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Climate of the Past
Discussions

Interactive comment on "Ocean Biogeochemistry in the warm climate of the Late Paleocene" *by* M. Heinze and T. Ilyina

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Response Reviewer #1

Reviewer's comment: This manuscript analyzes model simulations of ocean biogeochemistry for a climate scenario of the Late Paleocene. Little is known about this time period but it serves as the background climate for PETM, which has been used as an analog for the current perturbation to the climate/carbon cycle system (rapid release of carbon). The amount of carbon has been estimated using box models or simplified models. The authors think that a more comprehensive model may lead to different results, although this is not actually shown in the manuscript. However, I think the manuscript is helpful and contributes to the understanding of this time period and hence it should be published in CP. It is well written and illustrated. I don't think this

is a major advance but good enough for a paper. Most of my points below are minor issues/suggestions, except perhaps #2 (statements about carbon pumps). Reading the paper I was also wondering about the P and N cycles. Would be nice if the thinking on the P and ALK inventory was elaborated on and the modeled N cycle. E.g. how does denitrification and N-fixation respond to the simulated oxygen changes and how does this affect the N inventory? I suggest to add the recent review by Sijp et al. (2014, Global and Planetary Change 119, 1-22) as a reference.

Authors' response: Following the reviewer's suggestion we extended our analysis, it covers now also the marine N cycle. We give global numbers for the denitrification and compare it to the pre-industrial. We went over our statements of the carbon pumps again and hope to have addressed the reviewer's criticism with the applied changes (see point-bypoint comments).

Reviewer's comment: Page 1934, line 14-15: "affects the strength and spatial variation of the different carbon pumps." This has actually not been shown in the manuscript. I suggest to modify the manuscript or to remove the sentence from the abstract.

Authors' response: As we can not give a quantitative estimate of the strength of the physical carbon pump, but rather infer it from the weaker MOC (Figure 4), we removed the sentence from the abstract.

Reviewer's comment: Page 1935, lines 20-22: "The main deepwater : : :" add references.

Authors' response: A reference (Thomas et al. 2003) has been added.

Reviewer's comment: Page 1936, line 1: why was the lower limit of the CO2 estimates chosen here?

Authors' response: Heinemann et al. 2010 established a Late Paleocene climate state based on a 560 ppm CO2 atmospheric concentrations. The simulated surface and deep ocean temperatures match the proxy record quite well (Lunt et al., 2012). Since we are using Heinemann et al. 2010 data to force our model we also prescribe an atmospheric CO2 concentration of 560 ppm.

Added in line 25: The applied atmospheric CO2 concentrations and Late Paleocene boundary conditions cause a new equilibrium climate state, which fits the proxy record based SST quite well (Lunt et al., 2012).

Reviewer's comment: Page 1937, line 19-20: add “online” or “offline” to clarify how the tracer simulations were done.

Authors' response: The word 'online' has been added. The new sentence reads: HAMOCC is coupled online to the Max Planck Institute ocean model (MPIOM) (Marsland et al., 2003; Jungclaus et al., 2013), which computes tracer advection and mixing.

Reviewer's comment: Page 1939, line 14: interpolated on the 3.5 x 3.5 deg grid? Which grid is shown in Fig. 1?

Authors' response: Changed to: The model setup is based on the interpolation of a Late Paleocene 2° x 2° topography (Bice and Marotzke, 2001) onto our 3.5° x 3.5° ocean model grid (Figure 1).

Reviewer's comment: Page 1940, line 1: Where was the missing 14% water plus what is currently in the ice sheets?

Authors' response: Added in the text: Although the missing ice sheets in the Late Paleocene setup would suggest an increase in oceanic volume, the provided bathymetry from Bice & Marotzke, 2001 results in a reduced ocean volume compared to modern conditions. Miller et al., 2005 propose a ∼60 m higher sea level during the Late Paleocene in comparison to today, due to higher ocean-crust production and tectonic reorganization (i.e., opening of the Norwegian- Greenland Sea). We do not consider these details in our bathymetry. However, since we adapt the inventories of the ocean biogeochmical tracers (see 'Initialization biogeochemistry'), we hold on to the reduced ocean volume bathymetry, since it allows a better comparison of the results to other

models using this bathymetry (e.g., Panchuk et al., 2008, Heinemann et al., 2009). [Moved sentence from page 1941, line 11-13 to page 1940, line 1 for better understanding.]

Reviewer's comment: Page 1941, lines 1-3. Does the physical state of the ocean only model converge to that of the coupled model run?

Authors' response: The ocean only model results in a nearly identical physical state as the coupled run does. See for instance the MOC of the coupled model (Heinemann 2009, dissertation) in comparison to Figure 4 in the paper.

Reviewer's comment: Page 1941, lines 26-27: I don't understand this sentence. What does “adapted” mean and what “correction factor” is used for which “different pools”?

Authors' response: We balance the global sedimentation rate of opal, calcite and OM with constant uniform weathering fluxes at the surface, which is a common practice in models (Archer et al., 1998, Heinze et al., 1999). The sentence has been changed in the text to: The weathering fluxes depend on the long-term sedimentation rates. They are used for balancing the water column inventory of the calcite, silicate and OM pools. The annual amount which is leaving the system through sedimentation, is added (globally distributed) at the surface again.

Reviewer's comment: Page 1942, lines 12-15: I don't understand. Give formula.

Authors' response: Instead of giving a formula we describe the applied sediment acceleration in more detail, since we only divide volume and pore water by a prescribed factor.

Changed in the text to: In the sediment module, the sediment layers are subdivided into a solid sediment fraction and a porewater fraction. The fraction of solid sediment varies with depth, but not with time. The downward shifting of particles depends on the “filling” state of the sediment. For the sediment acceleration we simply divide the volume fraction of solid sediment and porewater by a prescribed factor, while keeping the sediment thickness constant. As a result, the surface area of the sediment is reduced relating to its vertical profile. From a modeling perspective this reduction in volume (area) is acceptable, since the proportion of the grid single cells (∼100 km x ∼15 cm) prevents horizontal gradients, anyway. By maintenance of mass conservation the tracers are distributed faster throughout the sediment, since the volume is reduced and the material is shifted faster to deeper layers. To prevent an overcompensation of the porewater, the diffusion has to be reduced by the same factor as the volume is reduced. As soon as the sediment is saturated and in equilibrium, the sediment module is extended to its original volume (area) again.

Reviewer's comment: Page 1944, line 17-18: at what depth does the inflow of Atlantic water occur?

Authors' response: The center of the sea strait is up to 2000 m deep. However, the sill depth between the two basins amounts only to about 700 m depth. The net-inflow of Atlantic water is strongest in the uppermost 100 m.

Added in the text: The inflow of Atlantic water via the Central American Seaway (strongest net-inflow in the uppermost 100 m) is causing the highest salinities.

Reviewer's comment: Page 1945, line 14. Compare to other models e.g. Sijp et al. (2014)

Authors' response: Added in the text: Southern Ocean sinking occurs in the Ross Sea, similar to other Paleocene-Eocene simulations (Sijp et al., 2014), whereas the North Atlantic deepwater source is not produced in all models.

Reviewer's comment: Page 1946 lines 10 and 12: these to statements seem to be contradictory. First it is said that T, S control pCO2 then it is CO2 and nutrients.

Authors' response: Changed in the text to: While the general spacial distribution of pCO2 is mainly defined by temperature and salinity, the high pCO2 areas in the equatorial and coastal areas result from upwelling of high CO2 and nutrient rich waters from

mid ocean depth.

Reviewer's comment: Page 1948, line 1: Does the model include prognostic iron? If so, does it include sediment fluxes. Describe here or in model description section.

Authors' response: The model includes prognostic iron in the water column and the sediment pore water. Iron is exchanged between the two pools.

Added in the model description: The sediment module is based on Heinze and Maier-Reimer (1999) and Heinze et al. (1999). It basically calculates the same tracers as the water column model. The solid components of the sediment comprise opal, CaCO3, organic carbon and chemically inert dust (referred to from here onwards as “clay”). The liquid sediment components (pore water tracer) are DIC, TA, PO4. O2, N2, NO3, Si(OH)4 and Fe. The tracer concentrations within the oceanic bottom layer and particularly the particle deposition from it determine the upper boundary for the sediment....

Reviewer's comment: Page 1949, line 9-10: Compare suboxic volume to modern. How does this affect the N cycle?

Authors' response: We added in the 'model parameter' table globally integrated numbers for N-fixation and denitrification.

Added in the text: Generally the phosphate and nitrogen cycle are treated very similar in the model, since they are connected via the Redfield ratio. However, bacterial processes such as nitrogen fixation and denitrification cause deviations between nitrate and phosphate distributions. In oxygen depleted zones denitrifying bacteria provide oxygen for remineralization, representing an additional sink for nitrate in these regions. In the Late Paleocene simulation intense OMZ's lead to low nitrate concentrations in the eastern boundary currents of the Atlantic and the Pacific. In global average the denitrification is ∼45 % higher than in the simulation for the pre-industrial climate state (Table 1). The increased denitrification originates from the low oxygen concentrations in mid ocean depth, which are induced by the reduced mixing of water masses during the Late Paleocene. Nitrogen fixation occurs in areas where the ratio of nitrate to phosphate is lower than the (constant stoichiometric) value of RN:P . This is primarily in the tropics, the North Pacific and the North Atlantic. Likewise, also nitrate fixation is higher in the Late Paleocene than in the pre-industrial climate state.

Reviewer's comment: Page 1950, line 8-9: "This indirectly : : :" Why? In the model of Schmittner et al. (2008, GBC) warmer temperatures lead to an increase in CaCO3 production and rain ratio. You may want to discuss the possible reasons for these different responses.

Authors' response: Schmittner and colleagues incorporated temperature-dependent growth characteristics of phytoplankton into their model. As a result the overall production increases, including calcite building organisms. However, the effect of ocean warming on primary production is not obvious (Pinsonneault et al., 2012). Even more unclear is the net effect on calcifiers, since calcifiers respond not only to the warming, but also to CO2 fertilization and an ocean acidification (not incorporated in Schmittner et al., 2008). Investigations show (Riebesell et al., 2001; Bellerby et al. 2008) a CO2 fertilization effect on rates of production of organic matter, but the magnitude of this stimulation on a global scale is quite uncertain (Gattuso & Hanssen 2011). Our model does not directly account for effects on the production due to warming or CO2 increase like the model of Schmittner et al., 2008 does. Instead, warming induced changes in the production in our model are primarily a result of the overturning circulation driven nutrient availability.

Reviewer's comment: Page 1951, line 15: I don't understand. I thought most POC was remineralized in the upper few hundred meters of the water column, and not at 400-1,000 m depths.

Authors' response: In our model POC is remineralized throughout the whole water column. The remineralization depth depends on the balance between particle sinking speeds and their rate of decay. We can not ultimately say in which depth the maximum

in aerobic and anaerobic remineralization of exported POC takes place, possibly in the upper several hundred meters. Nevertheless, the released nutrients and DIC are distributed in the water column to a depth of up to 1000 m.

Changed in the text to: In the vertical profile the maximum in DIC concentration around the equator, spreading from 400 to 1000 m depth (Figure 10), is related to biological processes. It marks the depth in which intense dissolution and denitrification of the exported particles takes place. The aerobic remineralization of POC is releasing DIC and consuming oxygen, while at the same time the dissolution of CaCO3 and the denitrification is increasing the TA at $\sim$1000 m depth (Figure 10).

Reviewer's comment: Page 1953, line 7: call Fig 12.

Authors' response: Corrected as suggested.

Reviewer's comment: Page 1954, lines 4-5: "Our model captures ... well" Please show results or remove statement.

Authors' response: We added the sediment core data of Panchuk et al., 2008 on Figure 12, for comparing our model results.

Reviewer's comment: Page 1955, line 1: again the strength of the different pumps is not shown, so either remove the statement or show it. Page 1955, lines 2-3: ditto

Authors' response: Changed to: The sluggish circulation affects the atmosphere–ocean exchange fluxes of CO2 by shifting its spatial patterns, i.e. uptake in the Indian and Southern Ocean compensates the CO2 outgassing of the Atlantic Ocean. Moreover, w e infer a reduced vertical transfer of carbon from surface to intermediate and deep waters due to the more stagnant circulation in comparison to pre-industrial conditions (Figure 4). Nevertheless, the enhanced ocean stratification is not prominent enough to prevent the supply of nutrients to surface waters and hence the global...

Reviewer's comment: Page 1956, lines 5-6: Why does the lower CO3:DIC ratio reduce the buffer capacity?

Authors' response: The lower surface ocean CO23- DIC ratio indicates a reduced carbonate buffer capacity because we have effectively less carbonate ions in the surface ocean. Consequently, if CO2 is added, less carbonate ions change to bicarbonate, but rather omega/pH is more directly decreased.

For clarification we changed the text to: The lower surface ocean CO32-:DIC ratio indicates a reduced carbonate buffer capacity and results in higher sensitivity towards additional CO2.

Reviewer's comment: Page 1956, lines 6-7: Why does the reduced CaCO3:opal ratio counteract?

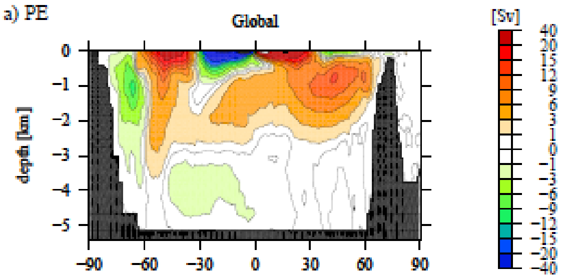
Authors' response: The reduced CaCO3:opal export ratio increases the buffer capacity in our simulation, because CaCO3 production consumes carbonate ions in the surface ocean.

Changed in the text to: Yet, the reduced CaCO3:opal export ratio counteracts this effect at least partially in our simulation, since effectively less carbonate is exported from the surface ocean.

Reviewer's comment: Fig. 9: plot zonally averaged data together with present day.

Authors' response: We added a zonal average plot for the Late Paleocene and pre-industrial.

Interactive comment on Clim. Past Discuss., 10, 1933, 2014.



Stream function of the MOC for the coupled (Late Paleocene) simulation usin concentration of 560 ppm (Heinemann 2009, dissertation).