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Interactive comment on "Causes and timing of future biosphere extinction" *by* S. Franck et al.

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General comments: The questions motivating the research in this paper are highly original and important: What are the potential lifespans of prokaryote, eukaryote and complex multicellular biospheres on Earth? A box model is presented to address this, which includes key geosphere and biosphere dynamics, although I take issue with some of its assumptions and parameter settings. The authors follow David Schwartzman (in his book 'Life, Temperature and the Earth') in arguing that the appearance of successive types of life (prokaryotes, eukaryotes, complex multicellular life) was in each case limited by high temperatures. This argument demands that the early Earth was hot (circa 70°C) and what are recognised as the Huronian glaciations of circa 2.4 Gyr ago were not glaciations at all. It also demands that the upper temperature limits for eukaryote and complex multicellular life are rather low (45°C and 30°C respectively) in order for heat to have held back their appearance. The existence, on a spherical planet with low obliquity, of polar habitats that are much cooler than the mean

(and equatorial habitats that are much hotter) is not addressed. In projecting into the future it is estimated that complex multicellular life and then eukaryote life will disappear because of their upper temperature limits being reached, with prokaryote life perishing due to lack of CO_2 (not long before temperature would have become prohibitively hot even for them). The order of disappearance seems reasonable although the causes are debatable. The system shows no sign of future bi-stability or rapid collapse, but this deserves further investigation.

Specific comments:

1. A different title such as "Lifespans of prokaryote, eukaryote and complex multicellular biospheres" would more accurately cover the content of the paper.

2. Abstract: It would be worthwhile including the future times that each type of biosphere disappears or calculating the total lifespan of each type of biosphere

3. Introduction: Lovelock and Whitfield's model was not purely qualitative - they had a simple computer program although the equations were not published

4. Introduction: the "different biotic enhancement of weathering" is only for complex multicellular life when in fact it is probably different for all three types

5. Model description: I tried solving equations (1)-(6) for steady state and soon found that on the basis of what is presented there are no unique solutions for C_{O+A} or C_C, whilst C_F is over-determined. Noting that weathering is a function of CO_2 and hence C_{O+A} suggests that a unique solution for C_{O+A} exists but nowhere can I see C_C, continental crust carbon, entering the equations. How does C_C manage to have a stable solution? I think weathering should depend on the carbon content of the rocks being weathered, i.e. C_C, and would like to know why it doesn't. The equations as presented raise more questions than they answer and a pictorial representation of the key reservoirs and fluxes might be more informative.

6. Weathering rates: Soil CO_2 partial pressure is increased by respiration of soil or-

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ganisms and only partly due to respiration from the roots of vascular plants. However, soil CO_2 is ultimately derived from primary productivity. The additional direct dependence of weathering on productivity is presumably due to the secretion of organic acids, chelating agents etc, and this deserves to be made explicit.

7. Equation (9): When multiplying out the two brackets one is left with a mixed term in Π and β which I can't see any justification for - is this equation written correctly? It doesn't make sense to me and needs clearer explanation/justification.

8. Biological production: Here I have major reservations about the choice of model parameters. It is noted that the tolerance windows are more restrictive than those given by other authors, but no real justification for this is given. For temperature they must represent the global average temperatures which make the planet uninhabitable to particular types of life. But noting that polar habitats will always be cooler and equatorial habitats hotter than the mean, I can't see a justification for the temperature limits used. Taking each parameter in turn:

a. T_{min} - why is this lower for complex multicellular life than prokaryotes? - that makes no sense - surely the boundaries for more complex life lie within those for prokaryote life - and freezing tolerant prokaryotes are well known.

b. T_{max} - 45°C for eukaryotes is too low - algae and fungi that can grow at 55-60°C (see: http://www.pnas.org/cgi/content/abstract/69/9/2426) have been known about for some time. 30°C for complex multicellular life doesn't make sense - we can survive at this temperature, and this is not so far from the global temperature predicted in some extreme global change scenarios for the coming millennium, or that estimated for the peak warmth of the Eocene or the mid-Cretaceous when complex multicellular life flourished.

c. Π_{max} - where are these values from? The current biosphere has primary productivity of about 60GtC/yr on land and a similar amount in the ocean so 20GtC/yr must be too low for at least one of the biosphere types.

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d. P_{min} - This looks like a typical lower limit for C4 photosynthesis - but how widespread are CO_2 concentrating mechanisms?

e. $P_{1/2}$ - This looks like a reasonable value for C3 plants - but why is it the same for all biosphere types?

f. T_{bio} - The residence time of C in large life forms must be longer than in smaller ones of similar productivity - the prokaryote biosphere can turn over faster than 12.5yrs, although reducing this parameter will mean a shorter time step to solve the equations

g. β - This is only enhanced for complex multicellular life - but Schwartzman and Volk suggest there is evidence of enhanced weathering by prokaryote and eukaryote life.

9. The overall question from the above points is: How sensitive are the model results to the parameter settings? This is explored for β but not some of the other potentially critical parameters such as the upper temperature limits.

10. Results and discussion: High Archaean temperatures from the oxygen isotopic composition of cherts are, as I understand it, still controversial. They are certainly controversial at the time of the Huronian glaciations circa 2.4 Gyr ago. I share the consensus view that these were glaciations and that the Earth has had a milder temperature history than the one predicted.

11. Eukaryotes need O_2 and the O_2 content of the atmosphere increased markedly in the Great Oxidation circa 2.3 Gyr ago. Arguing that they were held back by high temperatures when there had been glaciations circa 2.4 Gyr ago seems perverse to me. Furthermore, there is an active debate about when eukaryotes first appeared (ranging from circa 2.7 Gyr ago to circa 1 Gyr ago).

12. The argument that complex multicellular life awaited a further cooling of the planet also seems perverse given that there was a first Neoproterozoic glaciation circa 0.74 Gyr ago whilst the Ediacarans do not appear until circa 0.57 Gyr ago (significantly before the Cambrian explosion). Furthermore, the Neoproterozoic glaciations are as-

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sumed not to occur in the model temperature history.

13. The Cambrian explosion did not involve plants. Thus the “biological colonization of the land surface by metaphyta” is incorrectly linked with the Cambrian explosion. The rise of vascular plants happened much later, whereas the rise of lichens may have happened significantly earlier than the Cambrian explosion and could have been a causal factor in the Neoproterozoic glaciations.

14. There is evidence for small metazoans well before the Ediacarans and evidence for multicellular algae that count as ‘complex multicellular life’ - these points may be worth noting around the discussion of complex life being able to appear at 1.7 Gyr ago.

15. I’m not sure why $\beta < 5$ is considered the realistic regime - there are experimental and field studies that could support a value for vascular plant amplification of weathering of greater than 5 and Berner uses a value of circa 7 in his GEOCARB models.

16. Figure 2: This could be made clearer by removing the dashed line at -2.5 Gyr and by altering the type of line used as bounds on the cross-hatched area (i.e. not solid lines). It might also be better to plot time on the horizontal axis, increasing from left to right, as in figures 1 and 3 (i.e. rotate and flip the present figure 2).

Technical corrections:

1. Abstract: “aggregated reservoir ocean and atmosphere” better “combined ocean and atmosphere reservoir”

2. Abstract: “prokaryote biosphere always exists”? Not after 1.6 Gyr in the future!

3. Introduction: “the sixties of the last century” = “the 1960s”

4. Conclusions: “extinct” should be “become extinct” in three places

5. Conclusions: “only in...can our home planet harbour...”

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