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***Interactive comment on* “Effect of carbonate ion concentration and irradiance on calcification in foraminifera” by F. Lombard et al.**

Anonymous Referee #1

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Lombard and co-authors present an interesting view on the ‘Effect of carbonate ion concentration and irradiance on calcification in foraminifera’. The paper confirms earlier results of Bijma et al. (1999 and 2002), and Russell et al. (2004), and discusses the effect of decreasing carbonate ion concentration, calcification rate, and initial shell weight of planktic foraminifers at increasing [CO₂]. Among other questions arising, it would be interesting to get an explanation of the production of light shells at high [CO₂], i.e., 504 μmol kg⁻¹, although heavier shells are produced at slightly higher and lower carbonate ion concentrations. Mayor conclusion of the paper is that ‘at higher temperatures, foraminifera are usually more abundant (Bé and Tolderlund, 1971), have higher growth rates (Lombard et al., 2009) and larger shell sizes (Schmidt et al., 2006)’, ‘counteracting the negative impact of ocean acidification.’ To my view, the interpretation of data, and the discussion of the effects of changing seawater pH on the calcification of

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foraminiferal shells is too simplistic. In the following, I will discuss the major conclusion of the paper of Lombard and co-authors.

Taking into account the upcoming decrease in [CO₂] over the next century, as well as past variability in foraminifer test-CaCO₃ mass, the authors predict significantly reduced planktic foraminiferal calcite production in the near future, of >4 to <27 % in different species. Those numbers have possibly been produced on the assumption of linear extrapolation of earlier results. Data from fossil assemblages have often been interpreted in a too simplistic way, not taking into account the complexity of dissolution and incrustation processes during sedimentation, which has been discussed in depth by Lohmann (1995). Remineralization of foraminifer shells at decreasing [CO₂] in the mid water column has been quantified by Schiebel et al. (2007). Iglesias-Rodriguez et al. (2008) discuss increased calcification of coccolithophores at enhanced [CO₂]. Both negative and positive feedbacks of calcification to increased [CO₂], and decreased [CO₂], would be possible also in planktic foraminifers, which might be indicated by the 'surprising' data of the 504 μmol kg⁻¹ experiment of Lombard and co-authors.

The great advantage of the use of planktic foraminifers as proxy in paleoceanography is their occurrence over a broad range of sea surface temperature (SST), usually exceeding 10°C (e.g., Bé and Tolderlund, 1971). *Globigerina bulloides* occurs over the whole range of global SSTs (>25°C), and all of the genotypes of this morphotype are surface dwellers. Since the pioneering work of Thiede (1975), *G. bulloides* is known to be indicative of upwelled waters, i.e., waters which are colder than adjacent water bodies. The higher abundance of planktic foraminifers at colder waters is also evident from Bé and Tolderlund (1971; Fig. 6.27; and many other papers), although more recent studies present more complete data. Bé and Tolderlund (1971) show only the upper 10 m of the water column, and texts >200 μm (small specimens, and small species were unfortunately not sampled), according to which highest standing stocks are shown for equatorial and coastal upwelling areas, and for current systems including eddies and local upwelling cells. The warm, stratified, and nutrient depleted surface waters of

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the subtropical gyres host small standing stocks of planktic foraminifers. To conclude, the production of planktic foraminifers is mainly a result of trophic conditions and the availability of food, and neither of high nor low temperatures.

Growth rates of planktic foraminifers are surprisingly similar over a wide range of species specific temperature variability (Lombard et al., 2009, Fig 1). The same graphs presented by Lombard (2009) do also indicate that water temperature and growth rates are not linearly related but rather complex. The observations of Lombard et al. (2009) are very interesting, and so far not entirely explained. A combination of mechanisms could affect growth rates along a temperature gradient: (1) Methodological effects caused by discontinuous sampling. (2) Differential availability of food at different temperatures, or at different regions of similar temperature. (3) Scarcity of food at, for example, subtropical gyres, and slower growth or later reproduction of an average individual. A significant change in foraminiferal growth and global calcification rates over the expected SST change until 2100 is not evident though.

The statement that planktic foraminifers are larger at higher temperatures is not as simple as it seems (Schmidt et al., 2006), and needs further explanation. Indeed, planktic foraminifers were larger during the (relatively warm) Eocene than during the (colder) Oligocene, which is a result of a change in species assemblage, and possibly species specific survival strategies (r-strategy versus K-strategy) over long periods of time. A similar change in species composition can be found in the modern ocean, and the average size of tropical and subtropical species is larger than the size of polar and subpolar species. Average planktic foraminiferal test size changes over long periods of time, and over large distances, and is possibly best explained by nutricline depths and changes in nutrient redistribution (Schmidt et al., 2004). It is true, though, that very large tests of planktic foraminifers are often found at warm and nutrient and food depleted waters, and resulting starvation and retarded reproduction of foraminifer specimens. In turn, largest average planktic foraminiferal test size in Earth history has been achieved in the Quaternary icehouse world (Schmidt et al., 2004).

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To conclude, higher SSTs would cause diminished standing stocks of planktic foraminifers, and a rather unpredictable (but possibly small) reaction of growth rates at the predicted 0.5~2°C change in SST (IPCC, 2007; not including the Arctic Ocean). Large tropical species might be distributed over larger areas of the global oceans though, and would individually produce more calcite, but much fewer specimens. Planktic foraminifers are not affected by ambient water temperature within the temperature range of the global surface ocean, but by the quality and quantity of their food (algae and small zooplankton). Phytoplankton production is affected by light and nutrient utilization. However, nutrient redistribution and nutrient utilization might be affected by a global change in temperature distribution. Hydrographic fronts could change their position poleward, and cause a change in the species composition of primary producers and higher trophic levels. Those changes in the surface marine environment and the resulting change in planktic foraminifer population dynamics are not easy to predict.

Following to the above discussion, we could start talking about time-scales on which planktic foraminifer calcite production has a negative or positive impact on ocean acidification (p. 8599, line 6 of the manuscript of Lombard and co-authors).

I do agree to the final conclusion of Lombard and co-authors that the effect of changing ecological conditions and [CO₂] need to be further investigated. We need to achieve a better mechanistic understanding of planktic foraminifer calcification, and fluxes need to be quantified on various regional (in particular mesoscale) and temporal scales.

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