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# Deglacial Changes in Ocean Dynamics and Atmospheric $CO_2$

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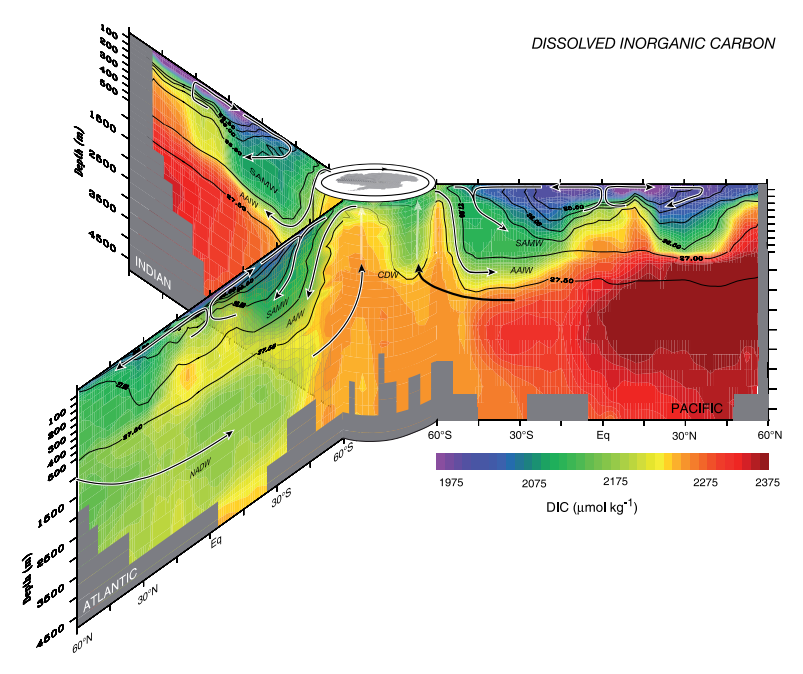


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# Effects of Changing Ocean Circulation on the Marine Carbon Cycle during the Paleocene-Eocene Thermal Maximum

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With 2 Figures

The Paleocene-Eocene Thermal Maximum (PETM) was a transient global warming event, which occurred 56 million years ago. During this period of abrupt environmental change the climate underwent a significant transformation within short geological timescales (<10 ka, Zeebe et al. 2009). The PETM is globally recorded in proxy-data by a negative $\delta^{13}C$ carbon isotope excursion and carbonate dissolution in the ocean, suggesting that the occurred warming was caused by massive carbon release. Despite several plausible hypotheses, the exact rate of carbon release and the ultimate location of the carbon source remain unknown. The deep ocean conditions must have been inhospitable to marine organisms, since PETM sediment records indicate a mass extinction of benthic foraminifera and vast dissolution of $CaCO_3$ sediments. Both, ocean circulation and marine biogeochemistry must have been affected by the carbon perturbation of the PETM.

Until now, however, modelling studies did not consider the changes in the ocean circulation together with the changes in ocean biogeochemistry. As ocean circulation state is the key in shaping the marine carbon cycle, the current interpretation of the PETM proxy record may be incomplete. To address this issue, we simulate the late Paleocene background climate and the onset of the PETM with the state of the art Earth System Model of the Max Planck Institute (MPI-ESM). The model has a horizontal resolution of ~3.5°. The atmospheric model is represented by 31 and the ocean model by 40 vertical levels. For the first time the onset of the PETM is simulated with a complex ESM, including a comprehensive ocean biogeochemistry model.

The late Paleocene background climate state is based on an atmospheric $CO_2$ concentration of 560 ppm, which is producing a global mean SST of ~24 °C (Heinze and Ilyina 2015). Unlike today, the main area of deep water formation is located in the Pacific and Indian sector of the Southern Ocean. Our model does not predict any deep water formation in the North Atlantic, which is consistent with proxy reconstructions (Tripati and Elderfield 2005, Thomas et al. 2003).

Starting from this already warmer background climate than present, we increase the atmospheric $CO_2$ concentration by 0.5 ppm $a^{-1}$ (equivalent to emission of 1 Gt C) over a period of 1300 years. Following the atmospheric $CO_2$ increase phase, the simulation is run for another 1700 years with fixed atmospheric $CO_2$ concentrations of 1173 ppm. Due to rising atmospheric $CO_2$, the global SST increases by 6 °C over the whole simulation period. The meridional temperature gradient flattens and the hydrological cycle intensifies, leading to in-

creased freshwater input in the deep water formation areas. As a consequence, the deep water formation is reduced and the vertical stratification of the ocean is increased (Fig. 1). Surface waters are facing low nutrient concentrations and reduced biological production because of weaker upwelling of nutrient rich waters. Consistent with recent boron isotope reconstructions (Penman et al. 2014), the surface ocean pH decreases by 0.28 in our simulation.

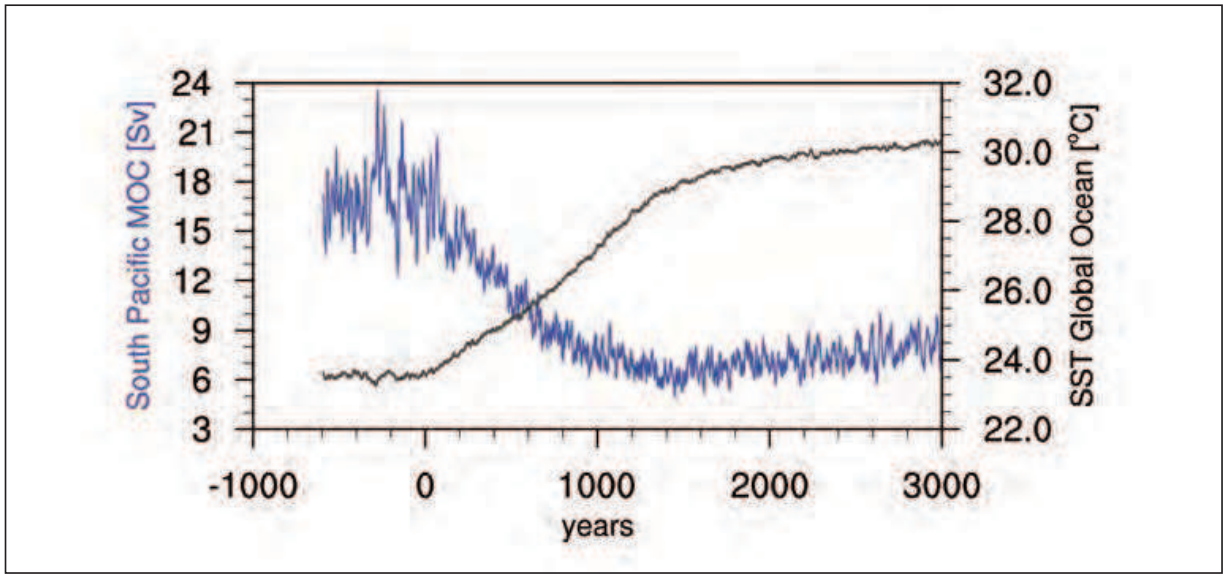


Fig. 1 Timeseries (10 year running mean) of the maximum MOC, below 1000 m depth in the South Pacific (blue line) and the SST (global, black line) for the PETM $CO_2$ emission scenario. Negative values on the x-axis correspond to the steady state in the control run.

Our results indicate that the significantly weakened deep-ocean ventilation is the key mechanism to reproduce the $CaCO_3$ dissolution pattern of the PETM, suggested by the proxy record. Transport of carbon to depth by physical processes is strongly reduced due to the increased ocean stratification. However, the increased respiration of organic matter and the accumulation of its remnants drive the deoxygenation and acidification of the mid and deep ocean instead. The reduced ocean ventilation causes the products of organic matter remineralization

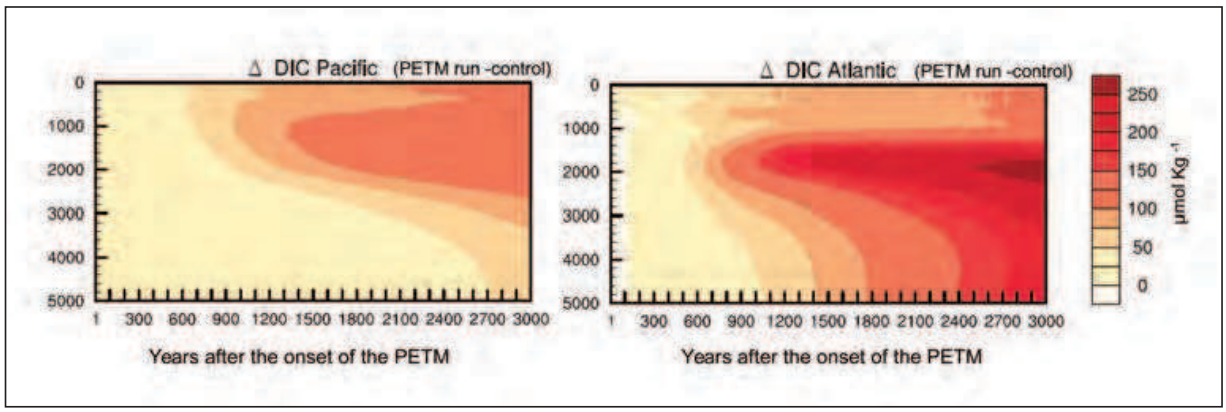


Fig. 2 Temporal evolution of anomaly (PETM run-control) in DIC concentrations, integrated over the whole Pacific (*left*) and Atlantic (*right*) basin.

(releasing $PO_4$, $CO_2$ and consuming $O_2$) to be trapped in intermediate waters (Fig. 2). Thereby carbon accumulates and triggers dissolution of $CaCO_3$ throughout the water column and the sediment. In terms of ocean acidification this long-term effect, occurring over timescales of several 1000 years, seems to be of high relevance also for future climate under rising $CO_2$.

In conclusion, our study highlights the role of changing ocean circulation on the carbon cycle during the PETM. Although we are focusing in our study on this warm period, similar processes could have played a crucial role during glacial cycles, controlling carbon exchange between surface and deep ocean.

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