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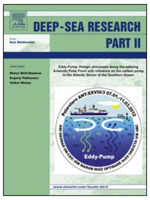

Temporal changes in ventilation and the carbonate system in the Atlantic sector of the Southern Ocean

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ABSTRACT

The Southern Ocean is the most important area of anthropogenic carbon (C_{ant}) uptake in the world ocean, only rivalled in importance by the North Atlantic Ocean. Significant variability on decadal time-scales in the uptake of C_{ant} in the Southern Ocean has been observed and modelled, likely with consequences for the interior ocean storage of C_{ant} in the region, and implications for the global carbon budget. Here we use eight cruises between 1973 and 2012 to assess decadal variability in C_{ant} storage rates in the southeast Atlantic sector of the Southern Ocean. For this we employed the extended multiple linear regression (eMLR) method. We relate variability in DIC (dissolved inorganic carbon) storage, which is assumed to equal anthropogenic carbon storage, to changes in ventilation as observed from repeat measurements of transient tracers. Within the Antarctic Intermediate Water (AAIW) layer, which is the dominant transport conduit for C_{ant} into the interior ocean, moderate C_{ant} storage rates were found without any clear temporal trend. In Subantarctic Mode Water (SAMW), a less dense water mass found north of the Subantarctic Front and above AAIW, high storage rates of C_{ant} were observed up to about 2005 but lower rates in more recent times. The transient tracer data suggest a significant speed-up of ventilation in the summer warmed upper part of AAIW between 1998 and 2012, which is consistent with the high storage rate of C_{ant}. A shift of more northern C_{ant} storage to more southern storage in near surface waters was detected in the early 2000s. Beneath the AAIW the eMLR method as applied here did not detect significant storage of C_{ant}. However, the presence of the transient tracer CFC-12 all through the water column suggests that some C_{ant} should be present, but at concentrations not reliably quantifiable. The observed temporal variability in the interior ocean seems at a first glance to be out of phase with observed surface ocean C_{ant} fluxes, but this can be explained by the time delay for the surface ocean signal to manifest itself in the interior of the ocean.

1. Introduction

Since the Industrial Revolution, mankind has accelerated changes to the global carbon cycle by releasing huge amounts of carbon dioxide (CO_2) into the atmosphere, primarily from fossil fuel combustion and land use change. This is particularly harmful because a higher CO_2 level in the atmosphere will enhance the greenhouse effect of the atmosphere, leading to a rise in global temperature and other changes. Fortunately for global climate, the global ocean is taking up a significant portion (~30%) of the excess CO_2 from the atmosphere (~155 Pg C through year 2010 (Khatiwala et al., 2013;)) thus diminishing some of the forcing of the greenhouse effect. The Southern Ocean has taken up, and stored, disproportionate amounts of anthropogenic CO_2 (e.g. Mikaloff Fletcher et al., 2006; Khatiwala et al., 2009; Takahashi et al., 2009; Lenton et al., 2013; Frölicher et al., 2015). Khatiwala et al. (2009) estimated the uptake south of 44°S to be 0.7 Pg C yr^{-1}, i.e. about one third of the total oceanic sink. A study by Le Quéré et al. (2007) identified a trend of decreasing CO_2 uptake by the Southern Ocean, suggested to be caused by enhanced vertical transfer upwelling of CO_2-charged subsurface water into the surface layer. An investigation including more recent data from the surface ocean spotted the end of this decreasing trend of CO_2 uptake in 2002 and by 2012 a full reinvigoration of the CO_2 uptake had taken place (Landschützer et al., 2015). Apparently, the dynamics of the carbon

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cycle of the Southern Ocean contain some surprising aspects which requires close observation.

Uptake of CO_2 occurs at the air-sea interface. As a consequence, the greatest part of anthropogenic CO_2 is stored in the surface layer from where it can be transported to the ocean interior. The uptake capacity of the oceanic surface layer will decrease further into the future due to the Revelle effect and climate feedbacks (e.g Sabine and Tanhua, 2010) although biological carbon draw-down might be more important in the future (Hauck and Völker, 2015). The large CO_2 storage capacity of the global oceans is not well exploited because of the sluggish mixing and water exchange between the surface water, where the uptake occurs, and the interior layers. In this respect the Southern Ocean is a vital region because of the close connection between all water layers, thus to a certain extent bridging a sluggish-mixing gap. In the Weddell Sea, very dense surface waters on the extensive shelves store anthropogenic CO_2, which is brought into the deep water layers during formation of Weddell Sea Bottom Water and Antarctic Bottom Water (AABW). This dense AABW, enriched in anthropogenic CO_2, leaves the Weddell Gyre thus contributing to global CO_2 sequestration on a centennial timescale. Ventilated AABW populates a major part of the bottom layers of the global oceans. Within the Weddell Gyre, anthropogenic CO_2 has been detected all through the water column (van Heuven et al., 2011; Huhn et al., 2013; Pardo et al., 2014).

A different, and more important, pathway of CO_2 sequestration in the Southern Ocean is via the formation of Antarctic Intermediate Water (AAIW) and Subantarctic Mode Water (SAMW) in the northern part of the ACC. Surface water moving northward absorbs anthropogenic CO_2, and subducts to form AAIW and SAMW that are separated from the surface layer near the Subantarctic Front (SAF). This is the main region for uptake and sequestration of anthropogenic CO_2 in the Southern Ocean (Caldeira and Duffy, 2000; Sabine et al., 2004; Gruber et al., 2009). Ventilated and anthropogenic CO_2-charged AAIW occupies the greater portion of the intermediate water layers of the Southern Hemisphere and even reaches further northward to subtropical latitudes of the Northern Hemisphere. Climate change in the form of modified wind tracks may via sea-ice export lead to changes in AAIW formation (Abernathey et al., 2016) and its uptake of anthropogenic CO_2.

The Antarctic Circumpolar Current (ACC) is the major circulation feature of the Southern Ocean and the brawniest current in the world oceans. Its high relevance for global climate is self-evident: This pertains to transport and distribution of heat and fresh water as well as chemical compounds and gases. The ACC is not a continuous, eastward flowing, uniform current, but rather consists of several strong jets alternating with calmer regions (Whitworth and Nowlin, 1987; Orsi et al., 1995; Sokolov and Rintoul, 2009). The jets are typically associated with oceanographic fronts – from north to south we distinguish (see Strass et al., 2017) the Subantarctic Front (SAF), the Antarctic Polar Front (APF), the Southern Polar Front and the Southern Boundary, the latter of which is the transition to the Weddell Gyre to the south (see Fig. 1).

The surface layer of the Southern Ocean consists of Antarctic Surface Water (AASW) in the south and Subantarctic Surface Water (SASW) in more northern regions. The divide between the two is formed by the APF. South of the front, the surface water reaches the freezing point in winter and sea ice is formed. North of the APF, a strong gradient of increasing surface temperature is observed towards the subtropical region. Between the APF and the SAF extends a belt of minimum surface salinities, which result from excess precipitation in this region and sea ice melt, and coin the salinity minimum that characterizes the AAIW after its subduction at the SAF. North of the SAF, deep mixed layers in winter generate Subantarctic Mode Water (e.g. McCartney, 1977; Tsuchiya et al., 1994). From the north, North Atlantic Deep Water (NADW) joins the ACC off South America; it can be identified as a wedge of water characterized by high salinity, high oxygen and low nutrient, CFC-12 and DIC content at roughly 3000–4000 m depth shoaling from north to south (e.g. Whitworth and Nowlin, 1987; Whitworth et al., 1991). NADW forms the main supply of the Lower Circumpolar Deep Water (LCDW), the most voluminous water mass of the ACC. The other part of the Circumpolar Deep Water, namely Upper Circumpolar Deep Water (UCDW), is characterized by an oxygen minimum and high nutrient concentrations compared to the NADW due to their longer circulation path from its origin in the deep waters of the Indian and Pacific oceans (Peterson and Whitworth, 1989; Tsuchiya et al., 1994).

South of the ACC lies the Weddell Gyre, an elongated cyclone with clockwise flow (Fig. 1). A main connection between the ACC to the north and the Weddell Gyre to the south is the inflow of Circumpolar Deep Water (CDW) into the gyre. The CDW is the dominant water and heat supply to the Weddell Gyre from which almost all other water masses in the gyre are derived. The CDW is locally known as Warm Deep Water (WDW) because of its temperature maximum below the surface layer. Within the Weddell Gyre, WDW is upwelled into the surface layer, thus shaping the features of the latter (Gordon and Huber, 1990). Along the margins, WDW also feeds into deep and bottom water formation leading to AABW as one of the mixing components, together with denser surface waters.

Ventilation processes, such as occurring in the Weddell Sea and northern ACC, are instrumental for the uptake and sequestration of anthropogenic CO_2. The degree of ventilation, as well as changes in ventilation, has major impacts on the future trend of the mass balance of oceanic CO_2. The transport of surface water into the ocean interior can be investigated by using transient tracers such as CFCs and SF_6. These tracers provide time information about ventilation processes since the atmospheric growth rate of these tracers is also reflected in the tracer concentration in the ocean interior due to the gas exchange between the atmosphere and the ocean (e.g. Fine, 2011). This time information can then be used to determine current states of ventilation and in the case of transient tracer time series also changes or trends in ventilation.

There are still many unknowns related to the ocean carbon cycle, particularly to that of the Southern Ocean, and its anthropogenic perturbation. Part of this is caused by the scarcity of data in this remote and relatively inaccessible region. High spatial variability in different processes appears to have a major impact on the uptake of CO_2 from the atmosphere, as recently demonstrated by Landschützer et al. (2015). Water mass formation occurs in restricted areas of the Southern Ocean, which accentuates the dependence on smaller-scale processes and its variability for water mass formation. Here we utilize new CO_2 and auxiliary data along a section at 10 °E crossing the ACC between 44° and 53°S near the northern boundary of the Weddell Gyre. Combining these new data with data that have been collected in the previous decades we investigate changes in local and regional dissolved inorganic carbon (DIC). This enables insights as to the anthropogenic impact on the carbon cycle. Implications for the wider Southern Ocean are discussed. This effort constituted part of the field work of the “Eddy-Pump” project (Wolf-Gladrow, 2013; Strass et al., 2017), and targeted measurements of biogeochemical and physical processes in and around Southern Ocean eddies, although this study focuses on temporal changes along a meridional section. The CO_2 uptake around eddies has been addressed in a separate study (Jones et al., 2016). For a more detailed description of the hydrography including water masses and fronts at the 10 °E section, see Strass et al. (2017).

2. Material and methods

2.1. Cruise data

In this work we analyze transient tracer and carbonate system data from the South Atlantic/Southern Ocean, focusing on a section along 10 °E between 44 and 53 °S. Not only is this an area of formation of AAIW, it is also relatively well sampled for carbonate system variables