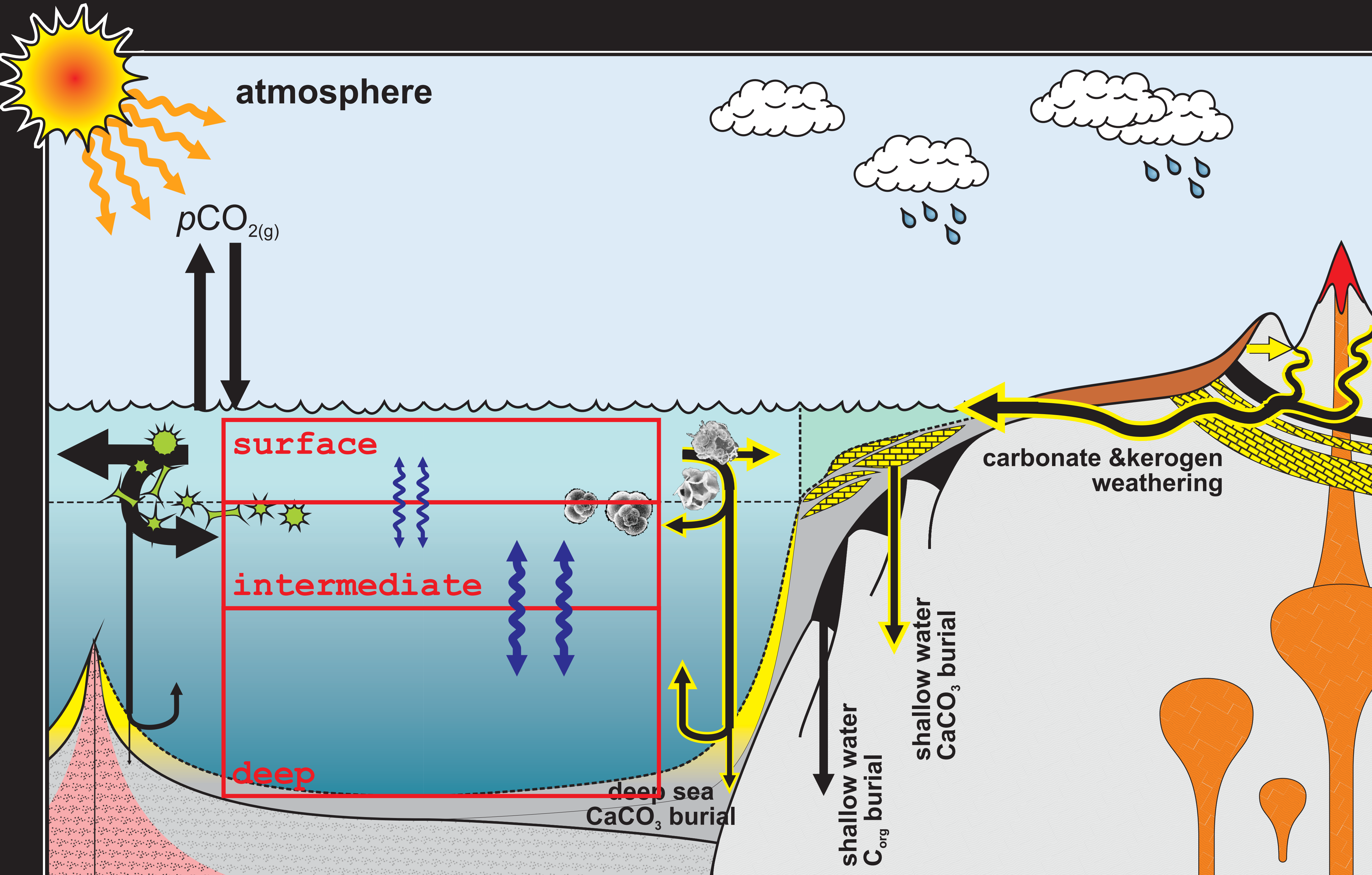
Glacial-interglacial CO2 audit
CO2 terms
CO2 (ppm)
LOSU
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

Classic CO_2 (and climate) problems

http://www.seao2.info/teaching.html

'UCR2015' ... 'C_Model' ... download and un-zip file

A brief guide to Toyby Tyrrell's JAVA 'C Model'



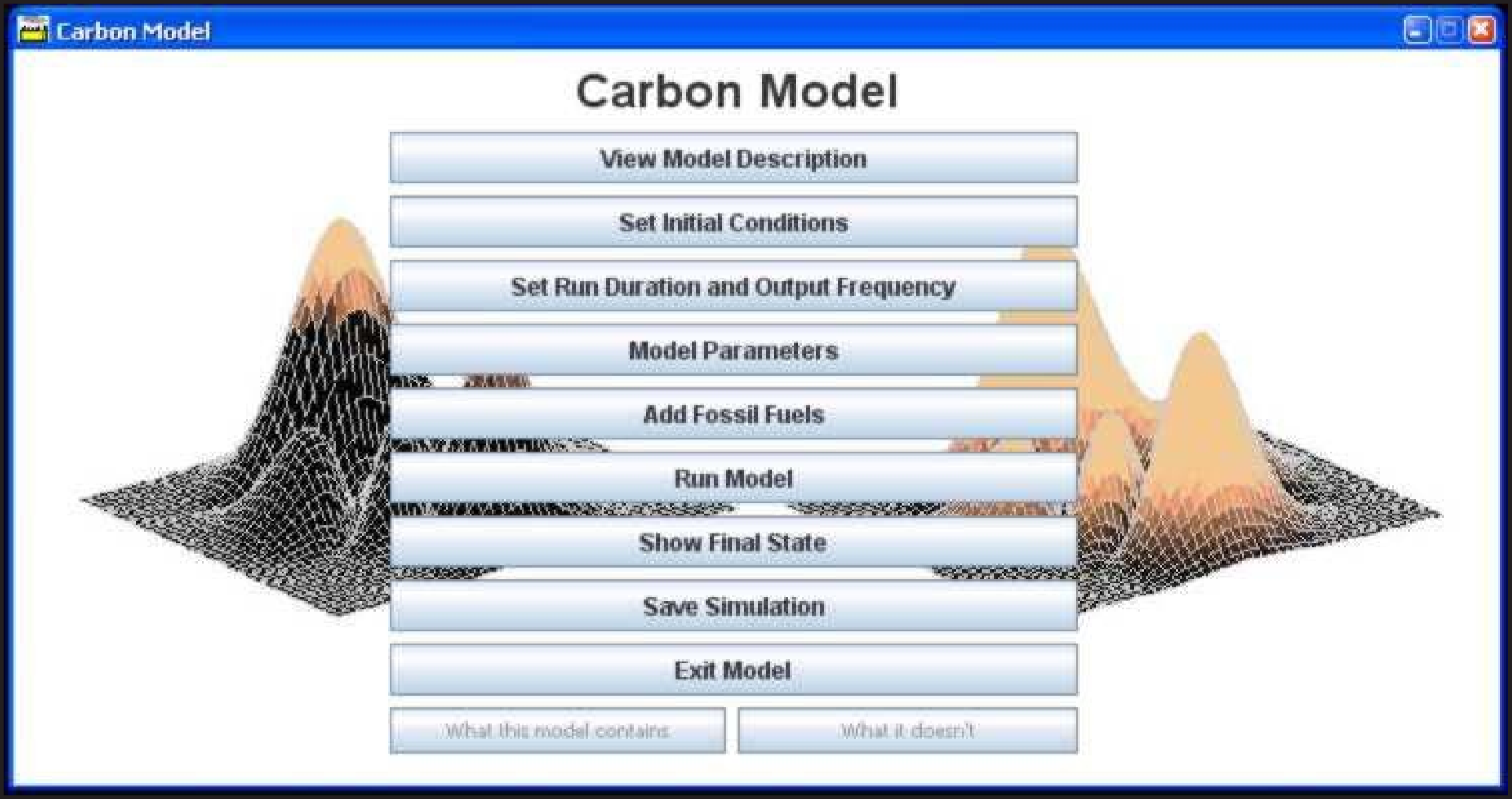
A brief guide to Toyby Tyrrell's JAVA 'C Model'

0.1 For some of you, using numerical models of the climate system and/or global biogeochemical cycles might seem about as much fun as sticking you tongue in an electrical outlet ...

However, the model you are going to use has a relatively simple (maybe *too* simple!) to understand configuration and comes with a graphical interface for setting up experiments and viewing the results.

Run (e.g. double-click) on **`C_Model.jar`**.

You should now have the following (Carbon Model) window on your screen:



0.3 This model includes many of the processes described in the lectures. Hence, by 'playing' with this model and changing some of the processes, one should be able to get a better feel for how biogeochemical cycles 'work' and how important they are (or not) to atmospheric pCO_2. This is one of the best uses of numerical models – improving your understanding of the Earth system (climate and global biogeochemical cycles). Numerical models are also a tool to answer 'what if …' questions you might have (and some of the brief exercises will be doing just this).

0.4 Quickly familiarize yourselves with the relevant controls and outputs of the model and judge to what extent the model is capable of representing the 'real World'.

0.5 First: without *changing anything* in the model: simply run it (click on the Run Model button in the main Carbon Model window). A pop-up window will open and show the model progress – it should take about 15 seconds or so to complete. (Note that the model does not solve all the equations in an instant – the solution is accomplished by taking little steps in time, one after another, and calculating the change in carbon cycle properties after each and every time step.)
When it finishes, a new Window (Carbon Model Plots) should appear containing 6 plots. There are in fact 3 pages of plots – you can move forward to the next page of plots via the Next button at the top of the screen, and back again (via Back).

0.6 First … note that all the lines either go straight across or are almost straight – i.e, they don't change with time (Time is on the *x*-axis and is in units of ky, i.e., thousands of years). This simply reflects that the initial values chosen for the various properties in the model (e.g., nutrient concentrations in the ocean boxes, atmospheric pCO_2) are about the same as the values reached after simulating thousands of years of nothing new happening, i.e., the model was already initial at (or close to) *steady state* (equilibrium). This is known as starting from a *spinup*. In the default setup of the model, it runs for 3000 years (i.e., the lines in the plots end at a value of 3.0 ky on the *x*-axis).

0.7 From the main Carbon Model control window – click on the Show Final State button. A window opens (called C_Model Final States) which provides a simple summary of some of the properties of the model reached at the end of the simulation. Again, there are several pages of values (contained in different 'tabs' – Summary, State Variables, and State Variables Cont).

0.8 You can alter the assumptions in the model via the Model Parameters button (in the main, Carbon Model window). You will see 7 different 'tabs', each with a different set of values you can change:
Physical, Rivers, Organic Carbon, Phosphorous, $CaCO_3$, Biological, Isotopes.

When you have altered all the parameters you need:
Click on the **Apply and Close** button (NOT the Close one) to get your changes accepted.

0.9 For an example: to release (fossil fuel) CO_2 to the atmosphere:

Click on the Add Fossil Fuels button (Carbon Model window).
Click on the On icon (in the Fossil Fuels box), then the Data icon (in the Specified According To: box).

Under Data Settings, you have the option of choosing different 'SRES' Future Emissions 2000 – 2100 CO_2 scenarios. (The SRES CO_2 emissions scenarios represent 'storylines' of development up until the year 2100. They "... describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving forces [and] cover a wide range of key "future" characteristics such as demographic change, economic development, and technological change".)

Keep the default selection of A1B.

Click on **Apply and Close**.

Before running the model, click on the Set Run Duration and Output Frequency button (main Carbon Model window). Set 2100 years as the Duration of run (so that the model finishes at year 2100 when the CO_2 emissions cease).

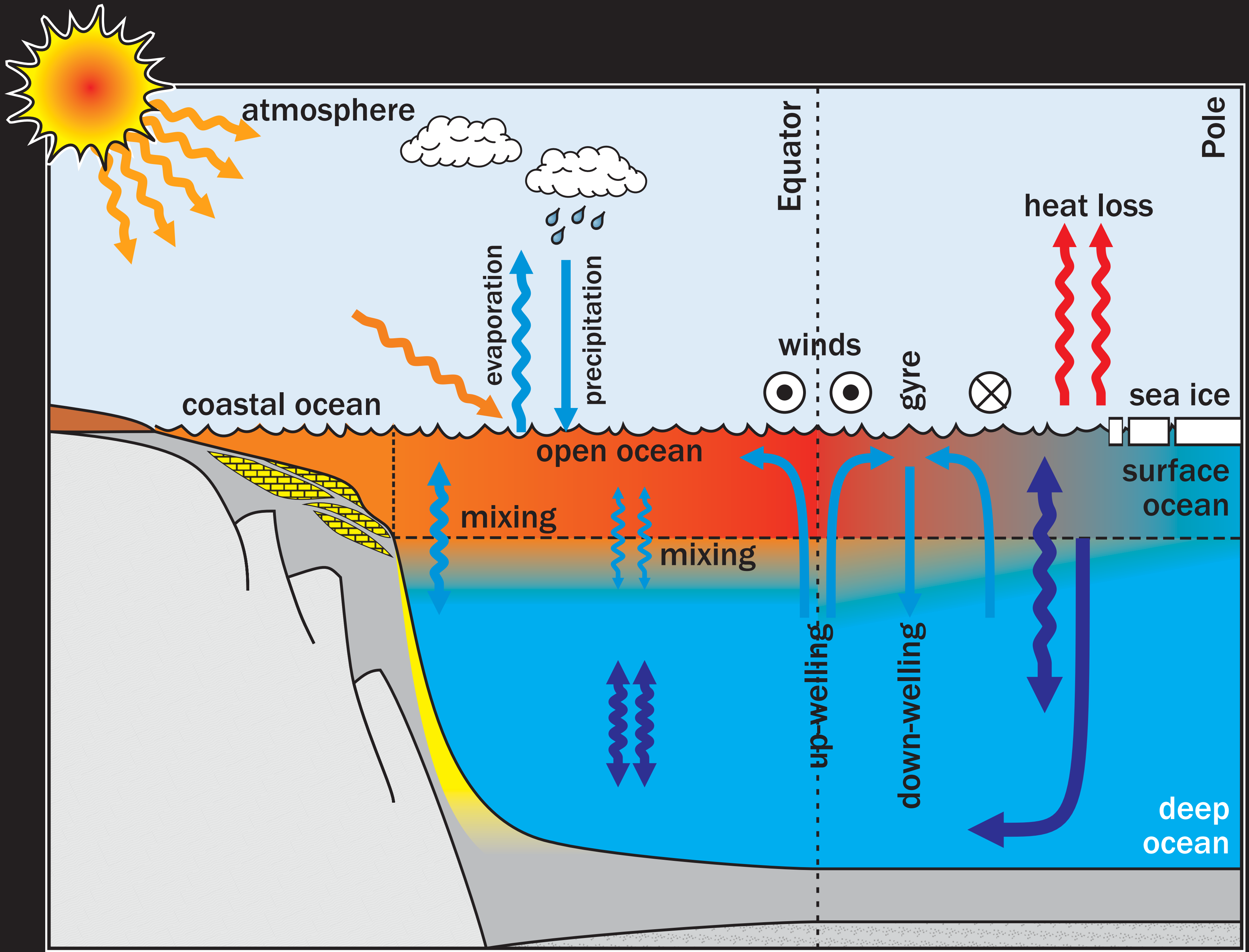
Click on **Apply and Close**.

Now run the model (**Run Model**).

1.0 You can restore all the default value in the model from the C_Model Parameter window by clicking on the **Default** button (it does not matter which 'tab' of parameter values is currently displaying) and **Apply and Close**. (To avoid confusion with previous experiments, it is advisable to close both the Carbon Model Plots and C_Model Final States windows.)

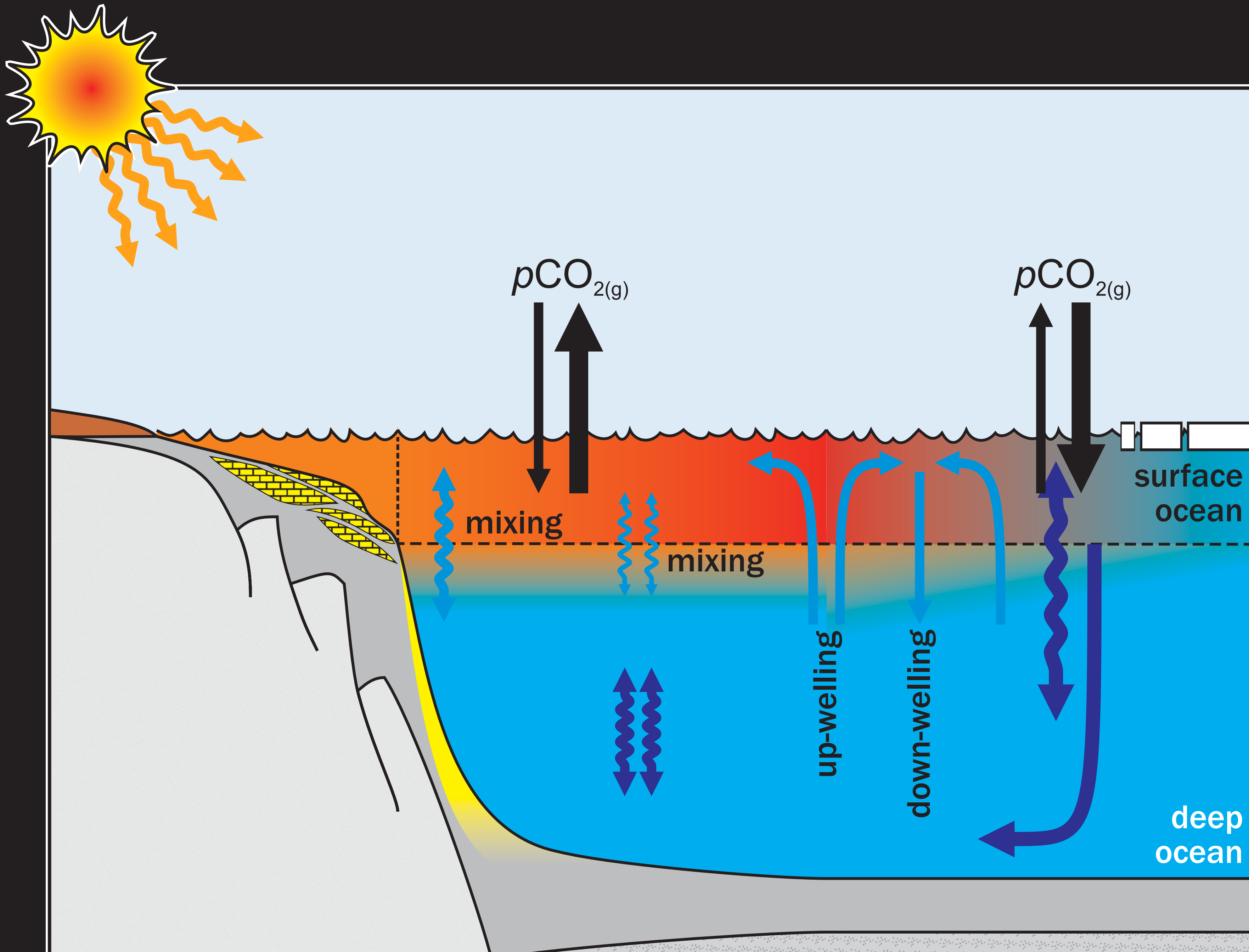
Running for 1000 years should be sufficient in all experiments.

SST



atmosphere
evaporation
precipitation
Equator
Pole
heat loss
winds
gyre
sea ice
coastal ocean
open ocean
surface ocean
mixing
mixing
up-welling
down-welling
deep ocean

SST

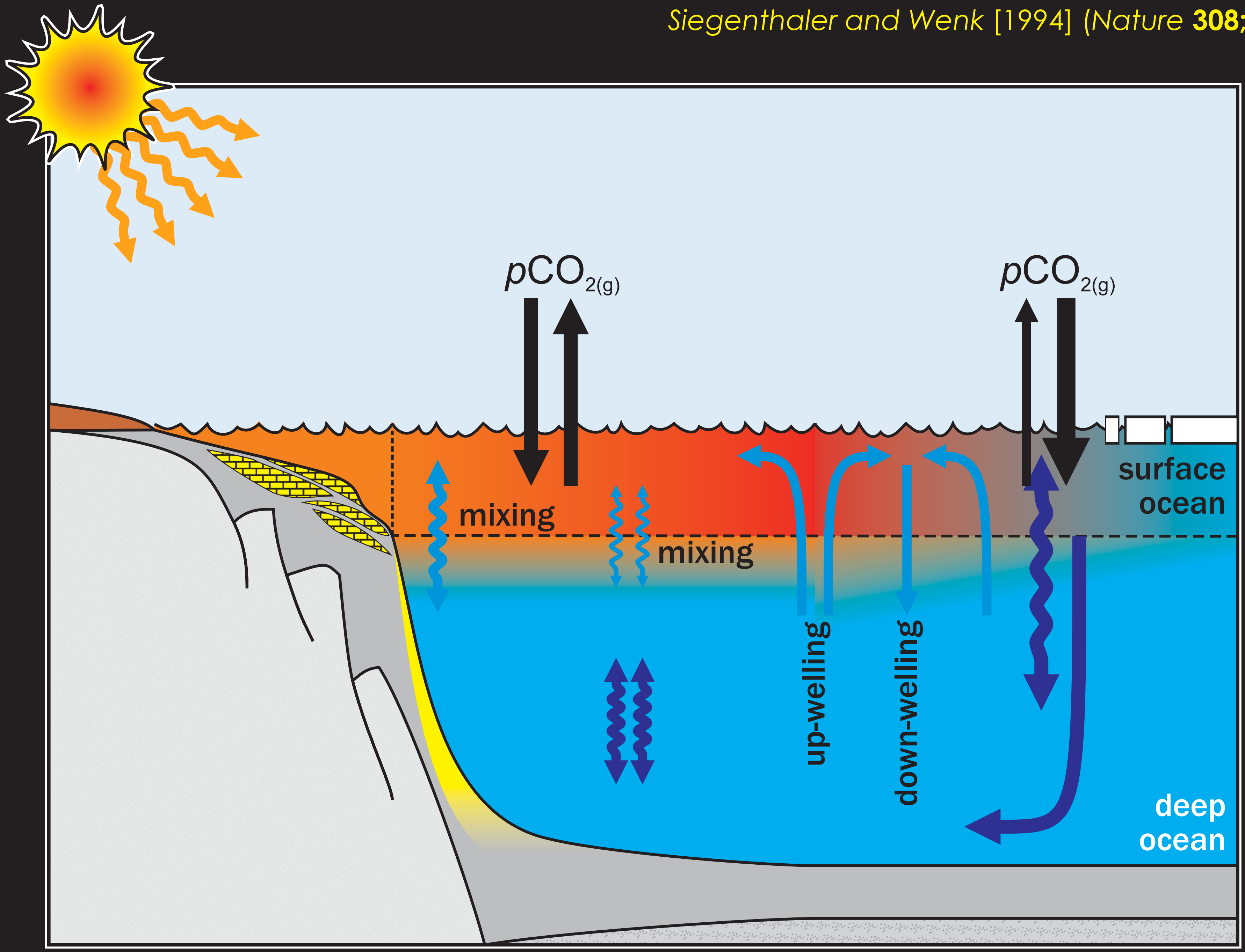


pCO2(g)
pCO2(g)
surface ocean
mixing
mixing
up-welling
down-welling
deep ocean

SST

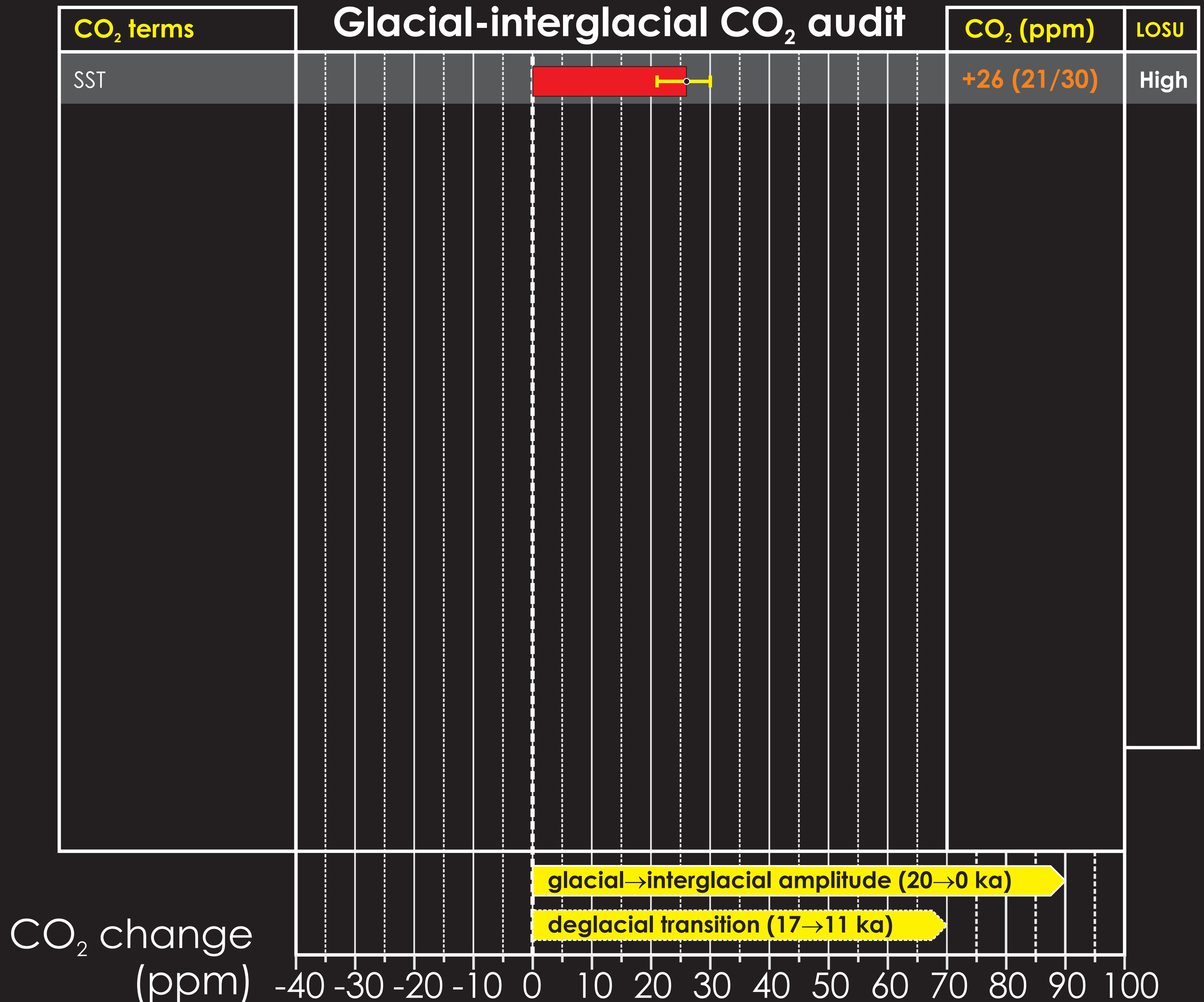
Lower LGM ocean surface temperatures enhance the solubility of CO_2, increasing the sequestration of CO_2 in the ocean interior.

Siegenthaler and Wenk [1994] (*Nature* **308**; *Keir* [1993] (*JGR* **98**)



> Change the ocean temperature in the **C-Model** and explore how sensitive atmospheric pCO_2 is to an e.g. ~4°C glacial cooling (relative to the Holocene).

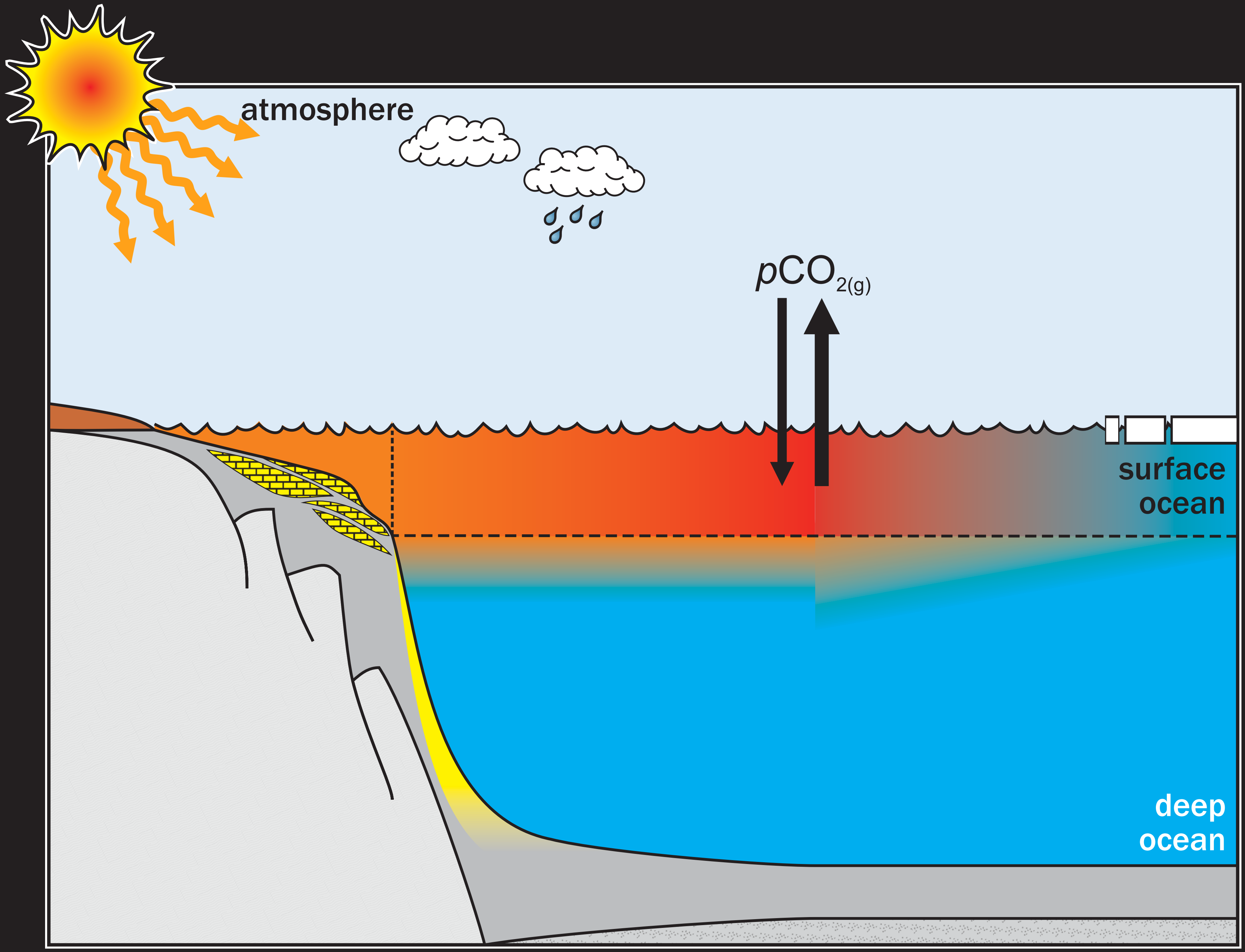
> ‘GUI’ interfaces -- limit what you can ‘access’ in a model, both in terms of input parameters and output.



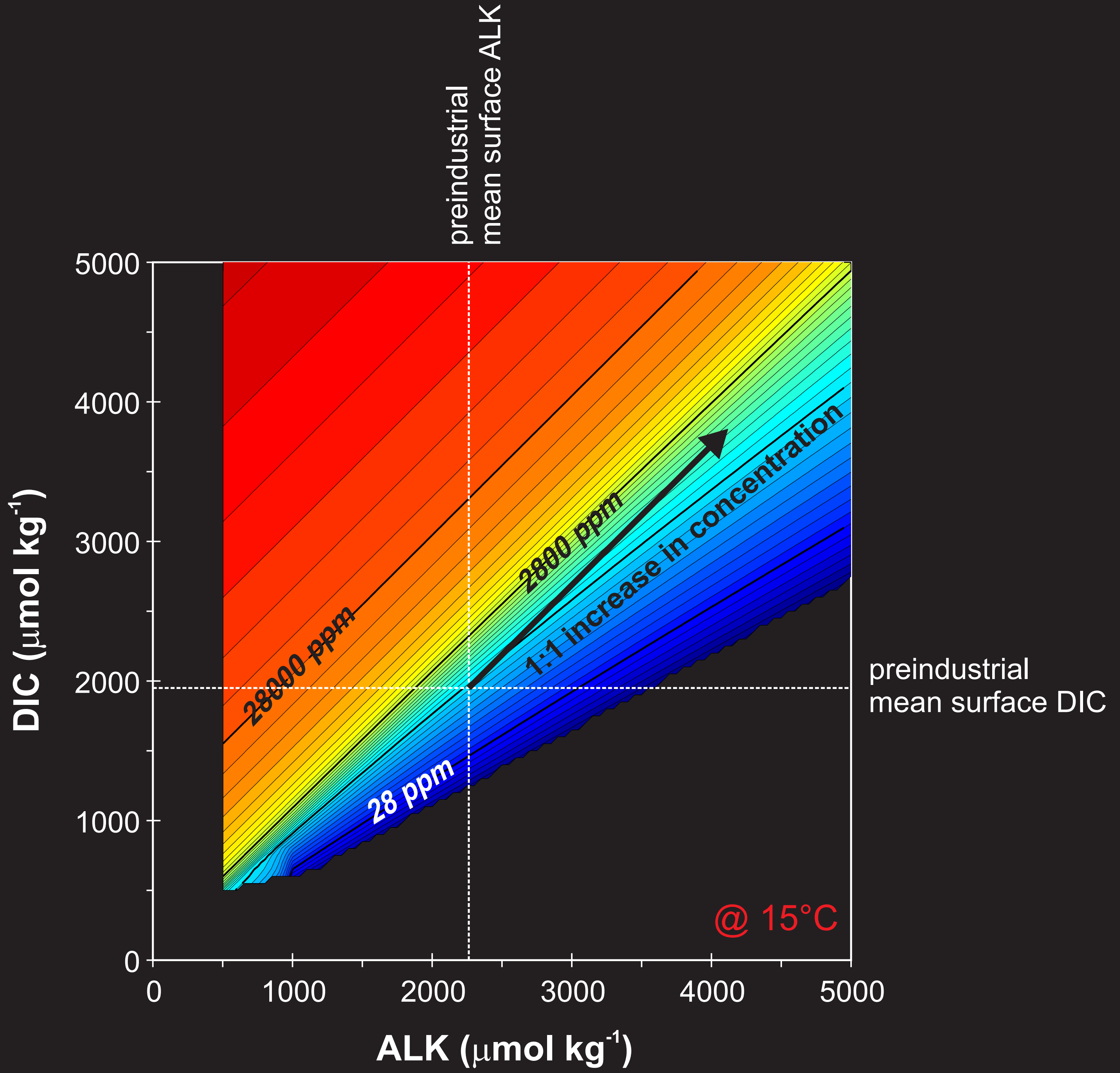
Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
SST
+26 (21/30)
High
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

SSS

Higher LGM ocean surface salinities suppress the solubility of CO_2, decreasing the sequestration of CO_2 in the ocean interior. (Also: DIC and ALK increased in 1:1 ratio.)



CO_2 chemistry in seawater

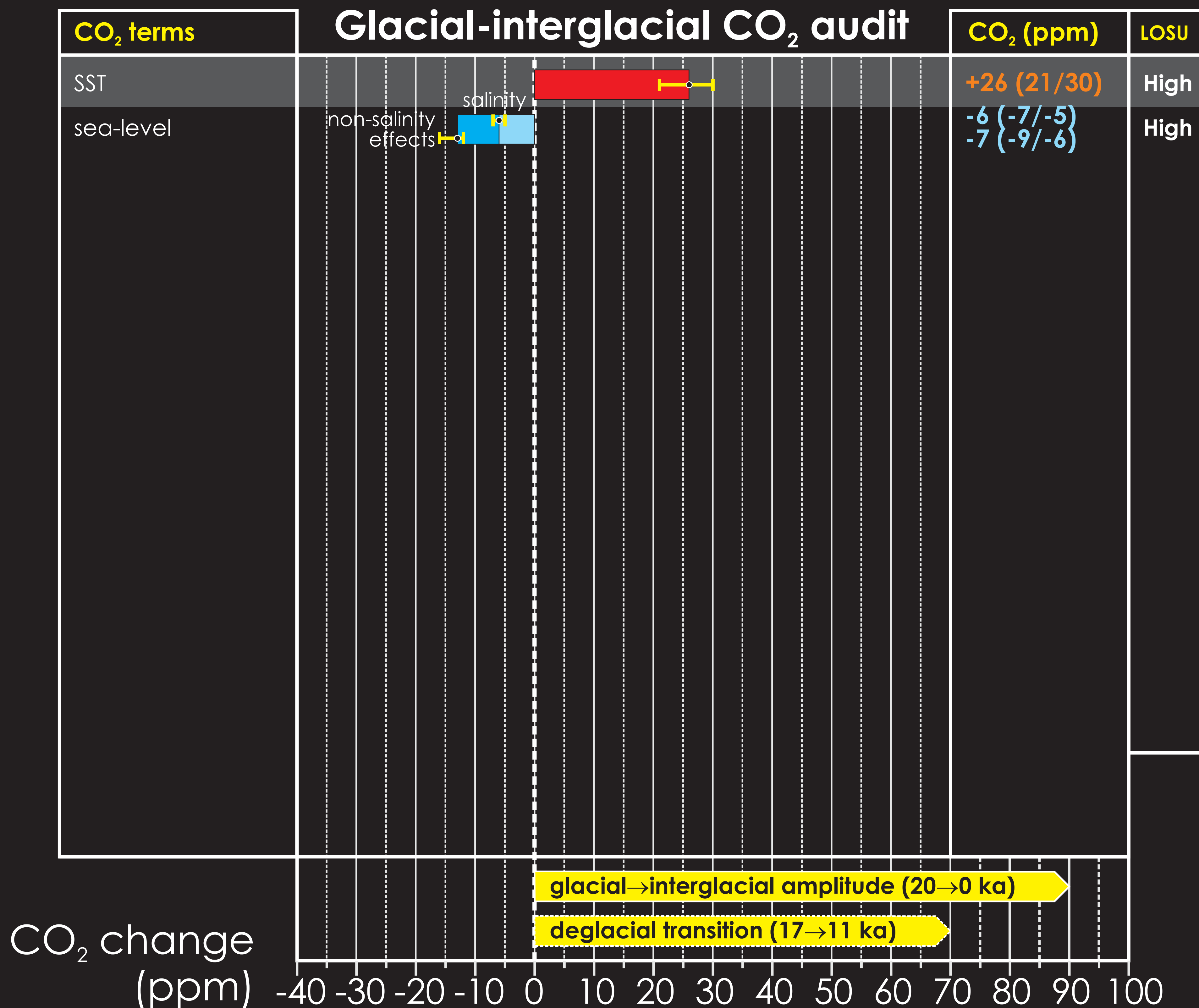


> To change ocean DIC and ALK in the **C-Model**:

> **Set Initial Conditions** (main menu)
> **Alkaliniy** and **Carbon** tabs – re-scale values in *each* ocean box (change value proportionally)
> **Apply and Close**
> **Run Model**

NB! <u>Before doing anything</u> – in each and every window in which you have previously changed parameters – press **Set to Defaults.** Or close program and re-start.

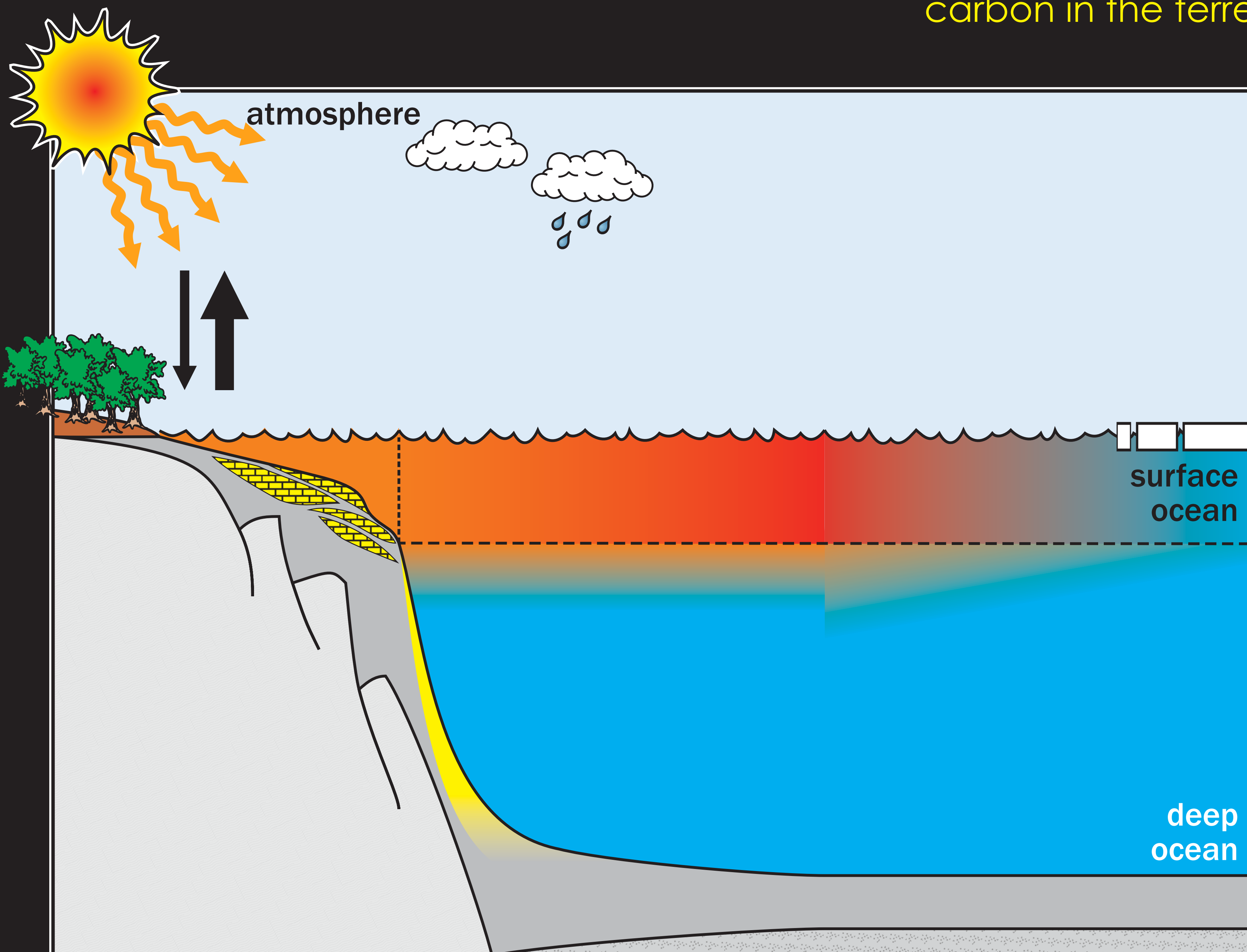
Q. What proportional change (increase) in LGM values is reasonable?
What is the impact on CO_2 and in what direction?



Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
SST
+26 (21/30)
High
sea-level
salinity
non-salinity
effects
-6 (-7/-5)
-7 (-9/-6)
High
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change
(ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

Terrestrial carbon

A colder, drier glacial climate, and lower pCO_2 and hence reduced CO_2 'fertilization' of productivity, is likely to have resulted in a reduced inventory of carbon in the terrestrial biosphere.



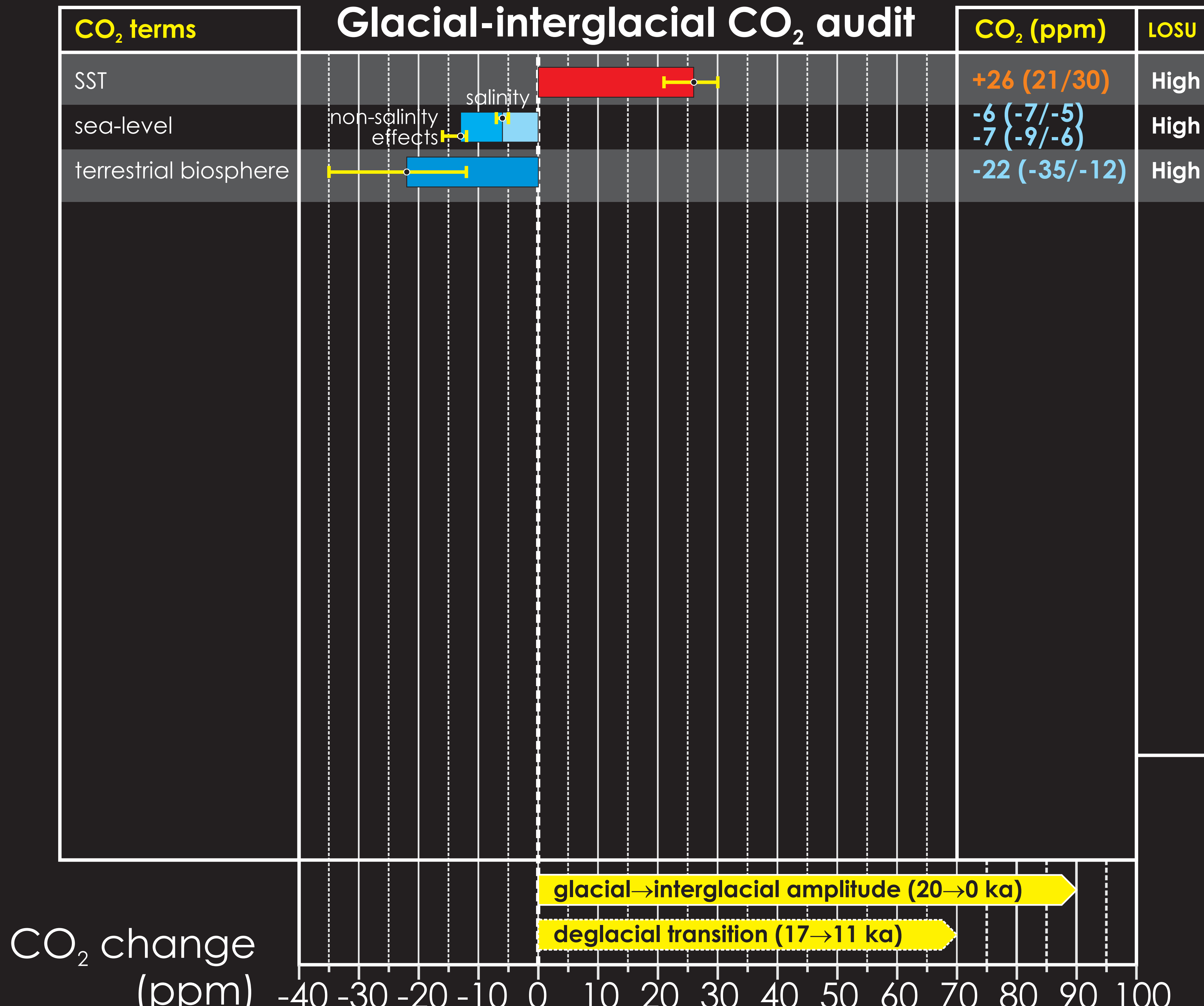
> Fossil fuel CO_2 emission experiments have been envisaged as the main application of the model but this can be made use of.

> Add Fossil Fuels
> Fossil Fuels *On*
> *Sinewave*
(avoids complications and additional emissions associate with SRES emissions scenarios)
> Enter a total amount

> Don't forget to restore default ALK and DIC values ...

Q. What constraints might there be on the amount of terrestrial carbon transferred to the ocean+atmosphere?

Q. How much added CO_2 stays in the atmosphere compared with in the ocean? (Is this independent of the amount of CO_2 released?)

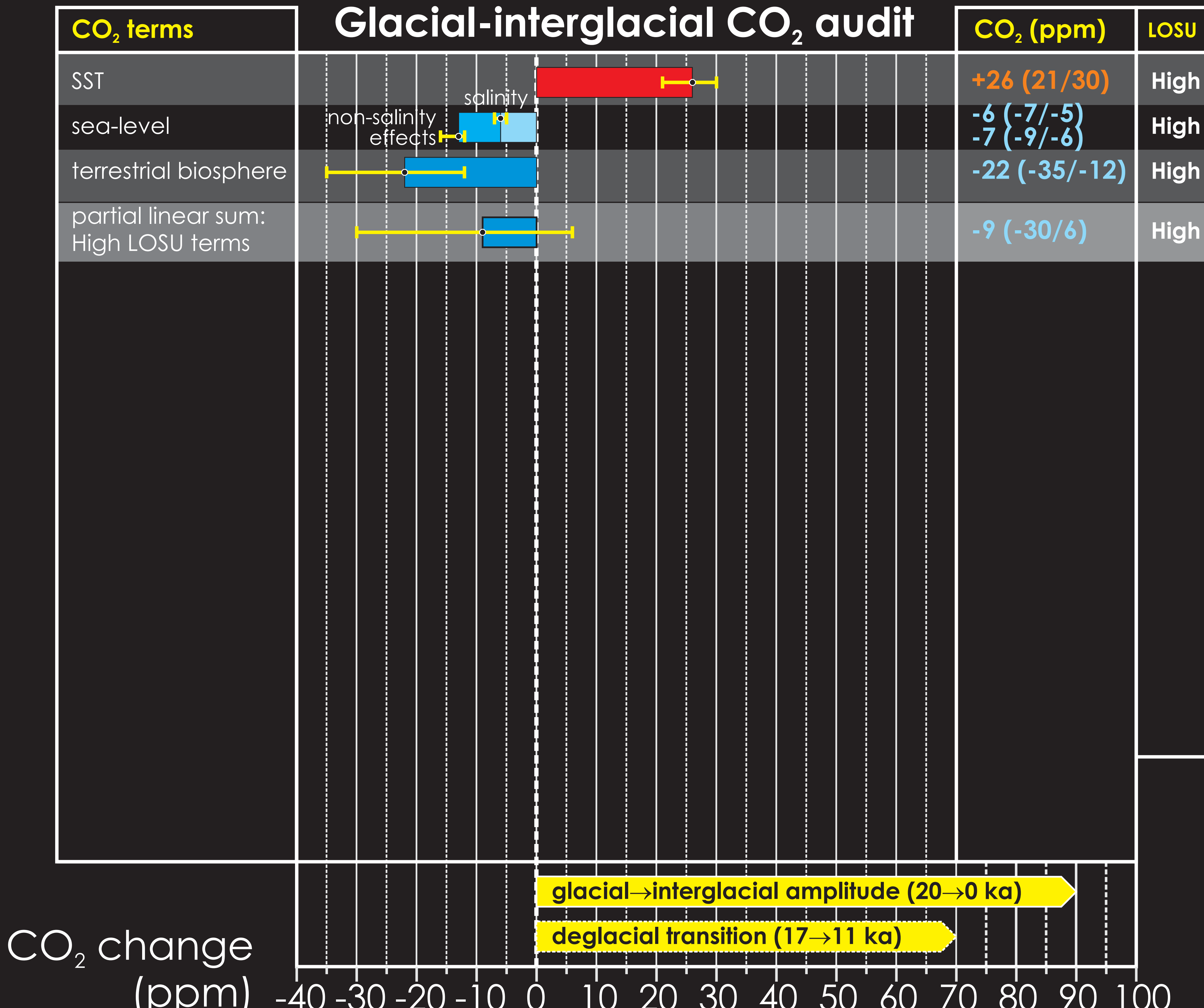


Glacial-interglacial CO2 audit
CO2 terms
CO2 (ppm)
LOSU
SST
+26 (21/30)
High
sea-level
salinity
non-salinity effects
-6 (-7/-5)
-7 (-9/-6)
High
terrestrial biosphere
-22 (-35/-12)
High
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

> pCO_2 is going in the 'wrong' direction if changes in salinity and terrestrial biosphere carbon storage are taken into account.

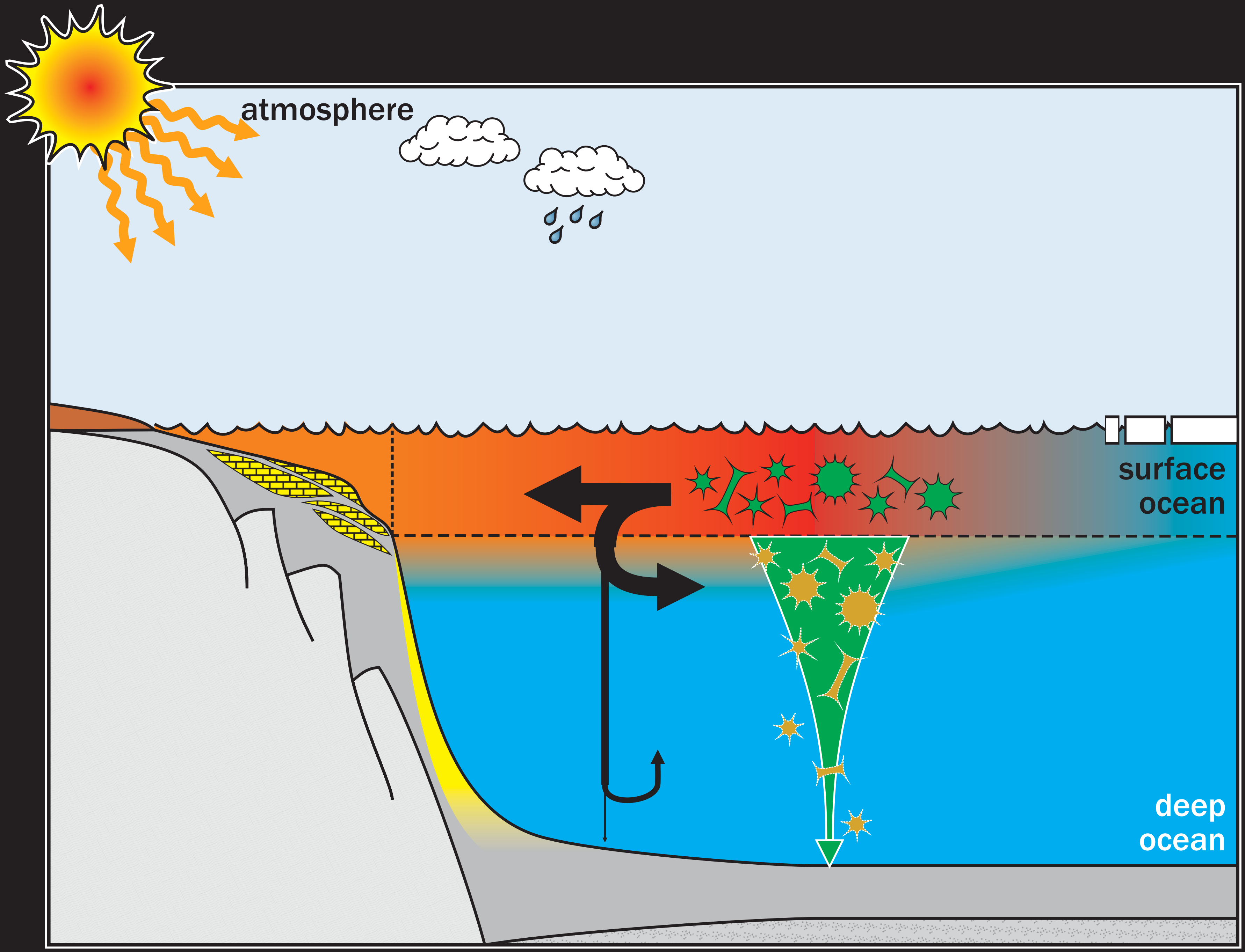
Q. Do you: <u>Include</u>, or <u>exclude</u>, salinity and terrestrial effects from the final net explained pCO_2 change?

Q. Are the impacts of salinity (changing ALK and DIC) and a transfer of carbon to/from the terrestrial biosphere, additive? (contract the 2 effects calculated separately, and combined in the C Model)

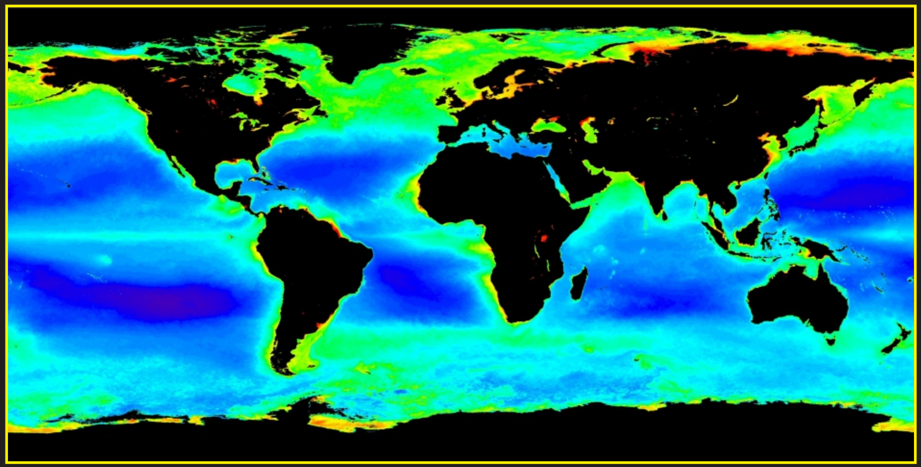


Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
SST
+26 (21/30)
High
sea-level
salinity
non-salinity effects
-6 (-7/-5)
-7 (-9/-6)
High
terrestrial biosphere
-22 (-35/-12)
High
partial linear sum: High LOSU terms
-9 (-30/6)
High
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

Marine biology and the 'biological pump'

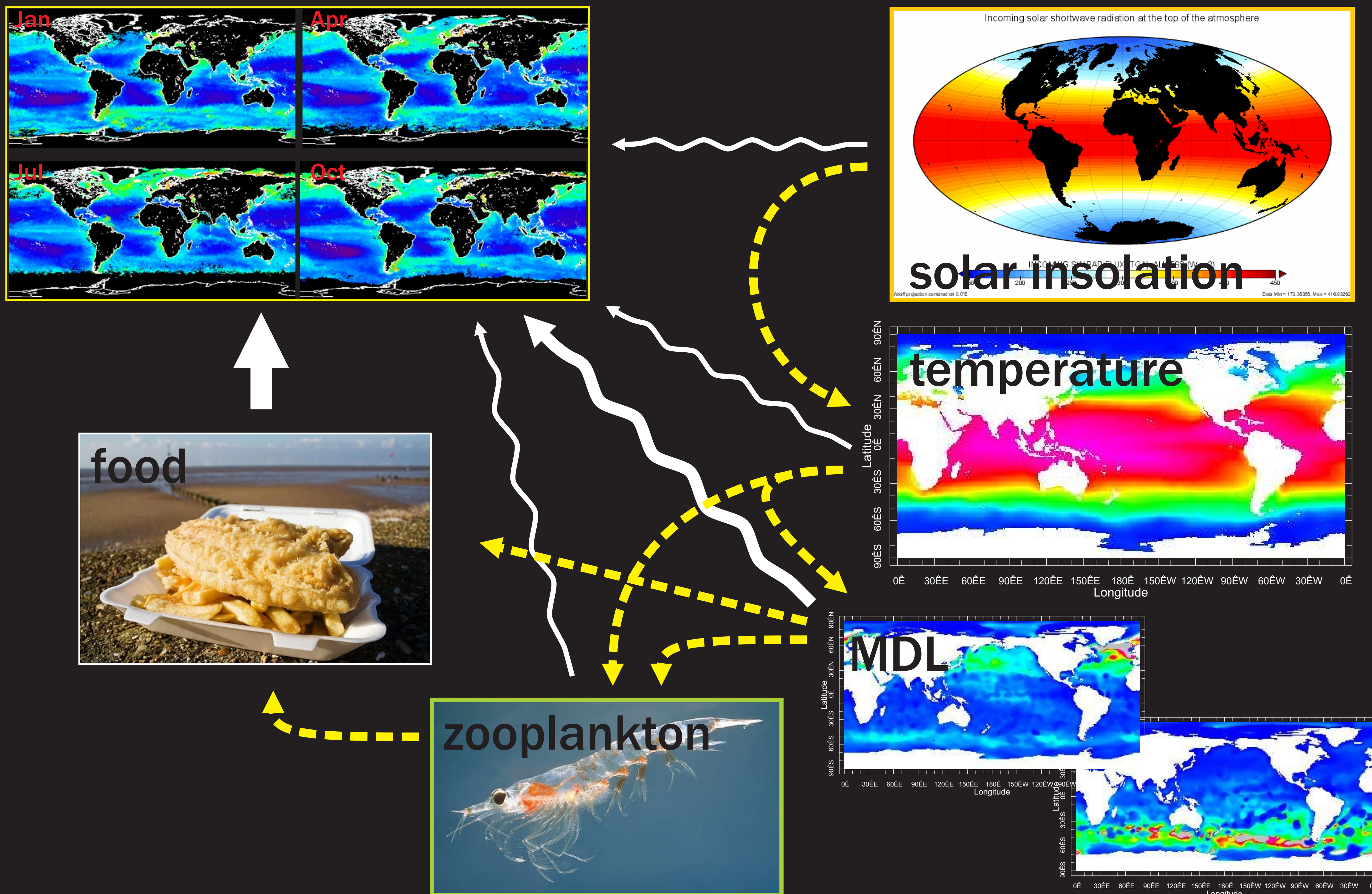


Marine biology and the 'biological pump'



Q. What factors control the spatial and temporal (seasonal) pattern of plankton productivity in the ocean?

Marine biology and the ‘biological pump’



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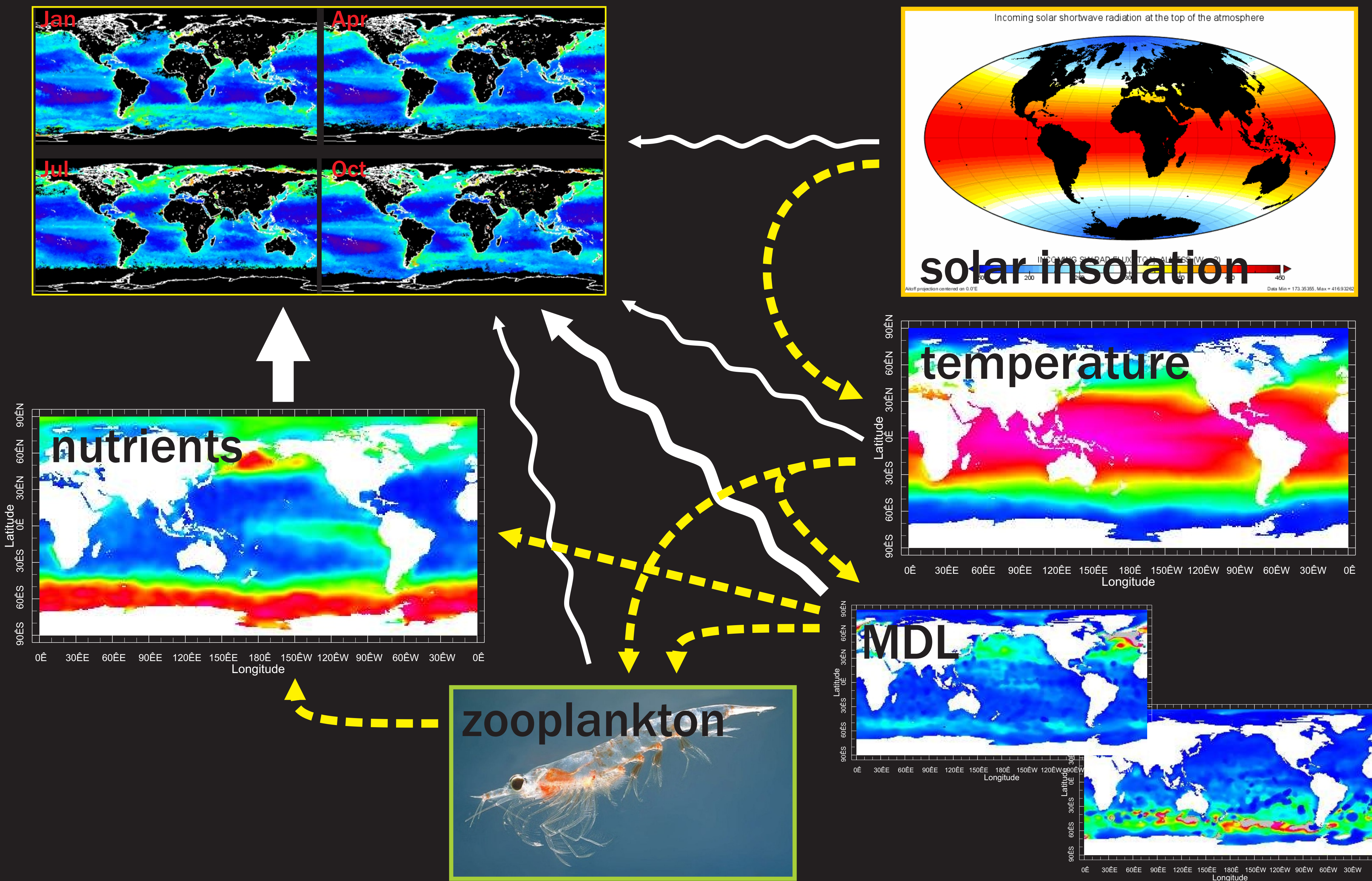

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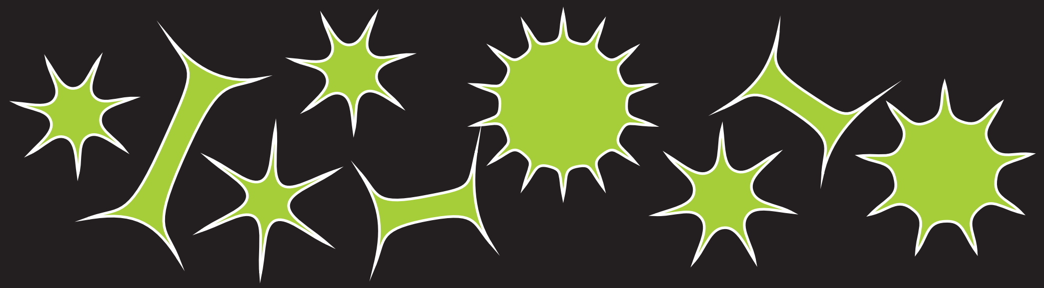
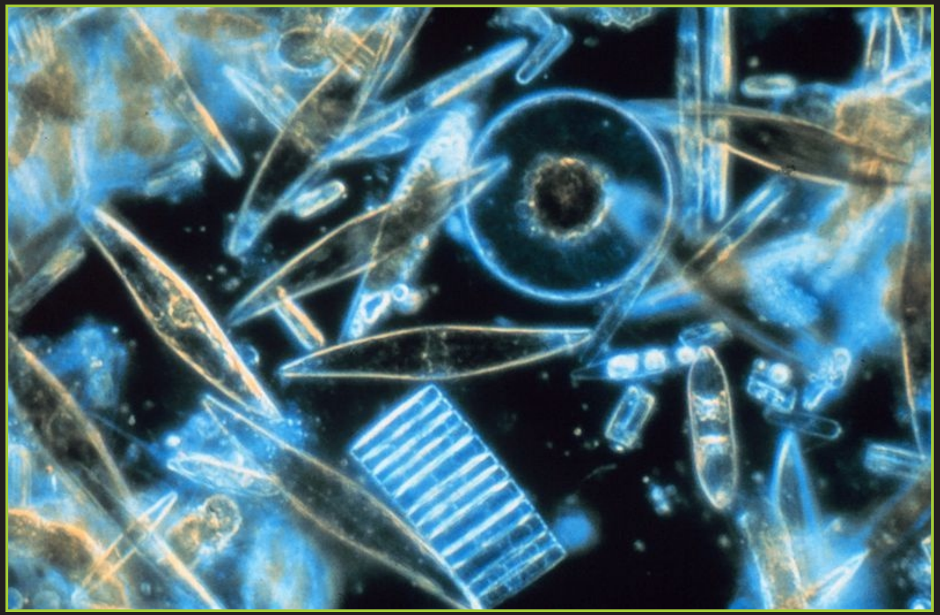


Nutrient requirement

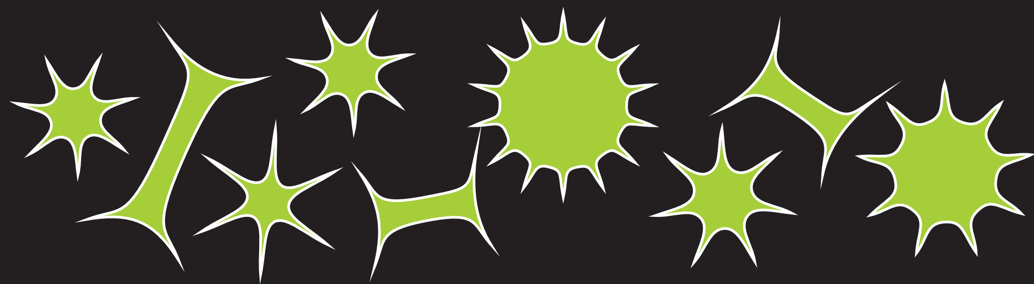
The basic building blocks of cells require the following elements: (amongst O, H etc):

Nucleus (DNA) – C-N-P
Ribosome (RNA) – C-N-P
Membranes – C-P
Cell wall – C-N
Proteines/enzymes – C-N

- Carbon comes from dissolved inorganic carbon (autotrophs).
- P comes from highly soluble PO_4 (phosphate) (as PO_4^{3-} in seawater).
- N comes primarily from highly soluble NO_3 (nitrate) (as NO_3^- in seawater). Some species of plankton can also assimilate NH^{4+} (ammonium) or even N_2 (nitrogen gas) directly (nitrogen fixers).



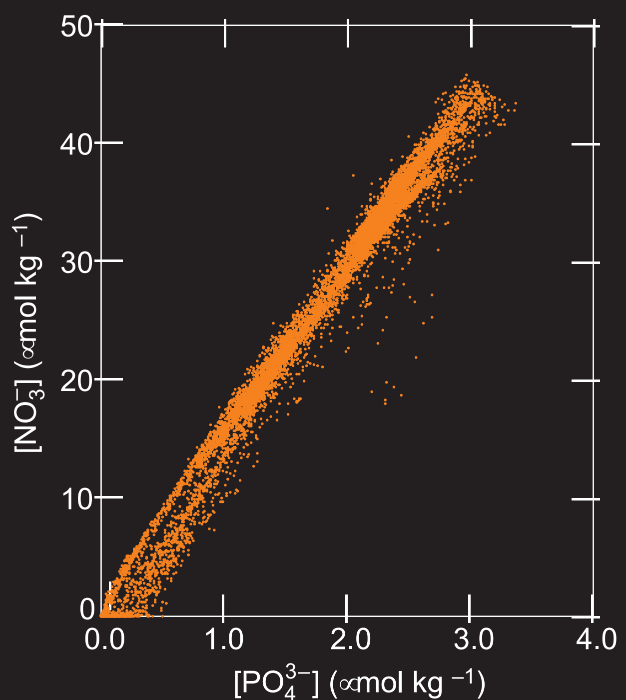
Marine biology and the 'biological pump'



The 'Redfield ratio' of (mean) cellular composition:

[*Redfield et al.*, 1963]

Observed PO_4 and NO_3 concentrations

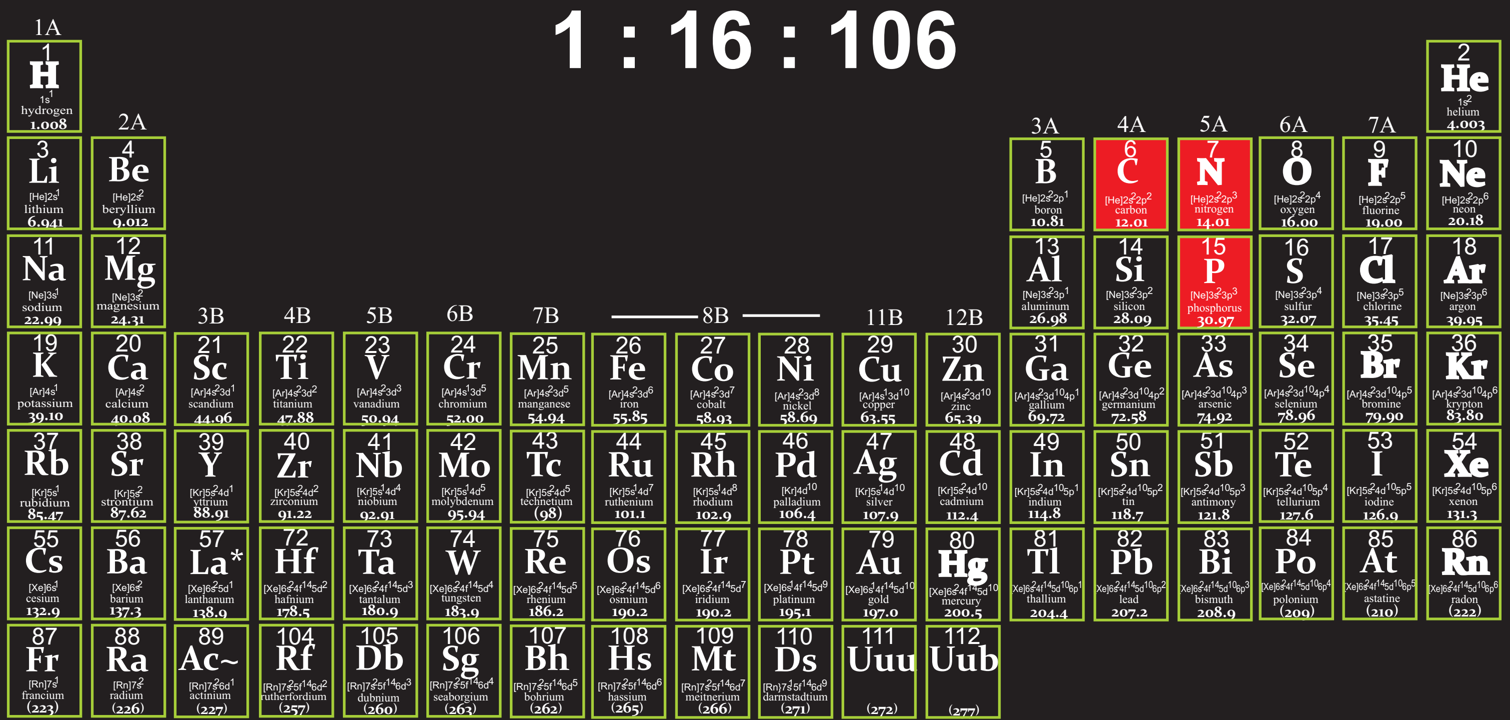


Tyrrell [1999]

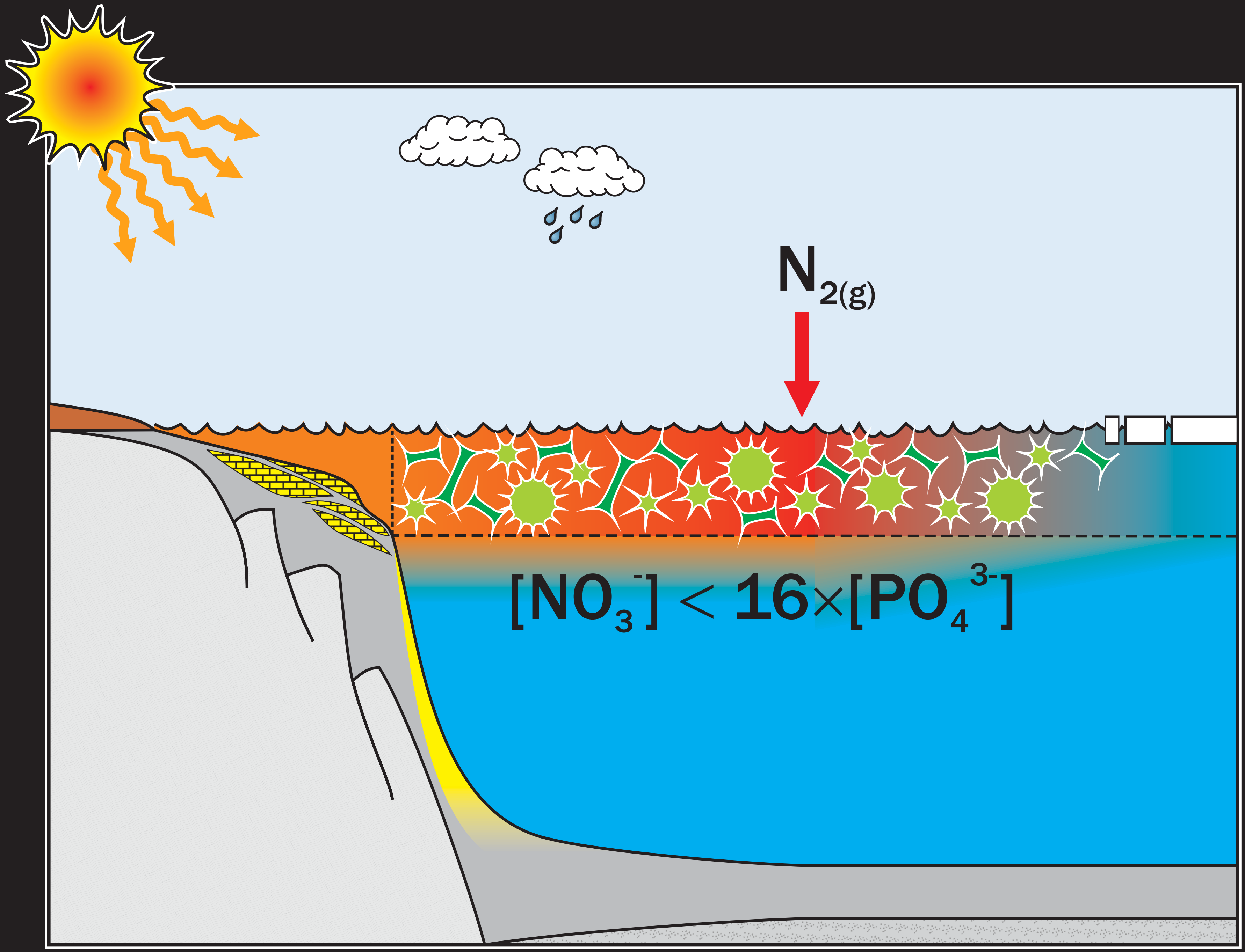
P : N : C

=

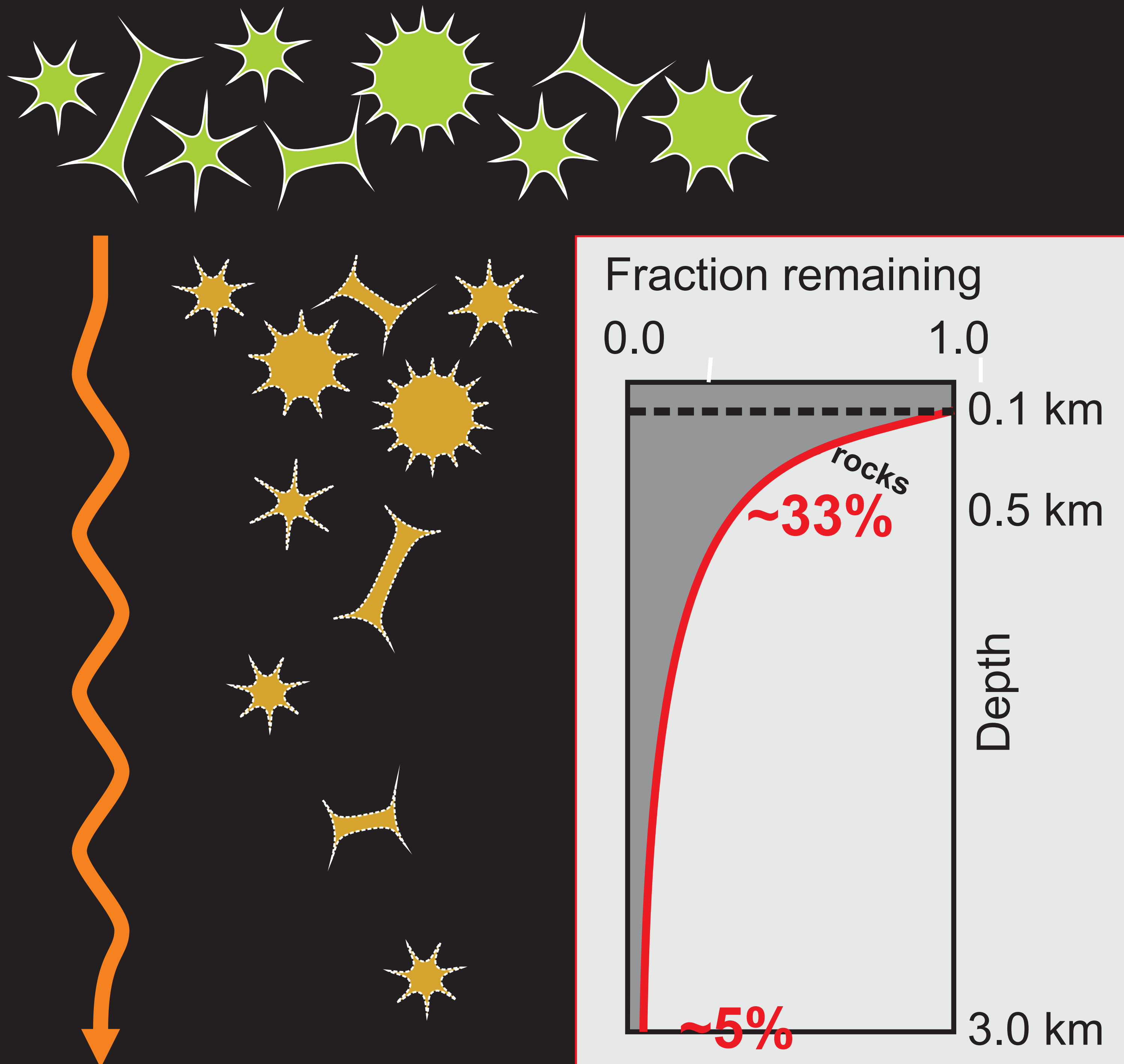
1 : 16 : 106



Marine biology and the 'biological pump'



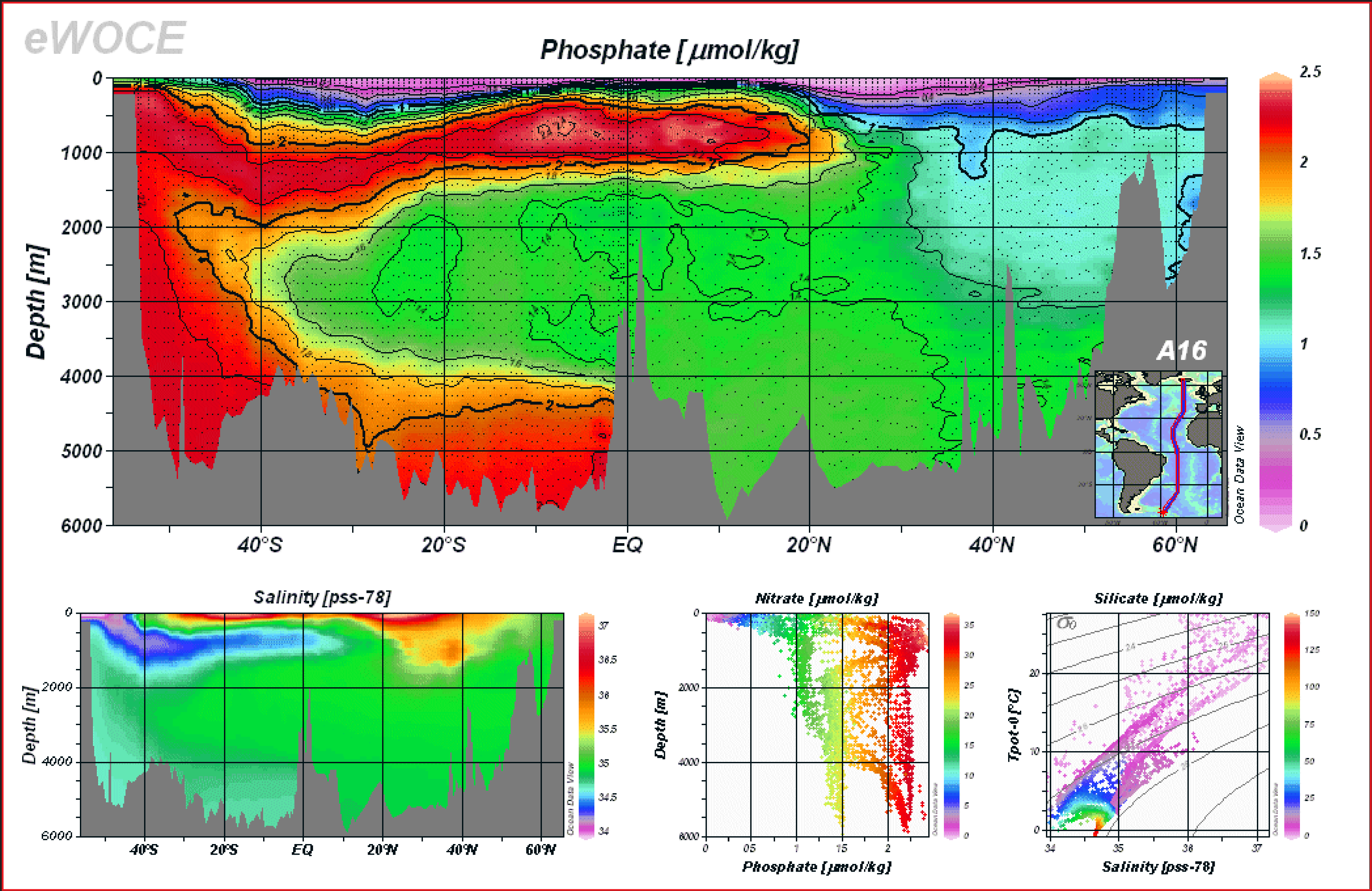
Marine biology and the 'biological pump'



Only about 20% of the primary production by phytoplankton (ca. 50 PgC yr^{-1}) escapes the surface ocean (primarily as dead cells and faecal pellets).

Of the 10 PgC yr^{-1}) leaving the bottom of the euphotic zone, only about 0.5 reaches the ocean floor, and very little of this (1%) is preserved and buried in accumulating sediments.

Marine biology and the ‘biological pump’



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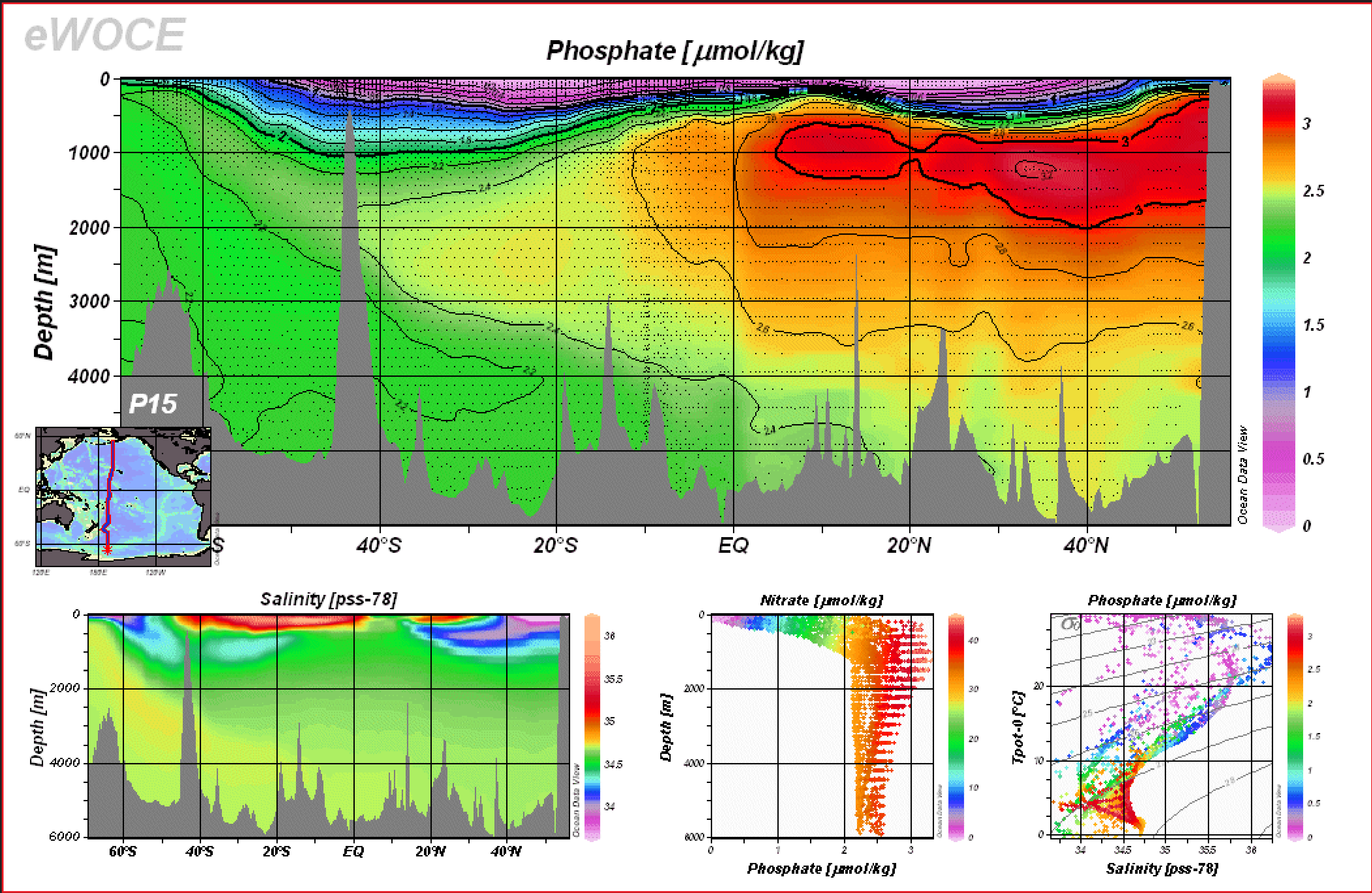
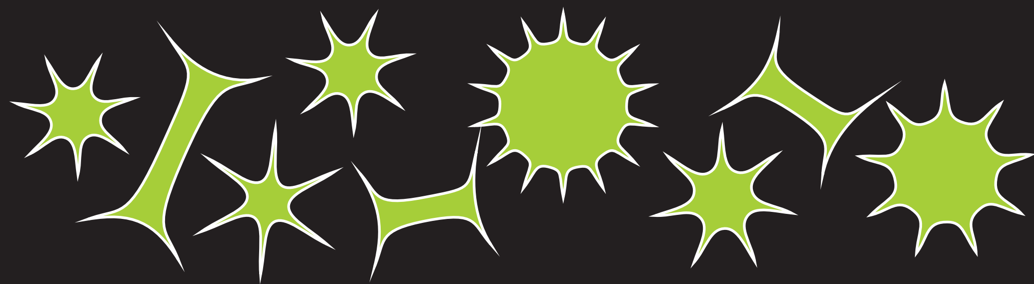
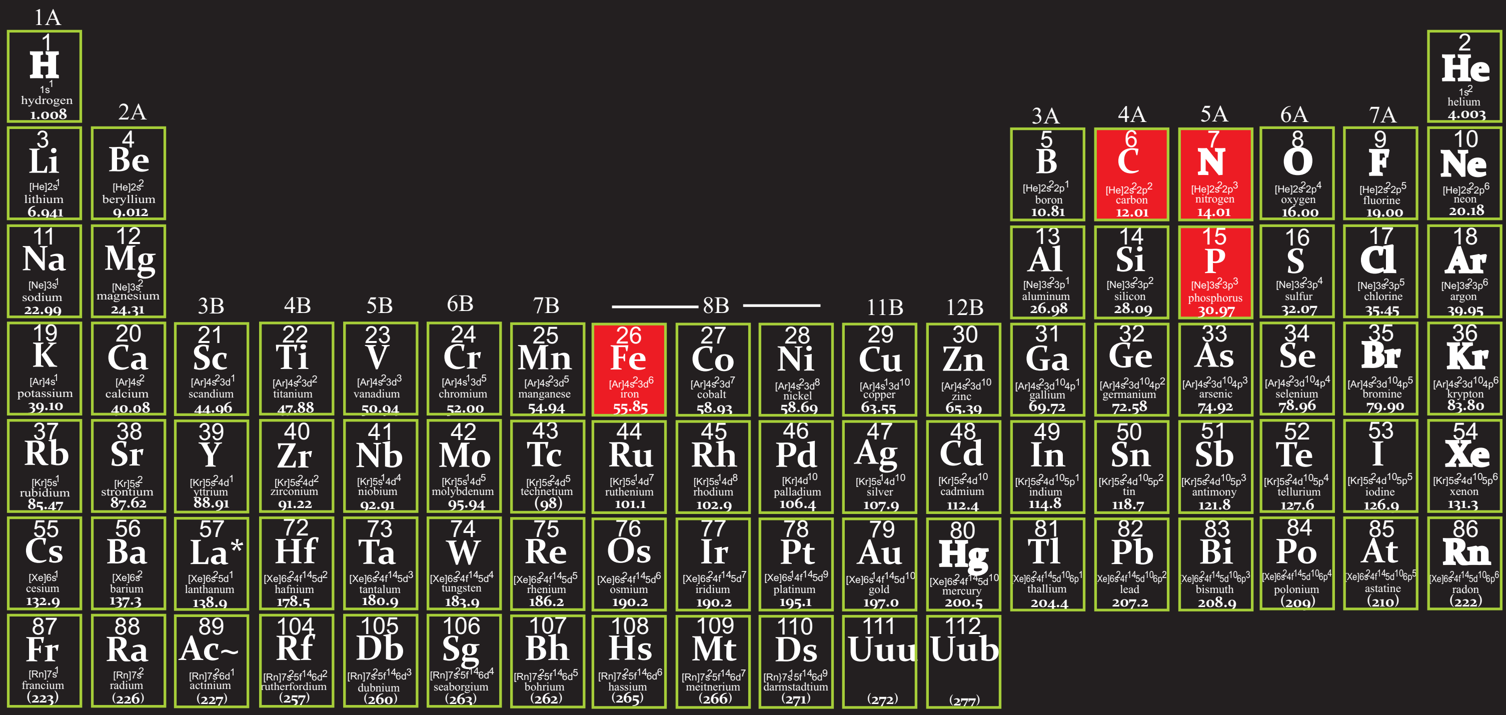
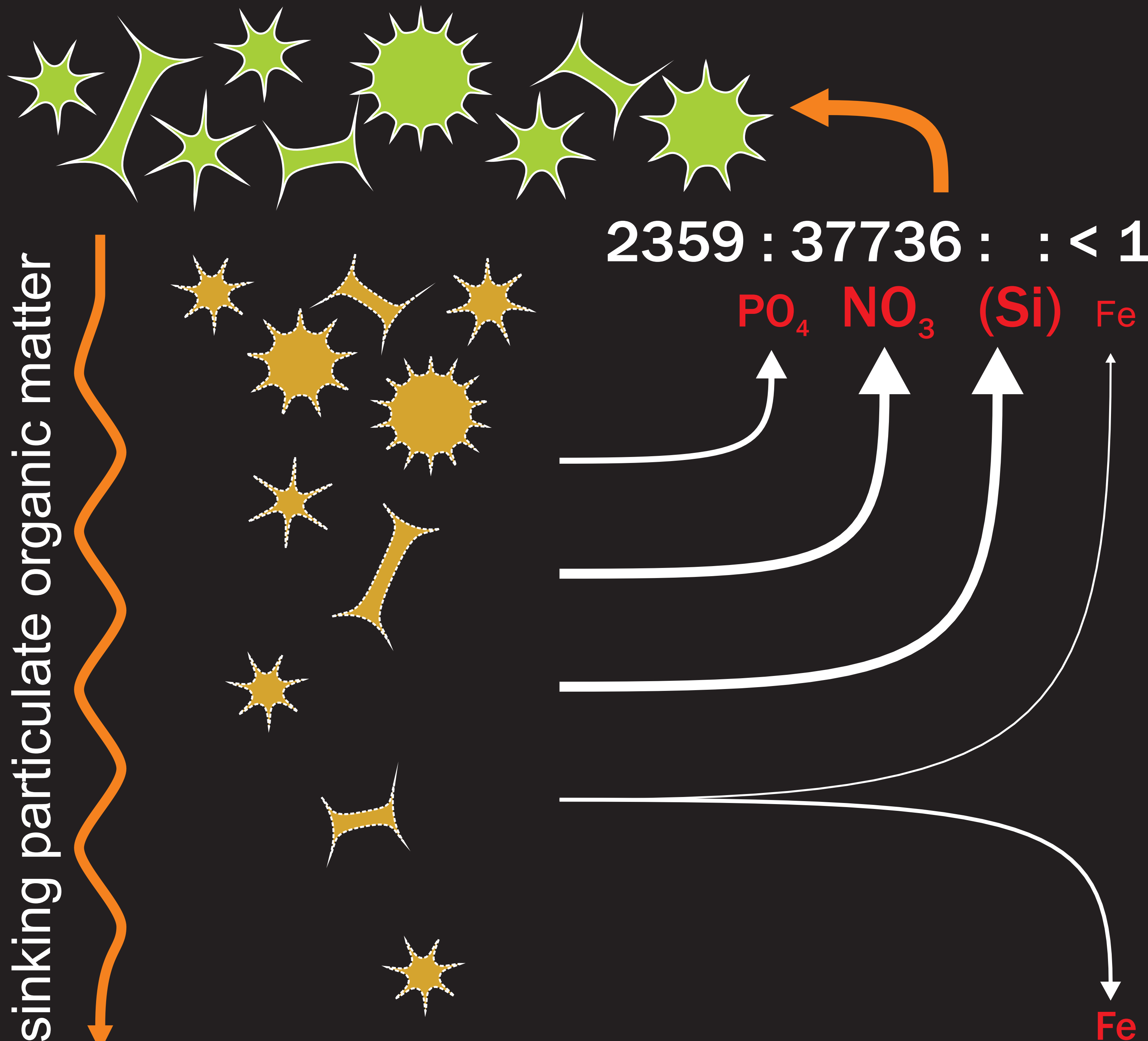


The ocean carbon cycle – Fe limitation



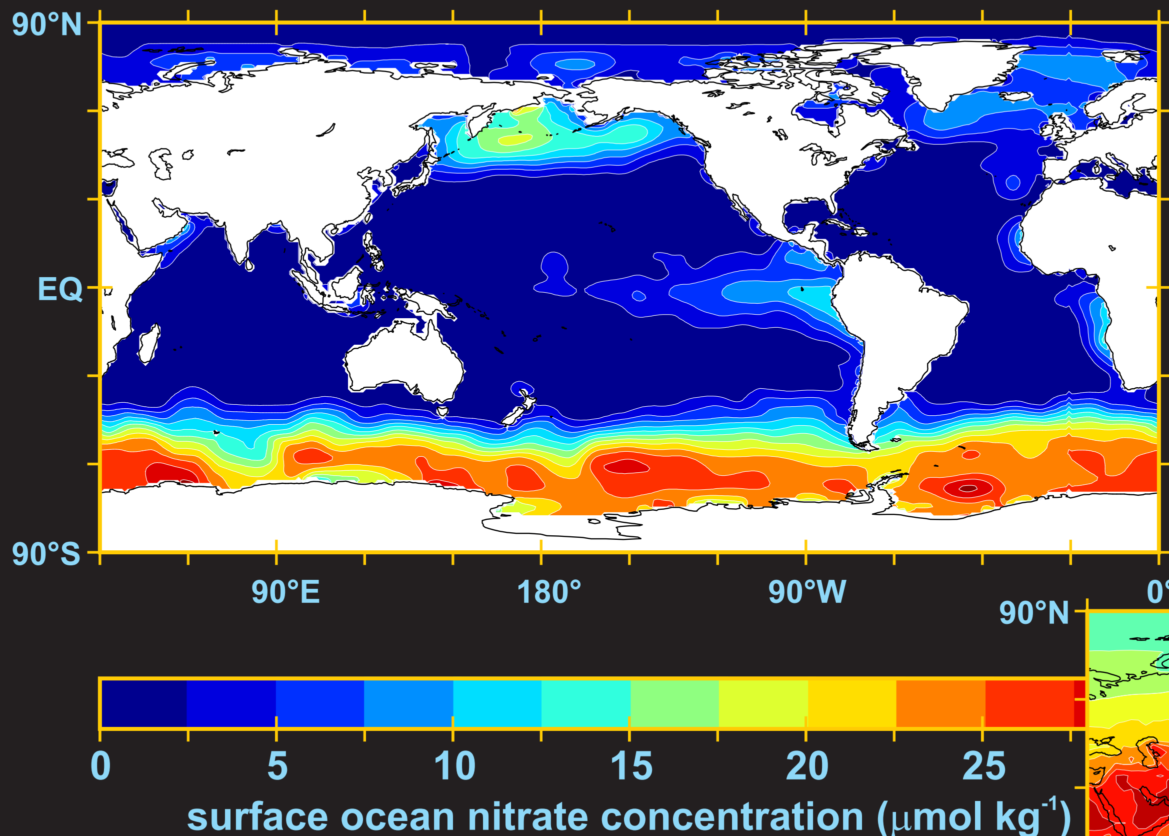


The ocean carbon cycle – Fe limitation

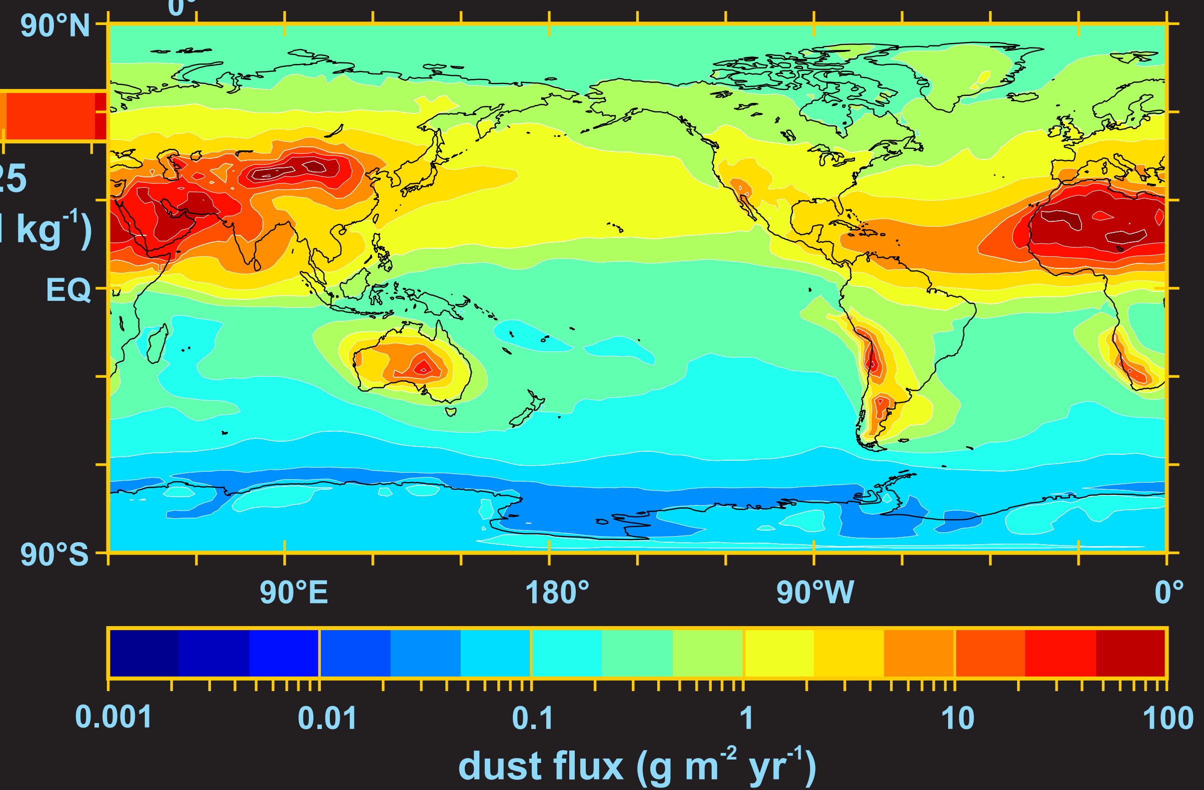


In oxic (oxygenated) seawater, Fe is only sparingly soluble, and tends to be ‘scavenged’ by particles and removed from the water column.

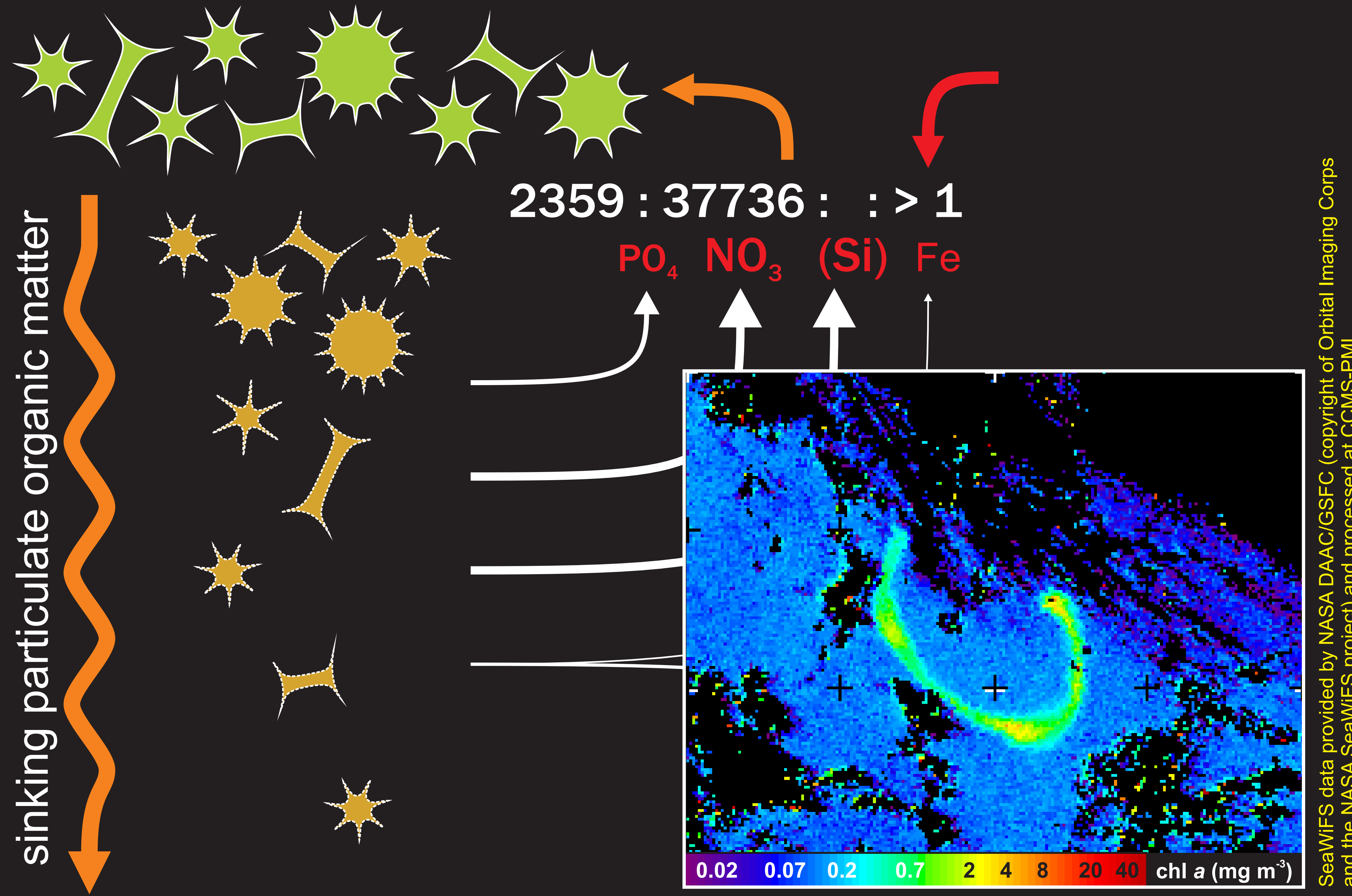
Global distribution of near-surface (30 m depth) ocean nitrate concentrations [*Conkright et al.*, 1994]



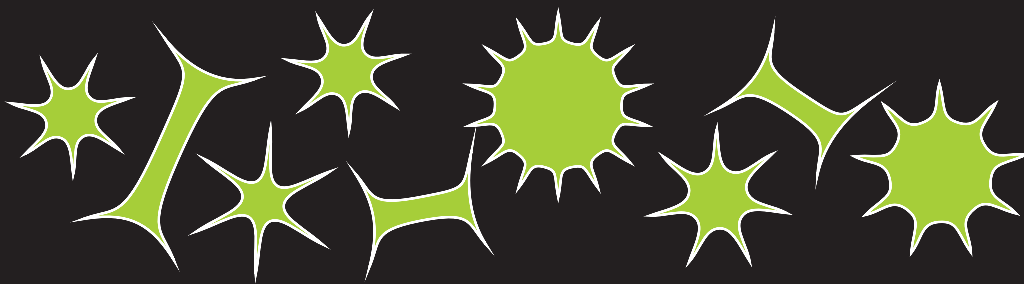
Model-simulated annual mean dust flux to the Earth's surface [*Ginoux et al.*, 2001]

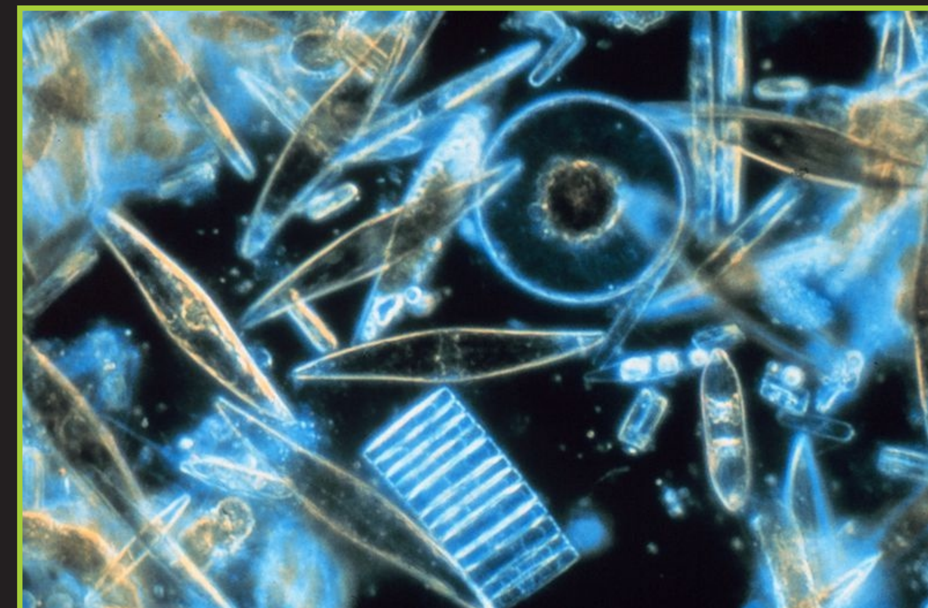


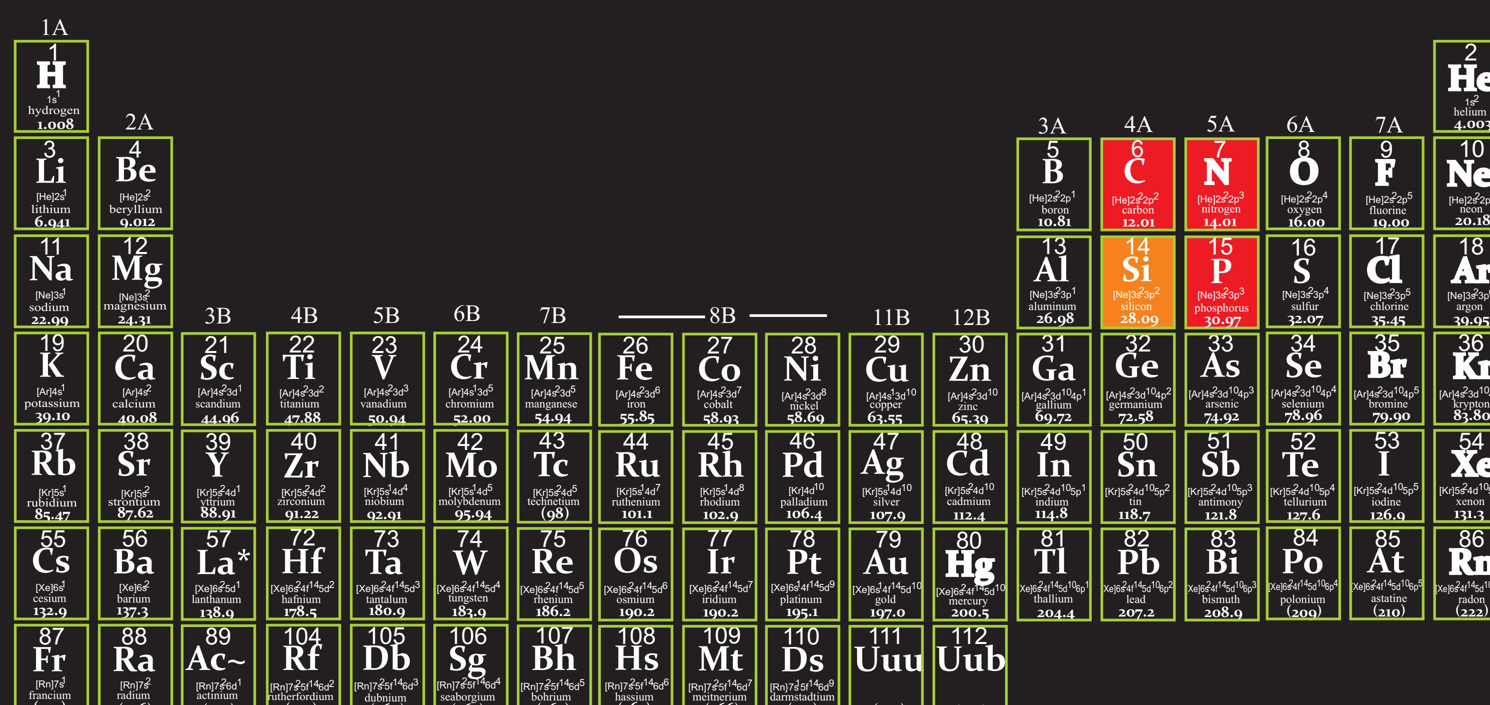
The ocean carbon cycle – Fe limitation



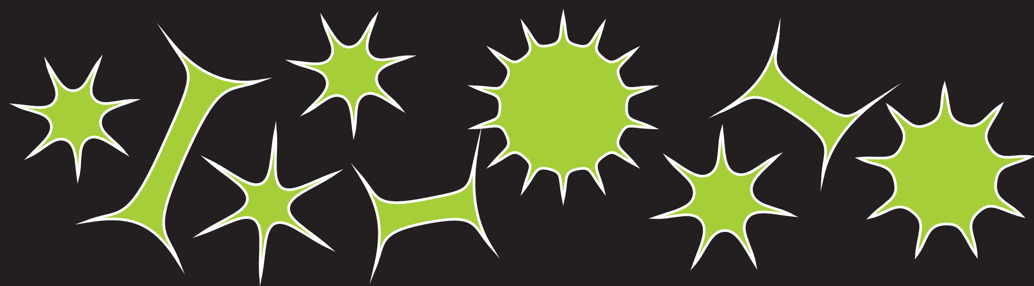
The ocean carbon cycle – Si and diatoms





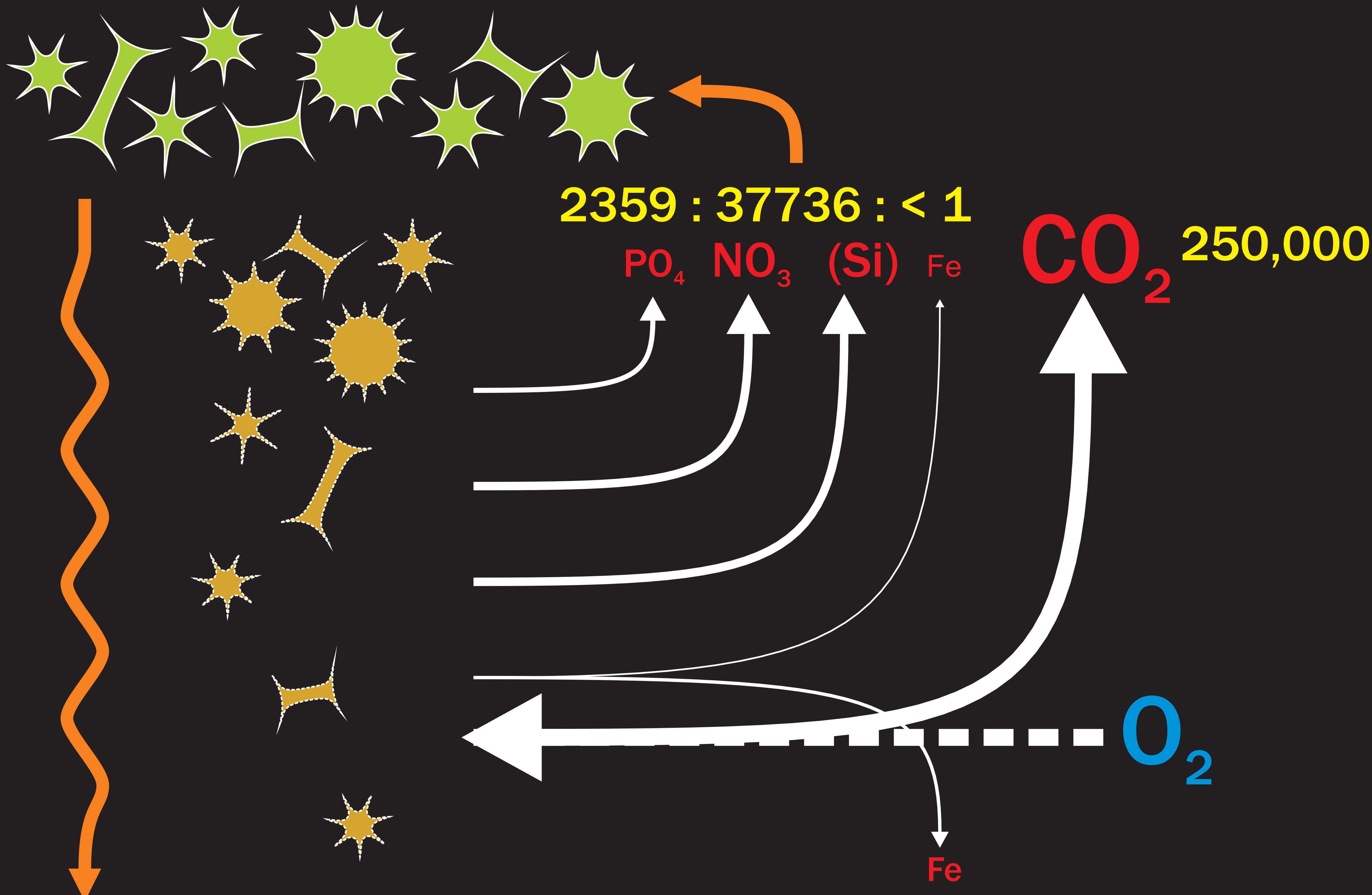


The ocean carbon cycle – other trace elements

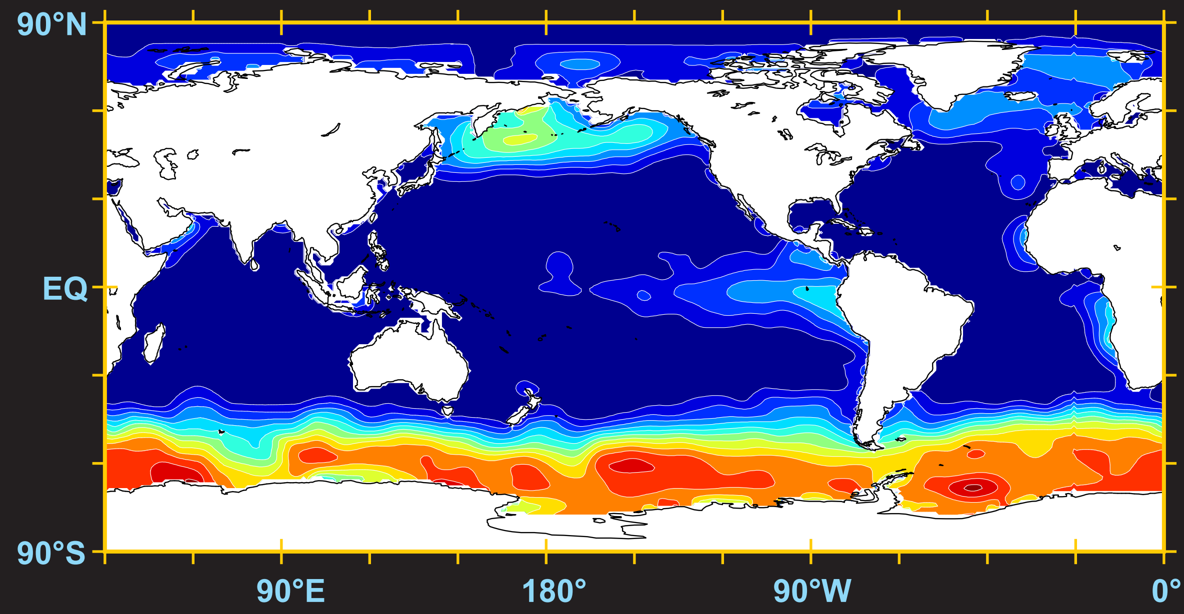


1A	2A	3B	4B	5B	6B	7B	8B	8B	8B	11B	12B	3A	4A	5A	6A	7A	
1 H hydrogen 1.008																	2 He helium 4.003
3 Li lithium 6.941	4 Be beryllium 9.012											5 B boron 10.81	6 C carbon 12.01	7 N nitrogen 14.01	8 O oxygen 16.00	9 F fluorine 19.00	10 Ne neon 20.18
11 Na sodium 22.99	12 Mg magnesium 24.31											13 Al aluminum 26.98	14 Si silicon 28.09	15 P phosphorus 30.97	16 S sulfur 32.07	17 Cl chlorine 35.45	18 Ar argon 39.95
19 K potassium 39.10	20 Ca calcium 40.08	21 Sc scandium 44.96	22 Ti titanium 47.88	23 V vanadium 50.94	24 Cr chromium 52.00	25 Mn manganese 54.94	26 Fe iron 55.85	27 Co cobalt 58.93	28 Ni nickel 58.69	29 Cu copper 63.55	30 Zn zinc 65.39	31 Ga gallium 69.72	32 Ge germanium 72.58	33 As arsenic 74.92	34 Se selenium 78.96	35 Br bromine 79.90	36 Kr krypton 83.80
37 Rb rubidium 85.47	38 Sr strontium 87.62	39 Y yttrium 88.91	40 Zr zirconium 91.22	41 Nb niobium 92.91	42 Mo molybdenum 95.94	43 Tc technetium (98)	44 Ru ruthenium 101.1	45 Rh rhodium 102.9	46 Pd palladium 106.4	47 Ag silver 107.9	48 Cd cadmium 112.4	49 In indium 114.8	50 Sn tin 118.7	51 Sb antimony 121.8	52 Te tellurium 127.6	53 I iodine 126.9	54 Xe xenon 131.3
55 Cs cesium 132.9	56 Ba barium 137.3	57 La* lanthanum 138.9	72 Hf hafnium 178.5	73 Ta tantalum 180.9	74 W tungsten 183.9	75 Re rhenium 186.2	76 Os osmium 190.2	77 Ir iridium 190.2	78 Pt platinum 195.1	79 Au gold 197.0	80 Hg mercury 200.5	81 Tl thallium 204.4	82 Pb lead 207.2	83 Bi bismuth 208.9	84 Po polonium (209)	85 At astatine (210)	86 Rn radon (222)
87 Fr francium (223)	88 Ra radium (226)	89 Ac~ actinium (227)	104 Rf rutherfordium (257)	105 Db dubnium (260)	106 Sg seaborgium (263)	107 Bh bohrium (262)	108 Hs hassium (265)	109 Mt meitnerium (266)	110 Ds darmstadtium (271)	111 Uuu (272)	112 Uub (277)						

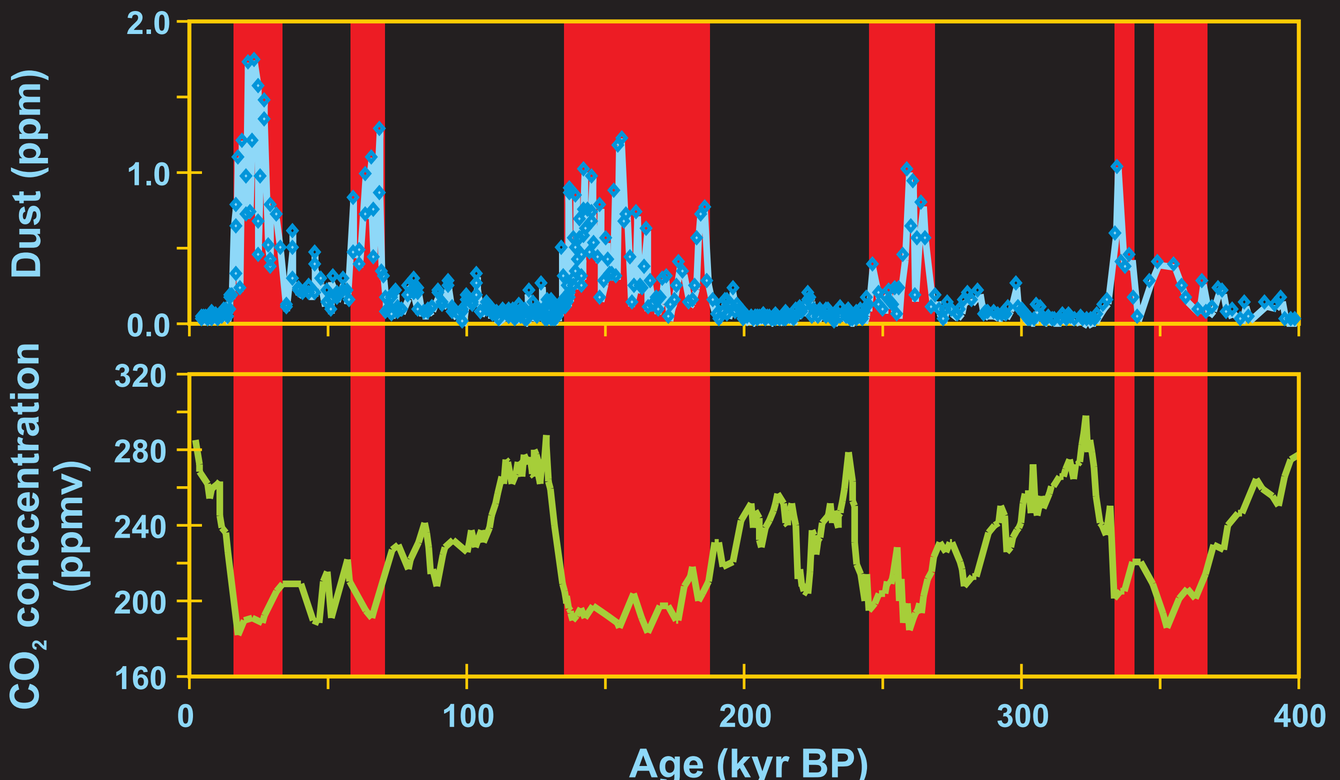
Life in the ocean – climate links



Global distribution of near-surface (30 m depth) ocean nitrate concentrations [*Conkright et al.*, 1994]



Dust concentration (blue, top) and CO_2 content of air bubbles (green, bottom) trapped in the ice, both from the Vostok ice core, Antarctica. [*Petit et al.*, 1999]



> Change the degree of iron limitation in the C Model:

> Model Parameters
> Biological
> Iron ...

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> Model Parameters
> Biological
> Iron ...

> WTF!

> Other ways of changing ocean productivity (and the biological pump) that are plausible and testable?

> Model parameters
> Biological
> Lower the 'half saturation' value.
Be careful not to increase the algal maximum growth rate too high ... you can crash the model ...

> Or:

> Set Initial Conditions
> Phosphorous
> *Surface*, *Middle*, and/or *Deep* Phosphorous

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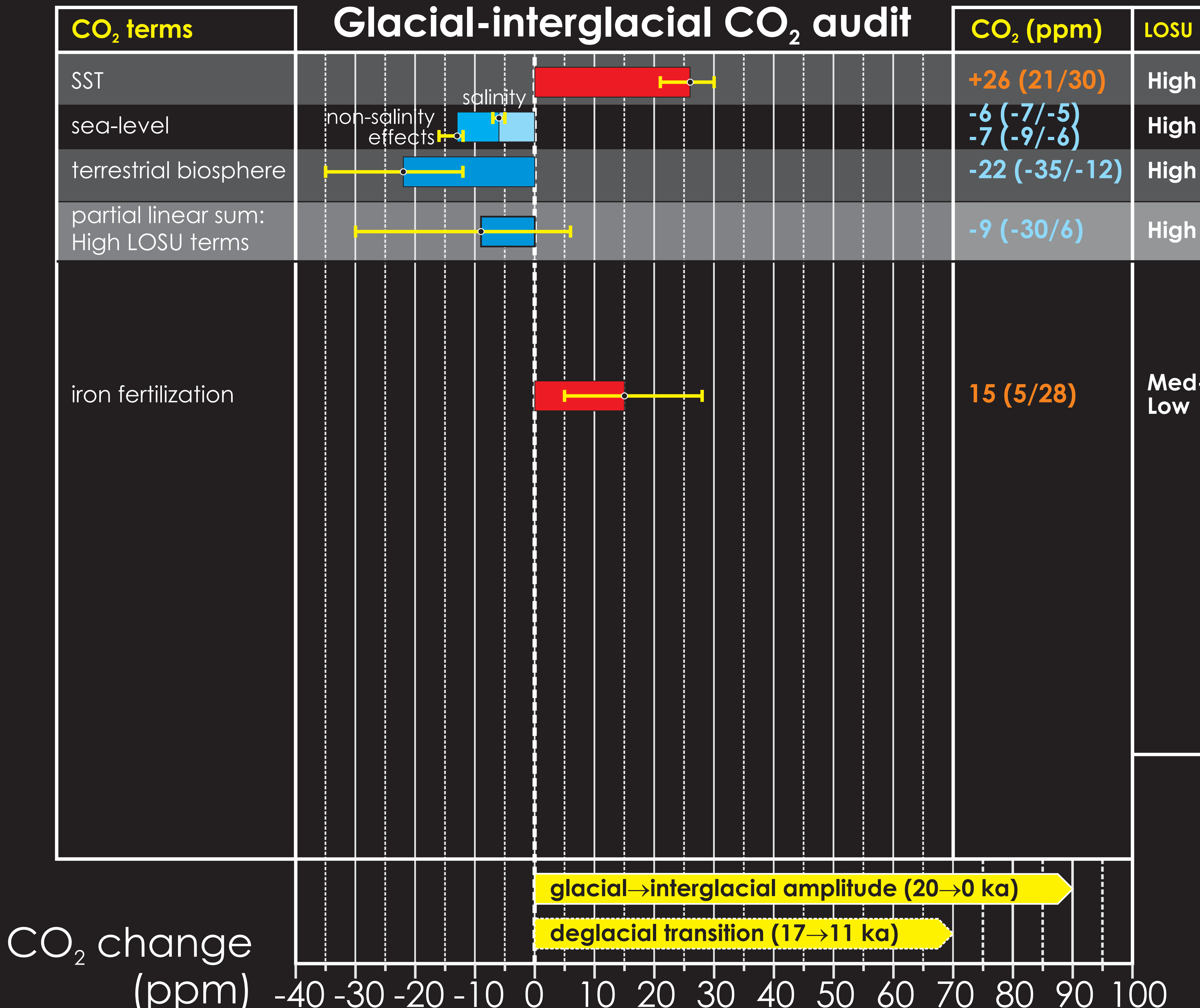
> Or:

> Set Initial Conditions
> Phosphorous
> *Surface*, *Middle*, and/or *Deep* Phosphorous

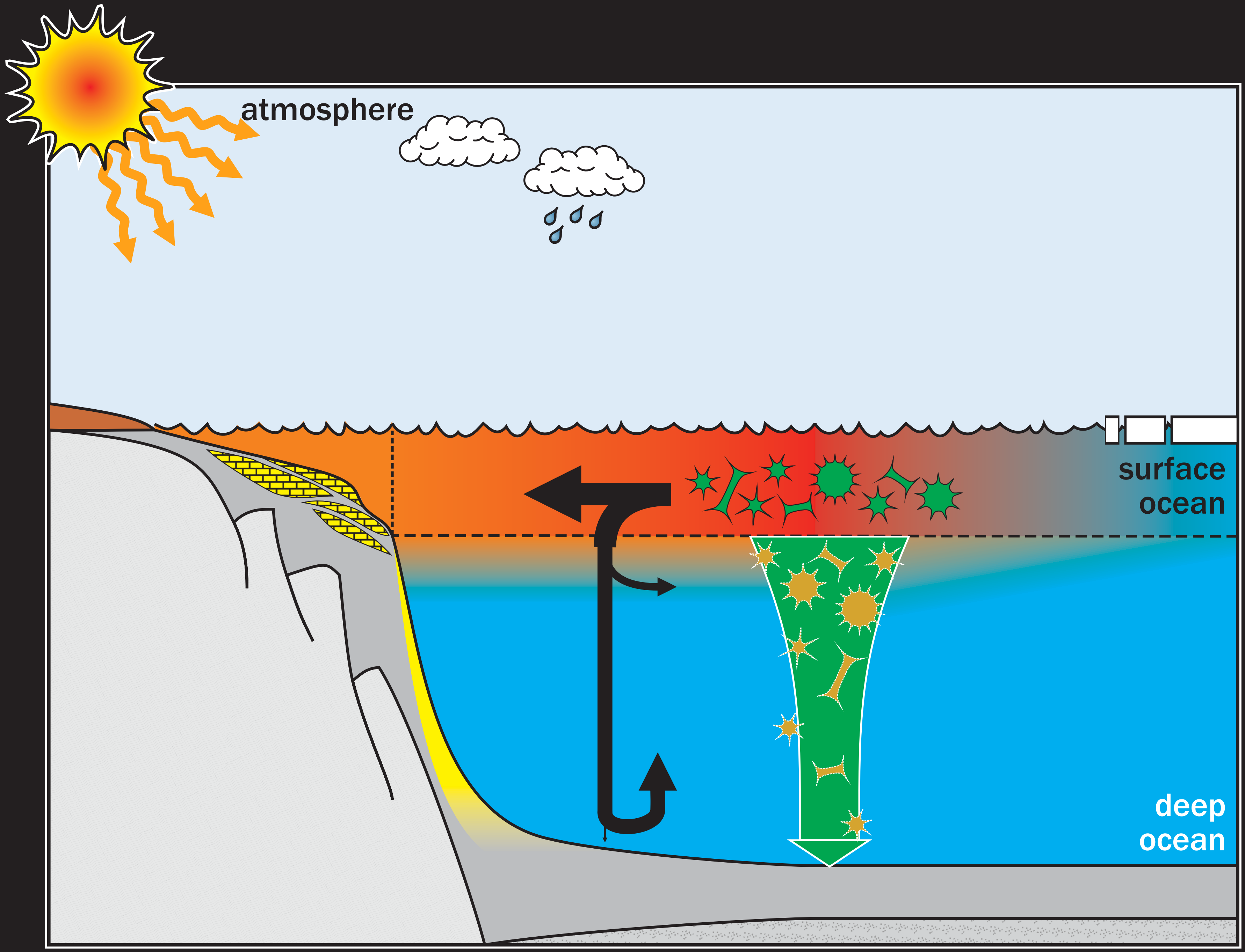
Q. What sort of paleoceanographic constraints can be brought to bear on the model?
i.e. what sort of impacts do you see in the model that might potentially be testable via some proxy measurement?



Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
SST
+26 (21/30)
High
sea-level
salinity
non-salinity
effects
-6 (-7/-5)
-7 (-9/-6)
High
terrestrial biosphere
-22 (-35/-12)
High
partial linear sum:
High LOSU terms
-9 (-30/6)
High
iron fertilization
15 (5/28)
Med-
Low
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change
(ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

Q. In what other (other than simply increasing total export) way might have the cycling of organic matter changed so as to help explain low glacial atmospheric CO_2?

Marine biology and the 'biological pump'



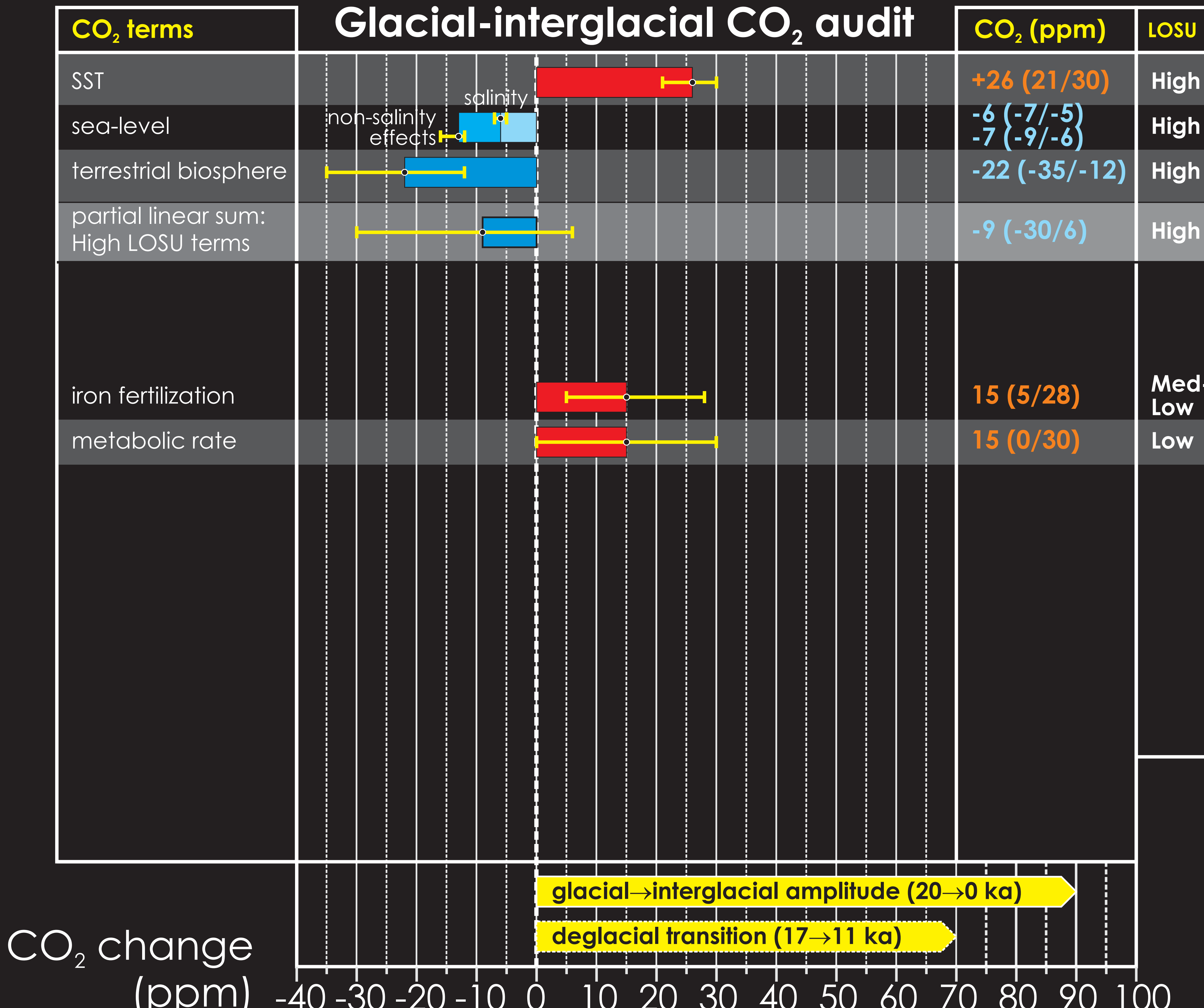
Q. Other further ways of changing the biological pump (efficiency)?

> Model Parameters
> Organic Carbon
> *Fraction Remineralized*

Q. Other further ways of changing the biological pump (efficiency)?

> Model Parameters
> Organic Carbon
> *Fraction Remineralized*

> Q. What sort of paleoceanographic constraints can be brought to bear on the model?
(And/or ice-core constraints?)


Glacial-interglacial CO2 audit
CO2 terms
CO2 (ppm)
LOSU
SST
+26 (21/30)
High
sea-level
salinity
non-salinity
effects
-6 (-7/-5)
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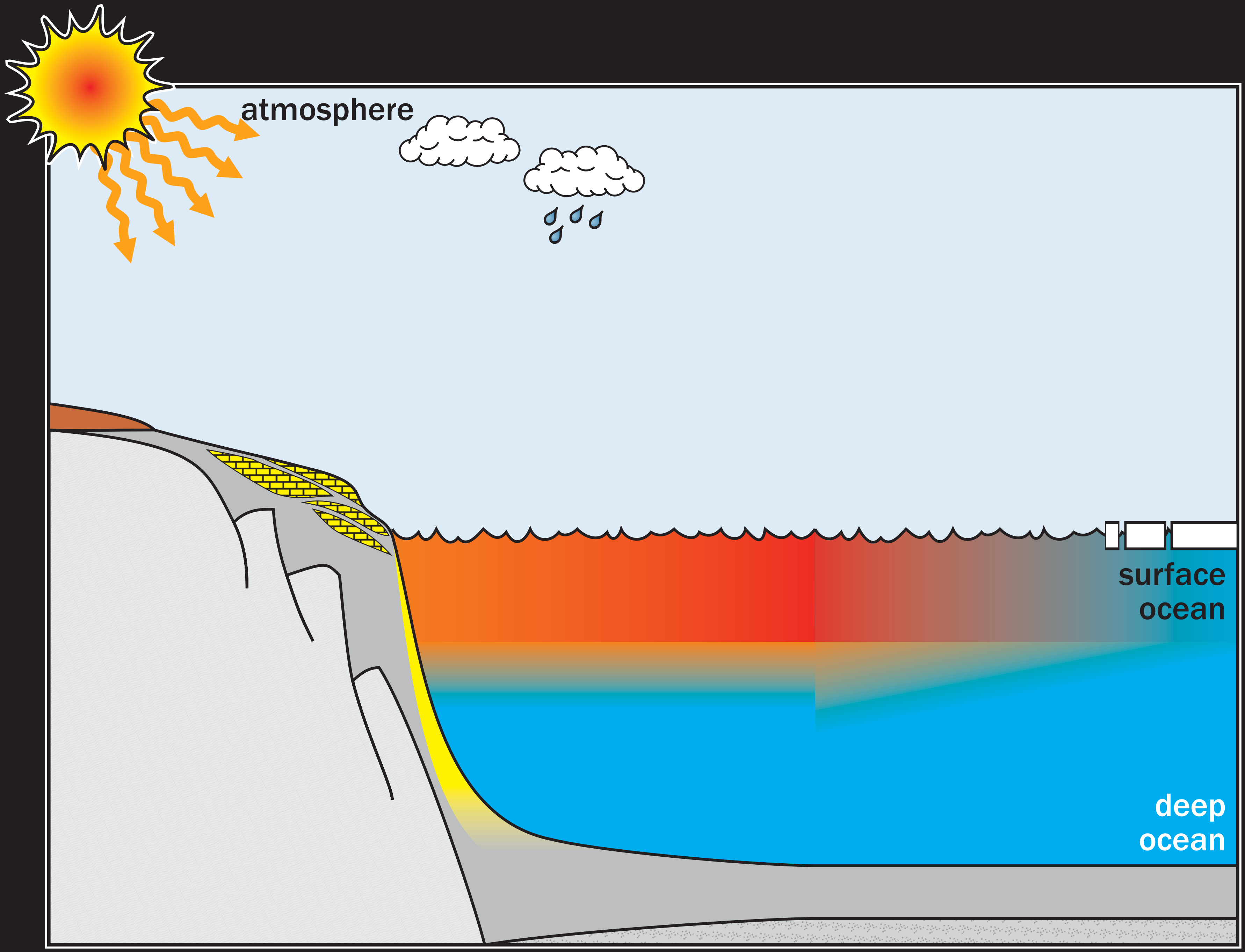
deglacial transition (17→11 ka)
CO2 change
(ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

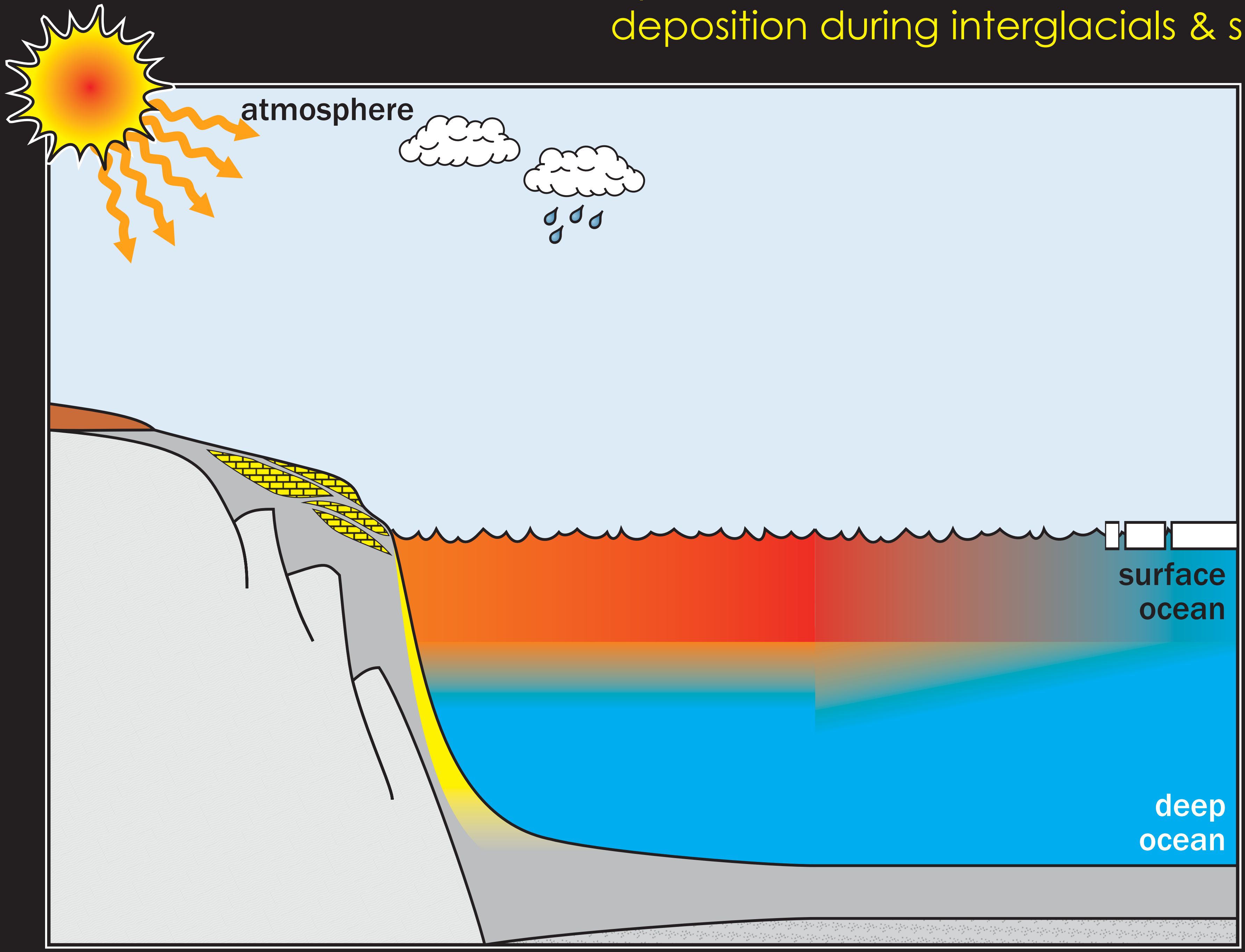
Sealevel ... ?



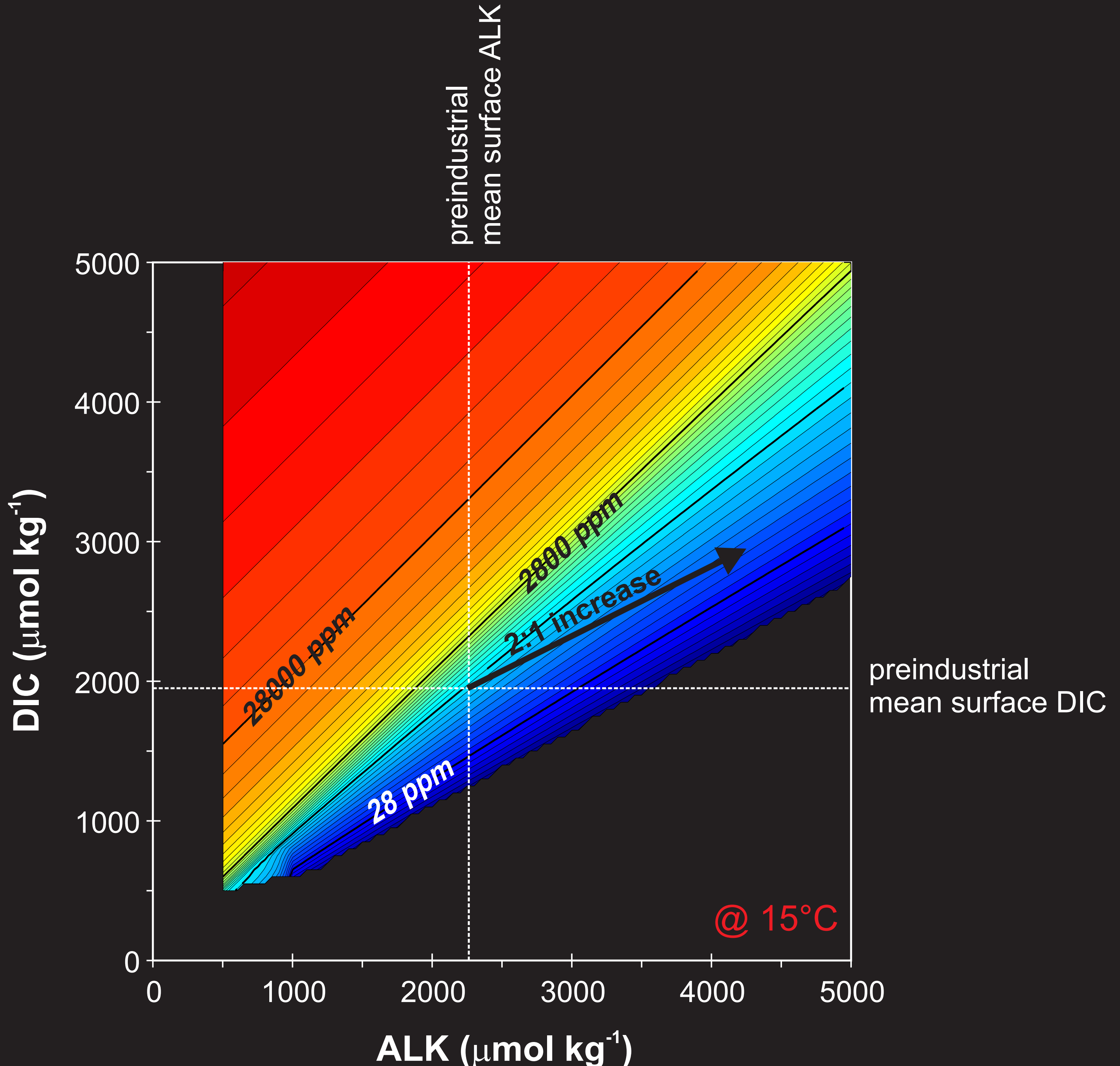
Sealevel ... ?

Erosion of carbonates on exposed continental shelves increased the ocean alkalinity inventory *Berger* [1982]

Conversely; increased area for shallow water carbonate deposition during interglacials & sea-level highs.



CO_2 chemistry *in seawater*



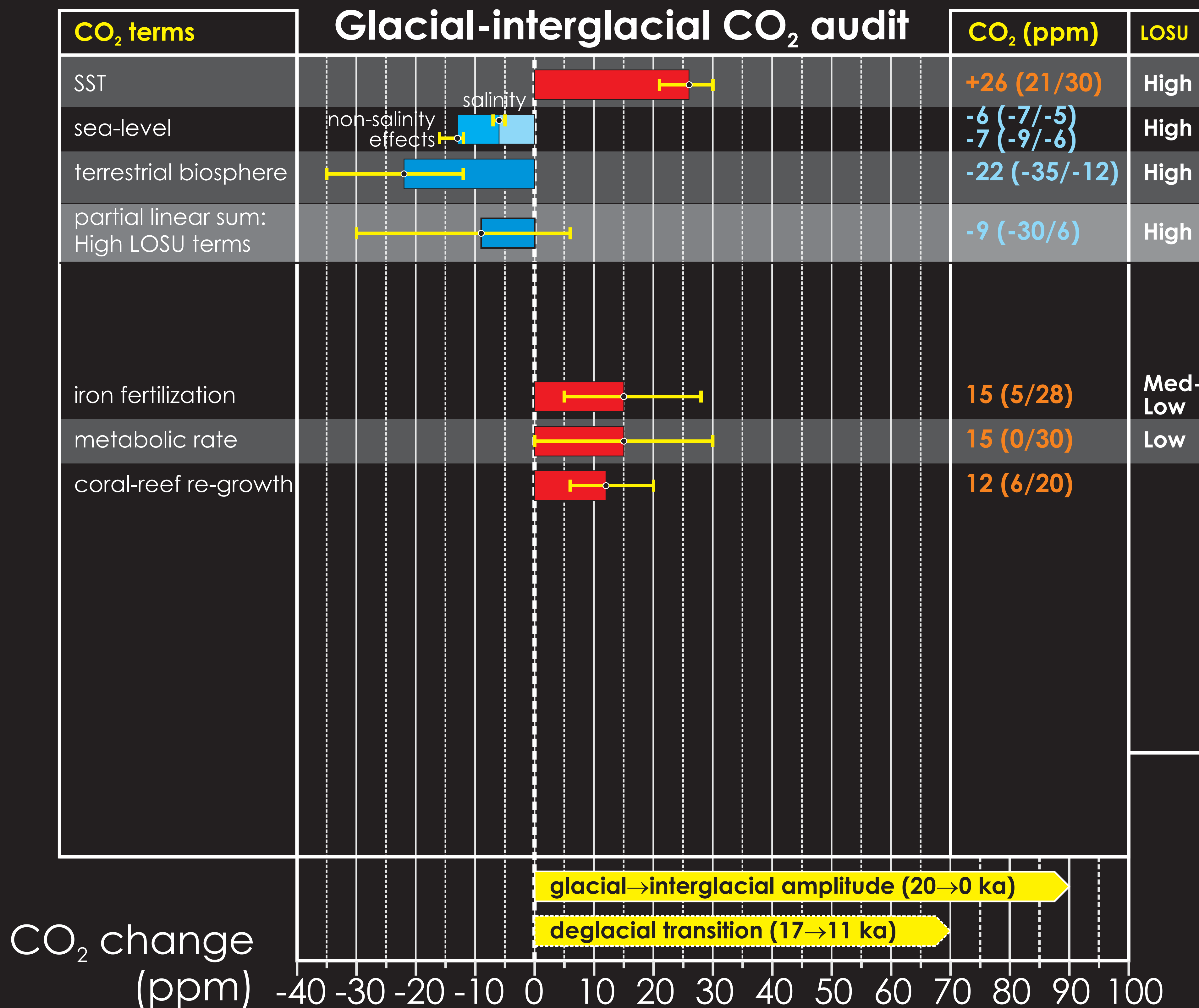
> To change ocean DIC and ALK in the **C-Model**:

> Set Initial Conditions (main menu)
> Alkaliniy and **Carbon** tabs – re-scale values in *each* ocean box (change value proportionally, BUT ALK at twice the relative change of DIC)
> Apply and Close
> Run Model

> OR ... **C Model** has a removal term for $CaCO_3$ buried in shallow water environments:

> **Model Parameters**
> **$CaCO_3$** tab
> **Fraction of $CaCO_3$ Burial in neritic environments** (e.g. set to 0.0)

NB! You might want to run the model for ca. 10,000 years to see the 'full' effect.



Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
SST
+26 (21/30)
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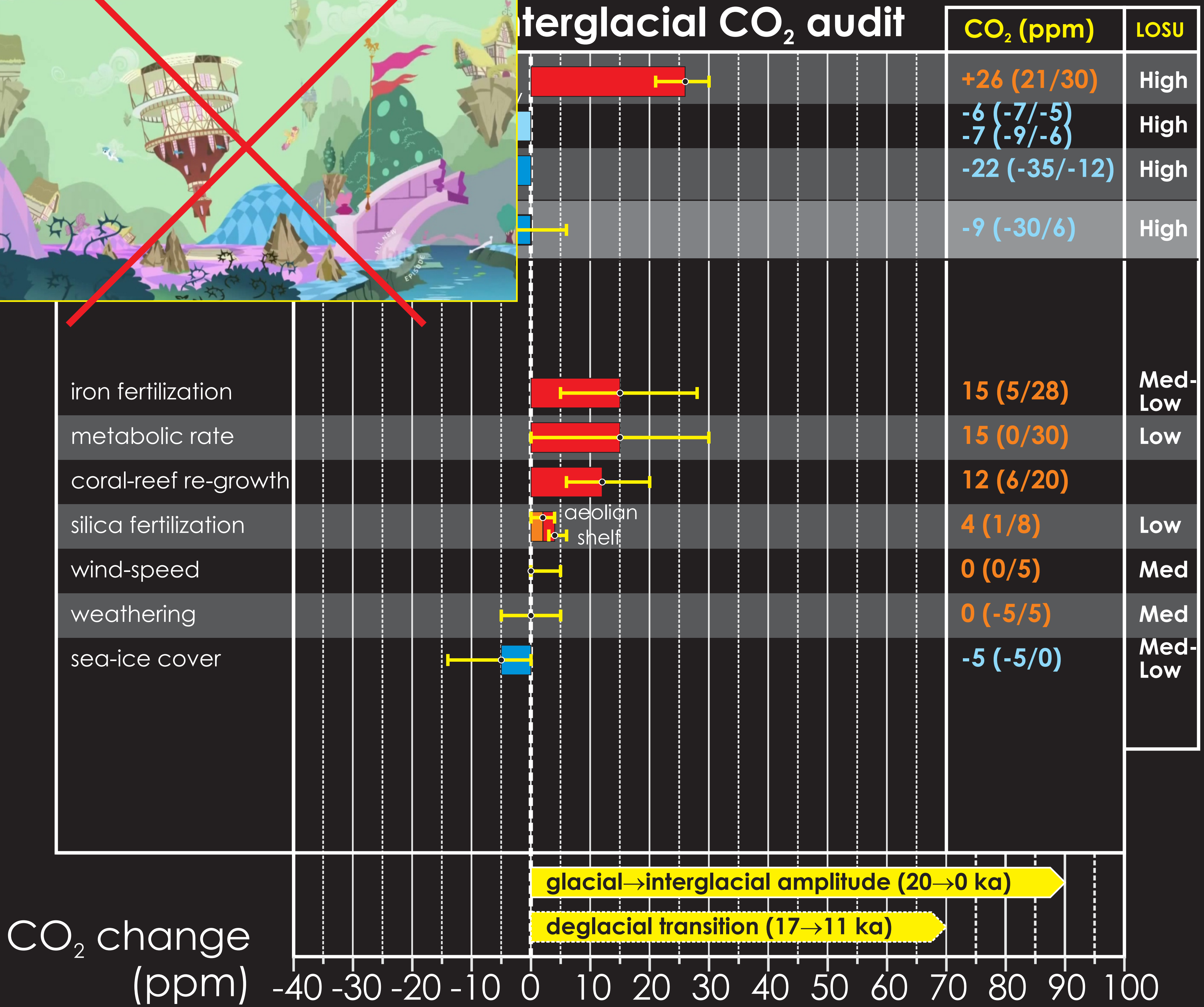
salinity
non-salinity effects
-6 (-7/-5)
-7 (-9/-6)
High
terrestrial biosphere
-22 (-35/-12)
High
partial linear sum: High LOSU terms
-9 (-30/6)
High
iron fertilization
15 (5/28)
Med-Low
metabolic rate
15 (0/30)
Low
coral-reef re-growth
12 (6/20)
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100



terglacial CO2 audit
CO2 (ppm)
LOSU
+26 (21/30)
High
-6 (-7/-5)
-7 (-9/-6)
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-22 (-35/-12)
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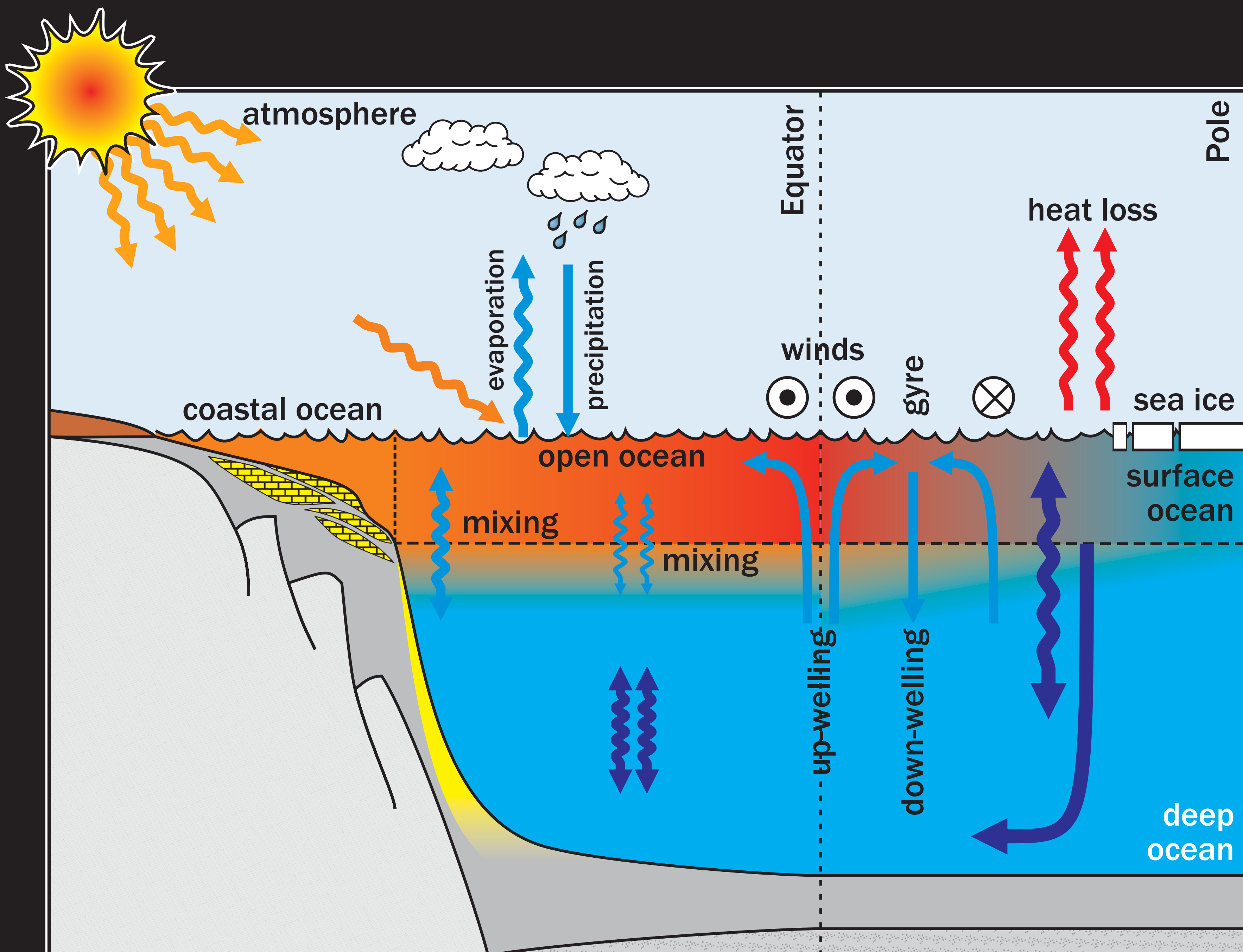
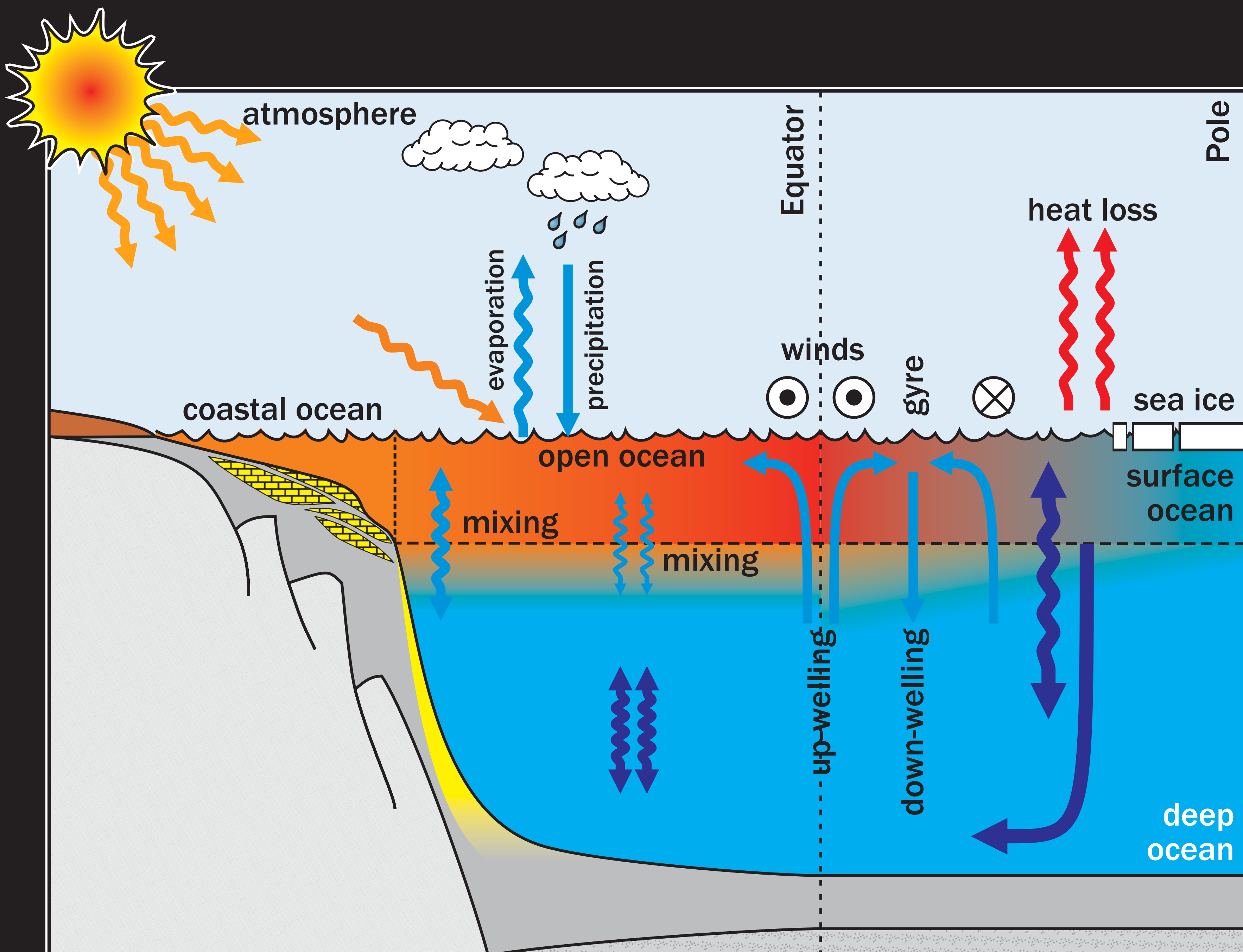
High
iron fertilization
15 (5/28)
Med-Low
metabolic rate
15 (0/30)
Low
coral-reef re-growth
12 (6/20)
silica fertilization
aeolian
shelf
4 (1/8)
Low
wind-speed
0 (0/5)
Med
weathering
0 (-5/5)
Med
sea-ice cover
-5 (-5/0)
Med-Low
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100

Ocean circulation ... ?



Ocean circulation ... ?

Return of remineralized DIC (respired CO_2) and nutrients to the surface?

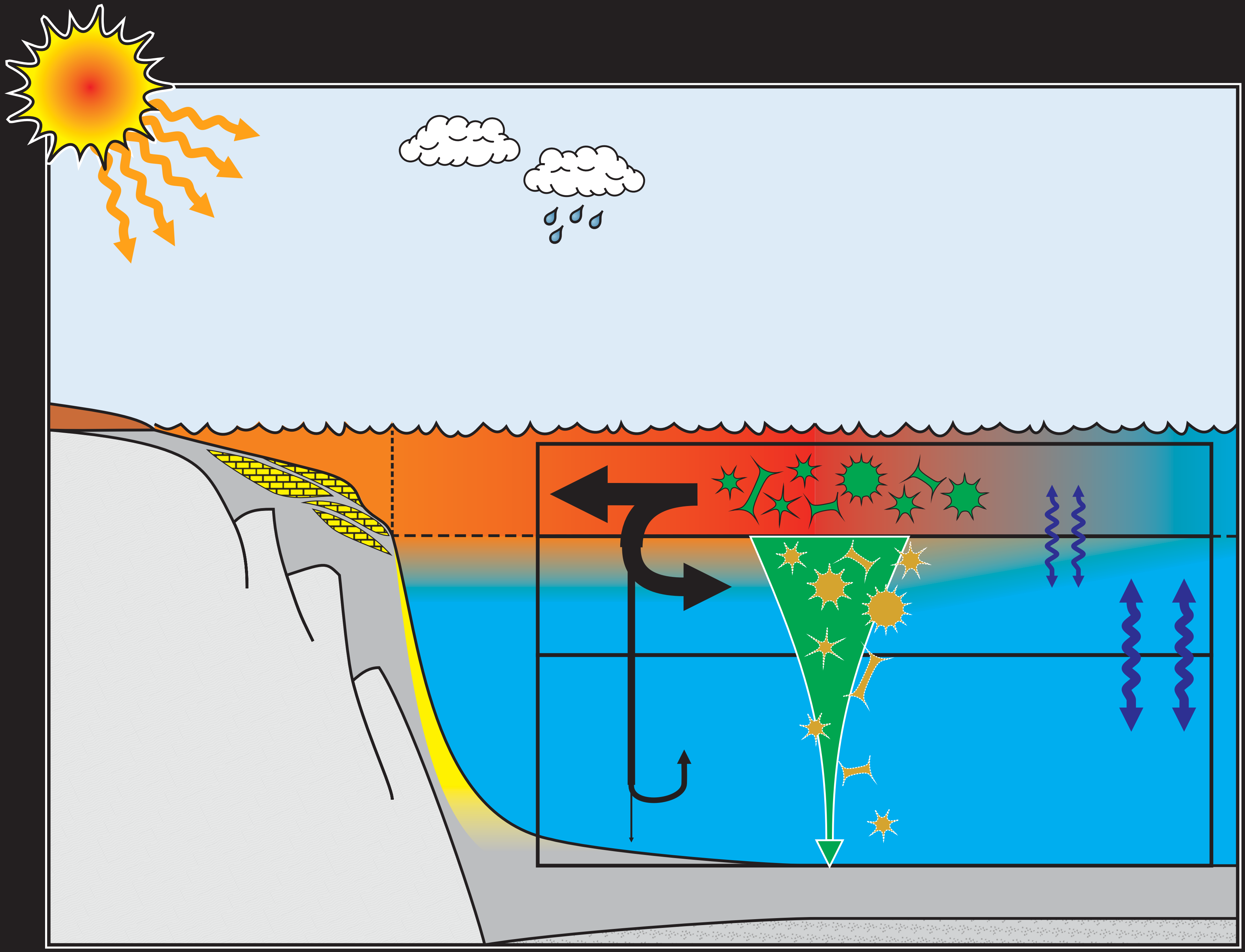


> AMOC, AABW/CPDW production changes ... ?

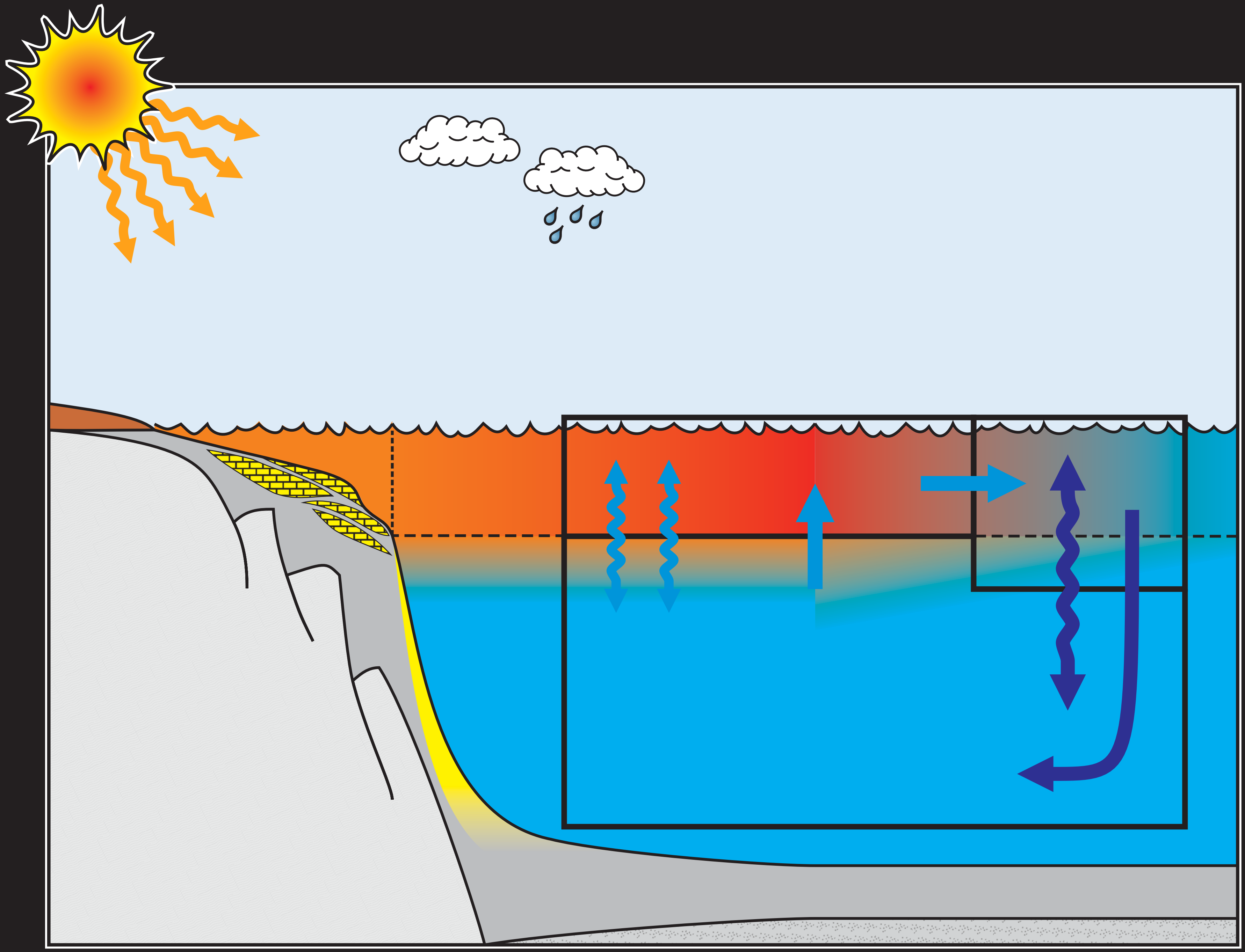
> What about testing deep stratification? (i.e. the idea that e.g. a deep highly saline layer sat at the bottom of the ocean).

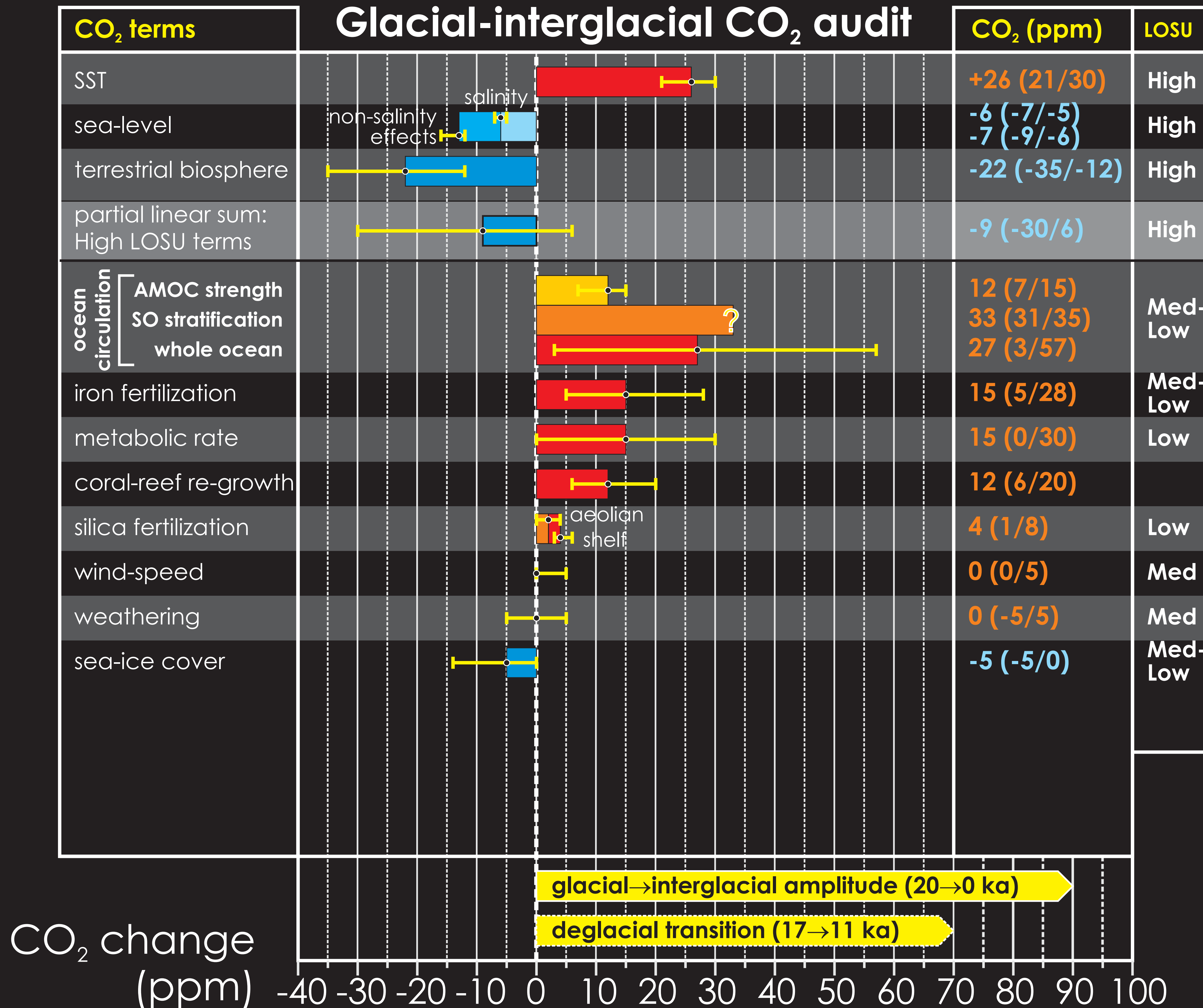
> Model Parameters
> Physical
> *mixing* (intermediate to deep)

C_Model



‘3-box’ model




Glacial-interglacial CO_2 audit
CO_2 terms
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partial linear sum: High LOSU terms
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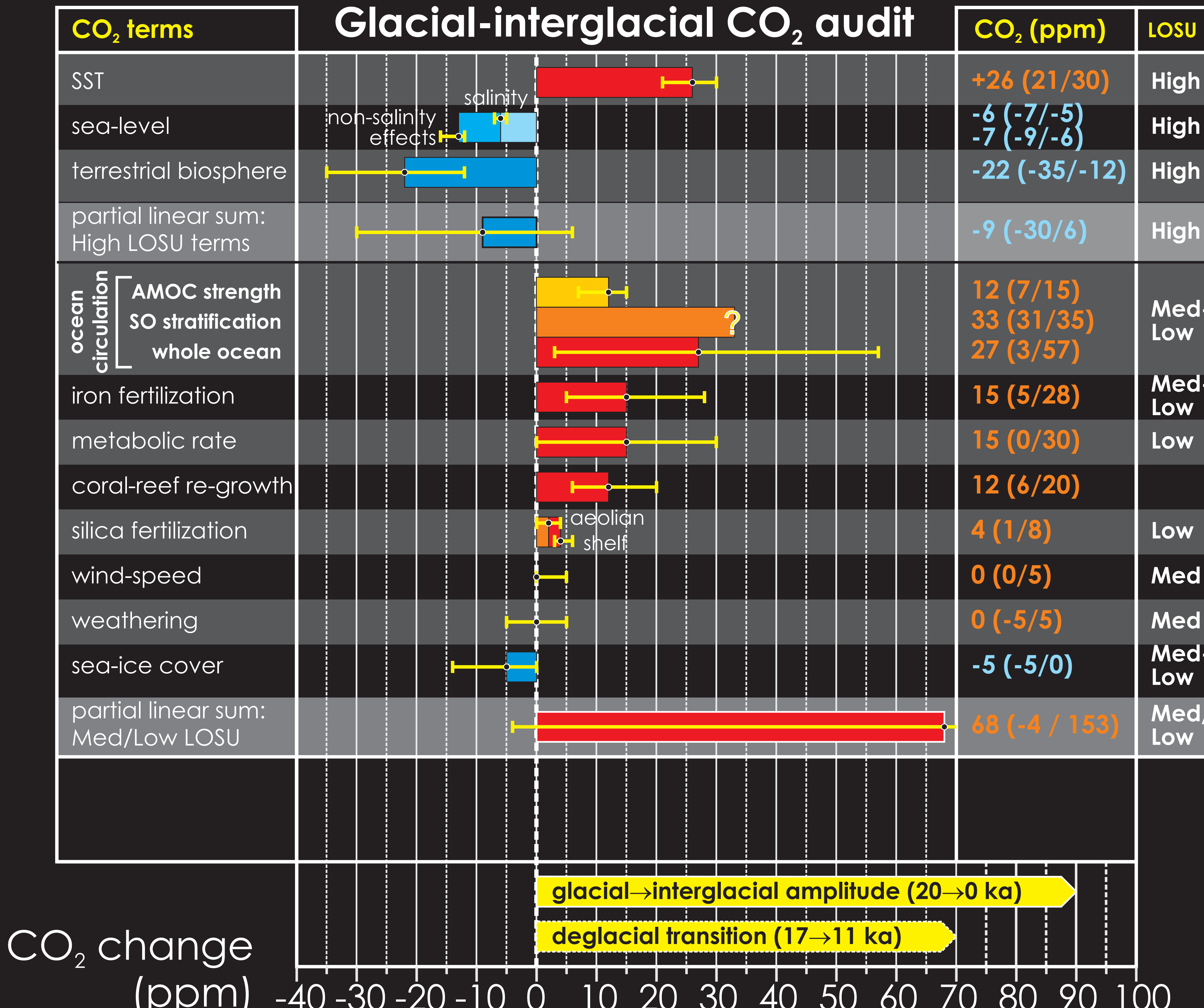
High
ocean circulation
AMOC strength
SO stratification
whole ocean
12 (7/15)
33 (31/35)
27 (3/57)
Med-Low
iron fertilization
15 (5/28)
Med-Low
metabolic rate
15 (0/30)
Low
coral-reef re-growth
12 (6/20)
silica fertilization
aeolian
shelf
4 (1/8)
Low
wind-speed
0 (0/5)
Med
weathering
0 (-5/5)
Med
sea-ice cover
-5 (-5/0)
Med-Low
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100



Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
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non-salinity effects
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partial linear sum: High LOSU terms
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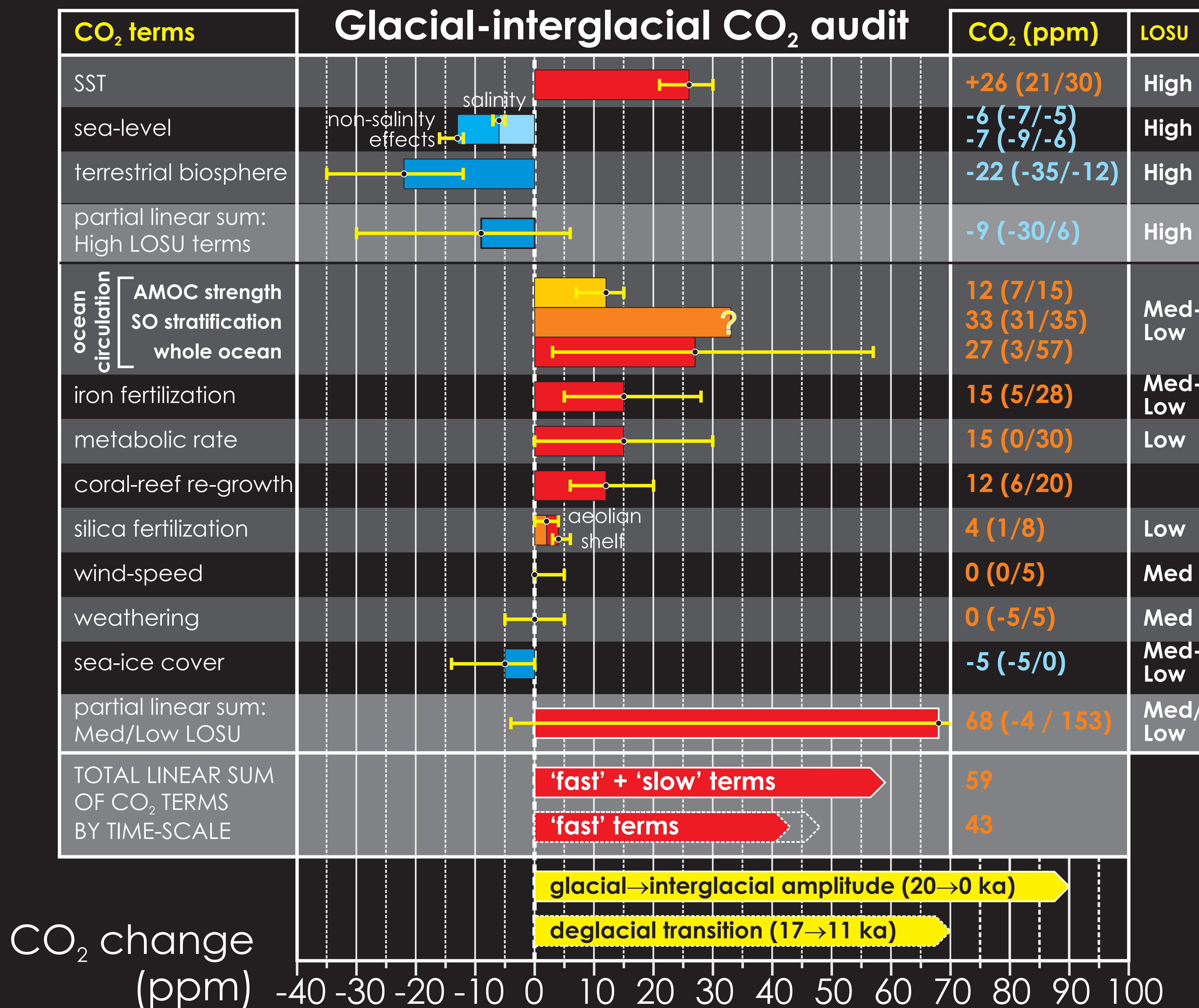
coral-reef re-growth
12 (6/20)
silica fertilization
aeolian
shelf
4 (1/8)
Low
wind-speed
0 (0/5)
Med
weathering
0 (-5/5)
Med
sea-ice cover
-5 (-5/0)
Med-Low
partial linear sum: Med/Low LOSU
68 (-4 / 153)
Med/Low
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100



Glacial-interglacial CO_2 audit
CO_2 terms
CO_2 (ppm)
LOSU
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High
partial linear sum: High LOSU terms
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High
ocean circulation
AMOC strength
SO stratification
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?
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Med-Low
metabolic rate
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aeolian
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4 (1/8)
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wind-speed
0 (0/5)
Med
weathering
0 (-5/5)
Med
sea-ice cover
-5 (-5/0)
Med-Low
partial linear sum: Med/Low LOSU
68 (-4 / 153)
Med/Low
TOTAL LINEAR SUM OF CO_2 TERMS BY TIME-SCALE
'fast' + 'slow' terms
59
'fast' terms
43
glacial→interglacial amplitude (20→0 ka)
deglacial transition (17→11 ka)
CO_2 change (ppm)
-40 -30 -20 -10 0 10 20 30 40 50 60 70 80 90 100