



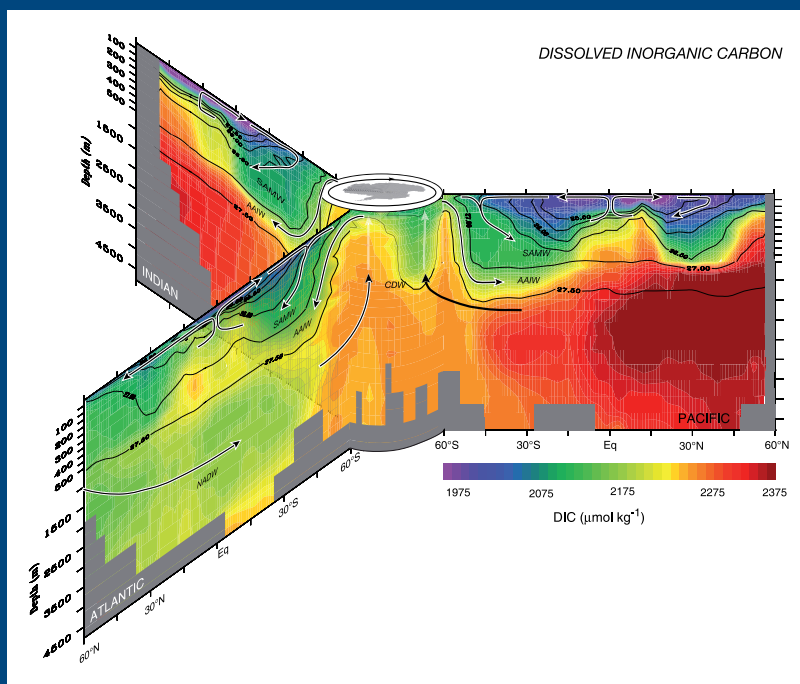
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Deglacial Changes in Ocean Dynamics and Atmospheric CO₂

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The Combined Effects of Changes in Ocean Chemistry, Biology, and Hydrodynamics on Alkalinity

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With 1 Figure

Seawater total alkalinity (TA; determined by the charge imbalance of the conservative ions in seawater) and total dissolved inorganic carbon (TCO₂; the sum of carbon species) control the variations of pCO₂ in seawater, which in turn directly determine the air – sea exchange of CO₂. Because TA and TCO₂ are conserved during mixing and are unaffected by changes in temperature and pressure (ZEEBE and WOLF-GLADROW 2001), they are key parameters of the marine carbonate system used as state variables in models of ocean biogeochemistry. Oceanic TA is altered by three main processes, being (i) changes in freshwater fluxes, such as precipitation/evaporation, riverine discharge of fresh water, ice growth and melting, (ii) production of CaCO₃ by calcifying organisms (e.g. coccolithophorids, corals, foraminifera) and CaCO₃ dissolution in the water column and deep-sea sediments; and (iii) production and remineralization of organic matter by microalgae. Increase in the surface ocean TA enhances the oceanic uptake of atmospheric CO₂, while decreasing TA lowers the oceanic capacity to take up and store carbon. Changes in seawater TA by a variety of mechanisms are thought to be responsible for modulating the variations of atmospheric CO₂ along glacial-interglacial timescales (e.g. RICKABY et al. 2010, KLEYPAS 1997, ARCHER and MAIER-REIMER 1994). Enhancement of TA has been proposed as a mean of deliberate manipulation of climate (KÖHLER et al. 2013, ILYINA et al. 2013a). Therefore, understanding the spatiotemporal distribution of TA changes is critical to grasp the oceanic capacity to uptake and store carbon. Furthermore, dissolution of CO₂ in seawater does not change TA, but may affect processes controlling its cycling. Hence, it is also interesting to study TA in the context of climate change, i. e. in a rising CO₂ ocean.

Projections of future climate change calculated within the 5th Phase of the Coupled Model Intercomparison Project (CMIP5) with the Max Planck Institute's Earth system model (MPI-ESM, GIORGETTA et al. 2013) will be presented. CMIP5 experiments examined here include a historical run covering the period 1850–2005 and three future climate change scenarios referred to as extended concentration pathways (ECPs) running from the year 2006 until 2300. These ECPs follow the standard RCP scenarios in terms of the achieved radiative forcing of 8.5, 4.5, and 2.6 W m⁻² by the end of the 21st century with simple stabilization assumptions for the atmospheric CO₂ concentrations made onwards. Such extended future climate change projections ran only in the low resolution model version (LR) of MPI-ESM driven by prescribed atmospheric CO₂ concentrations. The oceanic biogeochemistry component of MPI-ESM is the model HAMOCC (ILYINA et al. 2013b) which runs as a subroutine of the OGCM MPIOM. The horizontal resolution of the oceanic component of MPI-ESM-LR is about 1.5°.

The model HAMOCC simulates inorganic carbon chemistry (MAIER-REIMER and HASSELMANN 1987) and uses an extended NPZD-type description of marine biology (SIX and MAIER-REIMER 1996) in which phytoplankton and zooplankton dynamics depend on temperature, solar radiation, and co-limiting nutrients (phosphate, nitrate, iron, silicate). HAMOCC uses one phytoplankton type for primary production but separates two types of planktonic shell materials (opal and calcium carbonate shells, respectively), which are exported from the euphotic zone with different sinking rates. TA in the model is the sum of carbonate, borate alkalinities, and water dissociation products. TA is altered during production and dissolution of CaCO_3 . Dissolution of CaCO_3 is a function of the carbonate ion and the calcium ion concentrations, as well as temperature and pressure dependent stoichiometric constant, and is driven by the deviation from the saturation state. Biogenic calcite particles, produced in the euphotic zone, precipitate if seawater is supersaturated with respect to CaCO_3 and start dissolving if the water column or the sediment pore-water is undersaturated with respect to CaCO_3 . Seasonal growth of phytoplankton increases TA, while aerobic remineralization of organic matter decreases it. Additionally, TA is altered during denitrification. The model HAMOCC also includes a sediment module (HEINZE et al. 1999) which calculates formation and dissolution of sediments basically simulating the same biogeochemical processes as in the water column. Globally uniform weathering fluxes are prescribed over the simulation period.

Both the physical and the biogeochemical state of the oceans are undergoing major changes as a result of global warming and ocean acidification (IPCC 2013). These ongoing changes perturb fundamental mechanisms that act to modify TA in the ocean. Yet, resulting changes in TA are not intuitively projected. In our simulations, changes in the distribution of TA are calculated in response to the intensified hydrological cycle, reorganization of the circulation patterns, changes in biological processes and carbonate chemistry. Consistent with these, both positive and negative anomalies are projected in TA (Fig. 1). Because changes in TA are closely related to changes in salinity, TA anomalies at the surface resemble the patterns of salinity anomalies. Weaker correlation between anomalies in surface salinity and TA is found in the equatorial Pacific and in the Indian Ocean. These areas of the global ocean are characterized by higher primary production, including production of CaCO_3 , relative to other oceanic areas. In response to a decreased nutrients supply to the surface, the primary production and corresponding export production of organic matter and CaCO_3 is reduced. Furthermore, only rather small changes in salinity are projected in these regions of the ocean. Hence, changes in TA here are driven by changes in biological processes. In the subsurface and deep ocean, effects of changes in production and dissolution of CaCO_3 on changes in TA are not pronounced in our projections, as the ocean stays largely supersaturated with respect to CaCO_3 over the simulated time range. The contribution of carbonate dissolution becomes prominent on longer temporal scales (ILYINA and ZEEBE 2012). Additionally, reduced production of CaCO_3 due to ocean acidification can have a significant effect on the precipitation of CaCO_3 and thereby modify the global distribution of TA (e. g. ILYINA et al. 2009). Regionally, subsurface TA anomalies are also driven by changes in organic matter remineralization by respiration and denitrification.

In summary, we show that changes in seawater TA can modulate oceanic uptake of carbon. Furthermore, our results indicate that TA is projected to undergo changes, which should not be ignored when diagnosing the oceanic capacity to take up and store carbon in future projections, as well as in calculations of air-sea CO_2 exchange on glacial-interglacial time-

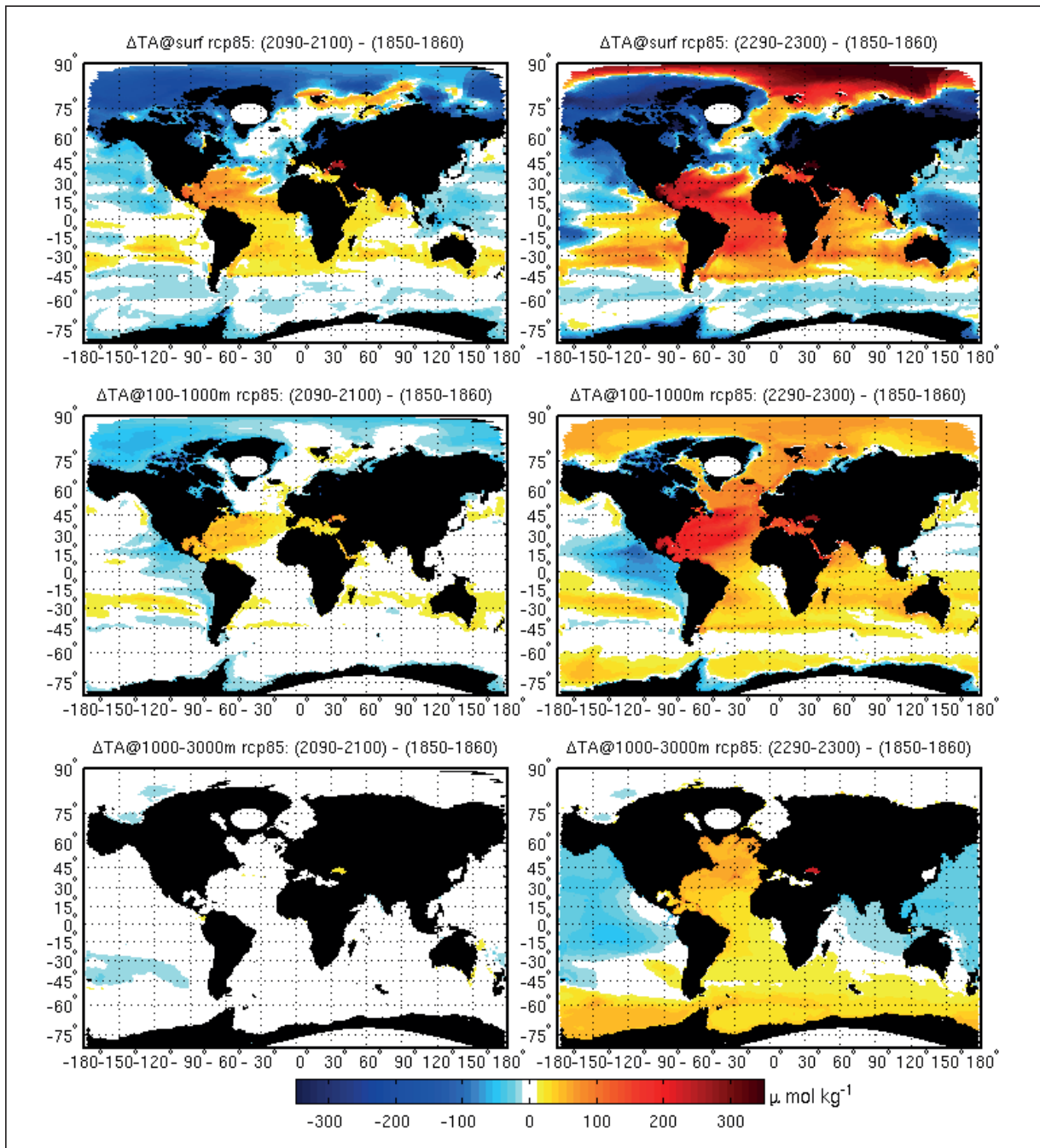


Fig. 1 Changes in TA $\mu\text{mol kg}^{-1}$ for the scenario RCP8.5 in 2090–2100 relative to 1850–1860 at the ocean surface, averaged over the upper 100–1000 m, and over the depth of 1000–3000 m.

scales. Finally, we show that changes in mixing/ventilation, production and dissolution of CaCO_3 , remineralization of organic matter by aerobic and anaerobic processes, and sedimentary fluxes act in concert to contribute to the projected changes in TA. Thus, these processes have to be included prognostically in modelling studies.

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