Decadal Changes in Ventilation and Anthropogenic Carbon in the Intermediate Depths of the Arctic Ocean

Balamuralli Rajasakaren[1], Emil Jeansson[1], Are Olsen[2], Toste Tanhua[3], Truls Johannessen[2] and W.M. Smethie Jr.[4]

1 Uni Research Climate, Bjerknes Centre for Climate Research, Bergen, Norway
2 Geophysical Institute, University of Bergen, Bjerknes Centre for Climate Research, Bergen, Norway
3 Helmholtz Centre for Ocean Research Kiel, GEOMAR, Kiel, Germany
4 Lamont-Doherty Earth Observatory, Palisades, NY 10964-8000, USA

BJERKNES CENTRE for Climate Research

Introduction

Studies have shown that the Arctic Ocean contributes significantly to the deep water of the Nordic Seas and overflow water (e.g. Karstensen et al., 2005; Tanhua et al., 2005) and hence, important for global circulation and climate. The Arctic Ocean also plays an important role in the global carbon cycle (McGuire et al., 2009).

"Ventilation" refers to the pathways by which surface waters are brought into the deep ocean. The "age of a water mass" refers to the time the water was last in contact with the atmosphere and gas-exchange took place before it is brought into the deep ocean.

Tanhua et al. (2009) conducted a study on the ventilation of the Arctic Ocean and provided mean ages and anthropogenic carbon (C_{ant}) concentrations at different depths. The Arctic Ocean anthropogenic carbon inventory was calculated to be 2.5 – 3.3 PgC (normalized to 2005) [~2% of global ocean inventory]. Yet most of this research was focused more on the general ventilation in the Arctic Ocean and to infer deep-water pathways. Here we investigate the decadal variability of the surface to intermediate waters in the Eurasian and Amerasian basins, which represent the Atlantic layers and intermediate depth waters where changes are observed and the associated evolution in anthropogenic carbon.

Data and Analysis

The data have been divided into basins: the data for the Eurasian region is divided into the two sub-basins the Nansen and the Amundsen Basins, while the Amerasian region is divided into the Makarov Basin, the West Canadian Basin and the South Canadian Basin (Figure 1).

The data used in this study comes from the recently updated GLODAPv2 (Global Ocean Data Analysis Project version 2) dataset (Key et al., 2015; Olsen et al., 2016). We have used all available Arctic Ocean data of the parameters: potential temperature, salinity and CFC-12 for the depth range 200 – 2000 m for this study. 2015 data was kindly shared by W.M. Smethie Jr.

CFC-12 data used to calculate age and C_{ant} using the transit time distribution (TTD) method (e.g., Waugh et al., 2006), where mixing is represented by the mean age (Γ) and the width of the TTD (Δ).

In our analysis, the mean surface saturation of CFC-12 (<20m) in both the Eurasian and Amerasian Basins was found to be 87% (±6% represent the 95% confidence intervals, which we will use for our uncertainty analysis). Δ/Γ ratio was also found to be lower in the Arctic (He et al., submitted) and thus, we have used a value of Δ/Γ ratio equals 0.8 in our analysis instead of unity as used by Tanhua et al., (2009). We have used Δ/Γ ratio equals 0.6 and 1 as the limits in our uncertainty analysis.

Anthropogenic CO_2 in the atmosphere has increased by about 16%, 21% and 21% from 1987 – 1990s, 1990s – 2000s and 2010 – 2015 respectively.

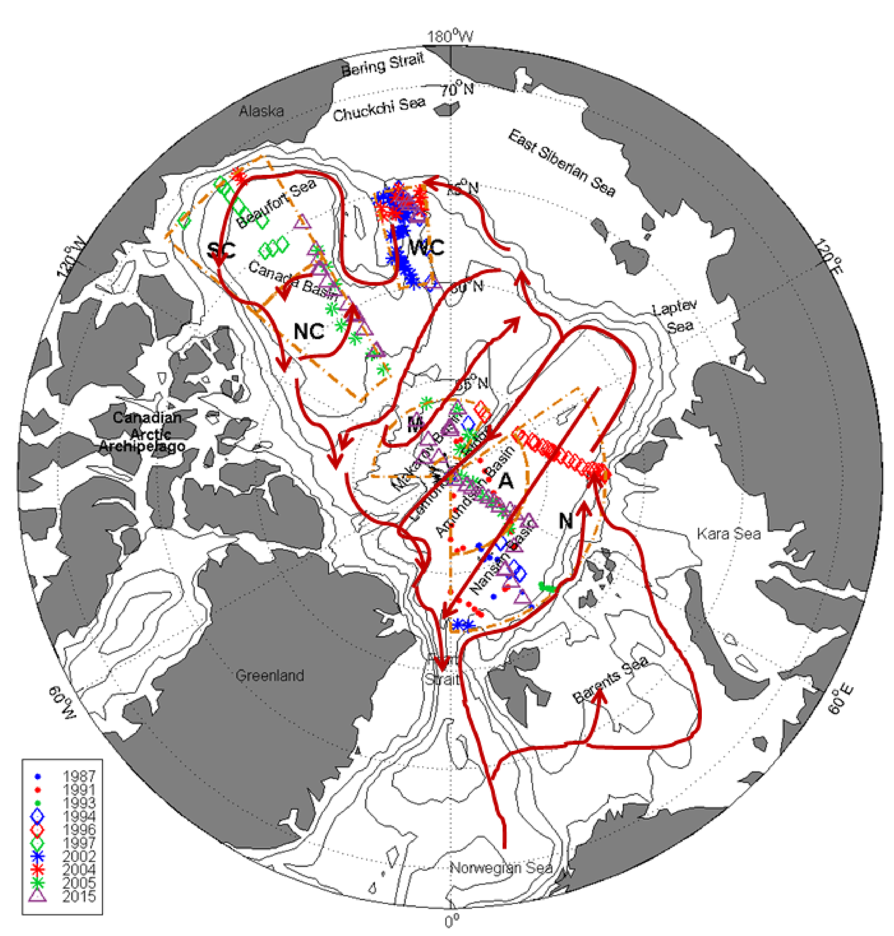

Figure 1: Map of Arctic Ocean with stations used for this analysis. The basins marked on the map: N, Nansen basin; A, Amundsen basin; M, Makarov basin; NC, North Canadian basin; SC, South Canadian basin; WC, West Canadian basin. The brown arrows indicate the schematic circulation of the main pathways of the Atlantic layer plus upper Polar Deep Water (depth range 200 – 1700 m) (following Bluhm et al., 2015)

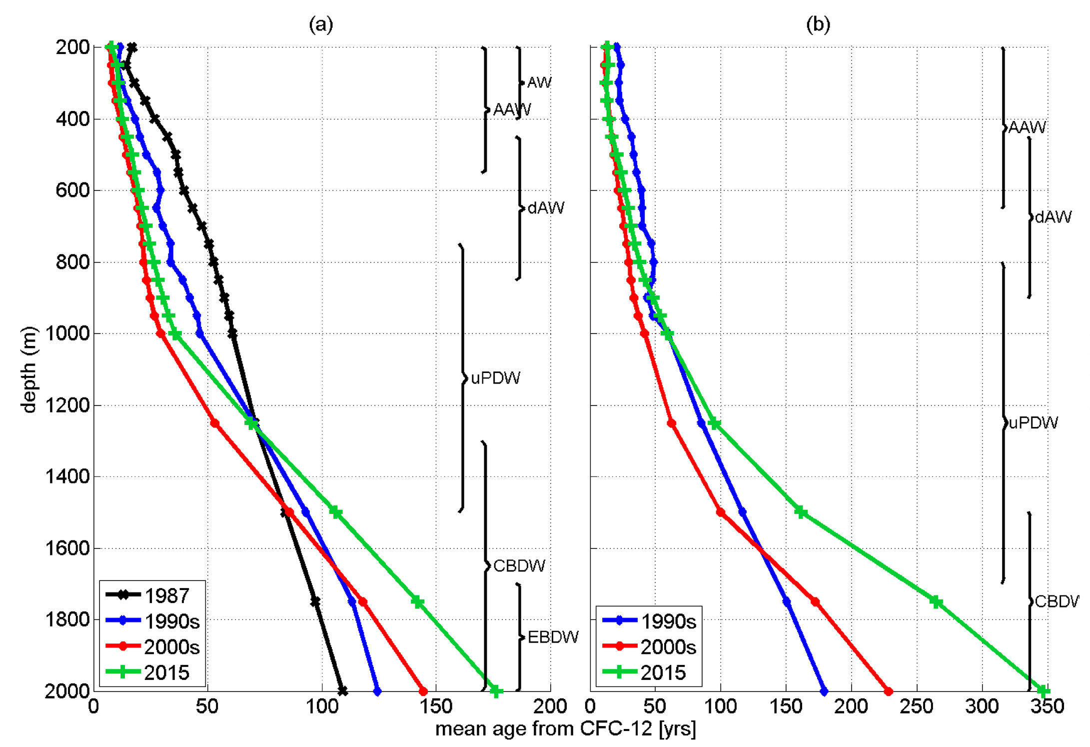

Figure 2: Decadal mean profiles of mean age in the Eurasian (a) and Amerasian (b) basins between 200 m and 2000 m for 1987 (black line), the 1990s (blue line), the 2000s (red line) and 2015 (green line).

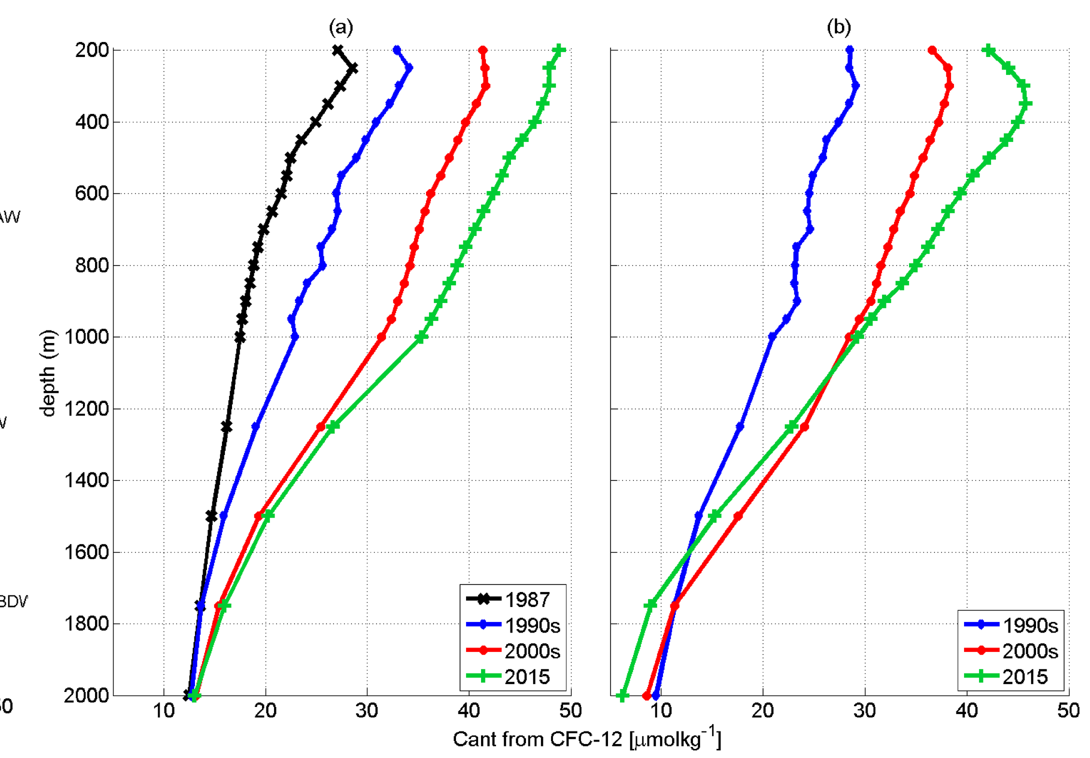

Figure 3: Decadal mean profiles of anthropogenic carbon in the Eurasian (a) and Amerasian (b) basin between 200 and 2000 m for 1987 (black line), the 1990s (blue line), the 2000s (red line) and 2015 (green line).

Ventilation and Mean Ages

Despite the limitations in the amount of data available for each of the decades, Figure 2a shows that there is increased ventilation in the Eurasian Basin in the upper 1600 m from 1987 to the 2000s, where mean ages have become younger by about 50 years. The upper 900 m in the 2015 profile shows very similar ages (about 1-4 years older waters) when comparing to the 2000s decade. Below 900 m to 2000 m, we see a change to older waters of about 5-30 years.

In the Amerasian basin (Figure 2b), there is ventilation in the upper 1600 m from the 1990s to the 2000s, with a decrease in mean age of up to 35 years. Waters are about 50 years older at 2000 m depth in the 2000s decade compared to the 1990s. Similar to the Eurasian basin, the 2015 profile shows similar mean ages to the 2000s in the upper 700 m (change of about 1-4 years). Below 700 m to 2000 m, we see older waters, up to about 120 years, in the Amerasian basin.

Anthropogenic Carbon

For the upper 1000 m in the Eurasian basin (Figure 3a), we see that C_{ant} increases about 5-7 µmol kg^{-1} from 1987 to the 1990s, increases about 7-10 µmol kg^{-1} from the 1990s to the 2000s and increases about 4-8 µmol kg^{-1} from the 2000s to 2015. Below 1000 m, there is an increase in C_{ant}, but the magnitude of the increase is smaller and C_{ant} is about 13 µmol kg^{-1} at 2000 m depth for all time periods.

The Amerasian basin (Figure 3b) also shows an increase of about 7-10 µmol kg^{-1} from the 1990s to the 2000s. Below 1000 m, the increase in C_{ant} is much smaller in magnitude and below 1700 m, there is a decrease in C_{ant}. From 2000s to 2015, however, we see an increase in C_{ant} of about 1-8 µmol kg^{-1} between 200 – 1000 m and a decrease in C_{ant} of about 1-8 µmol kg^{-1} between 1000 – 2000 m.

Uncertainties

There are uncertainties resulting from the Δ/Γ ratio and surface saturation of tracers. In general, surface saturation uncertainty estimates (Figures 4a, 4b, 5a and 5b) are smaller compared to the uncertainty estimates in the Δ/Γ ratio (Figures 4c, 4d, 5c and 5d).

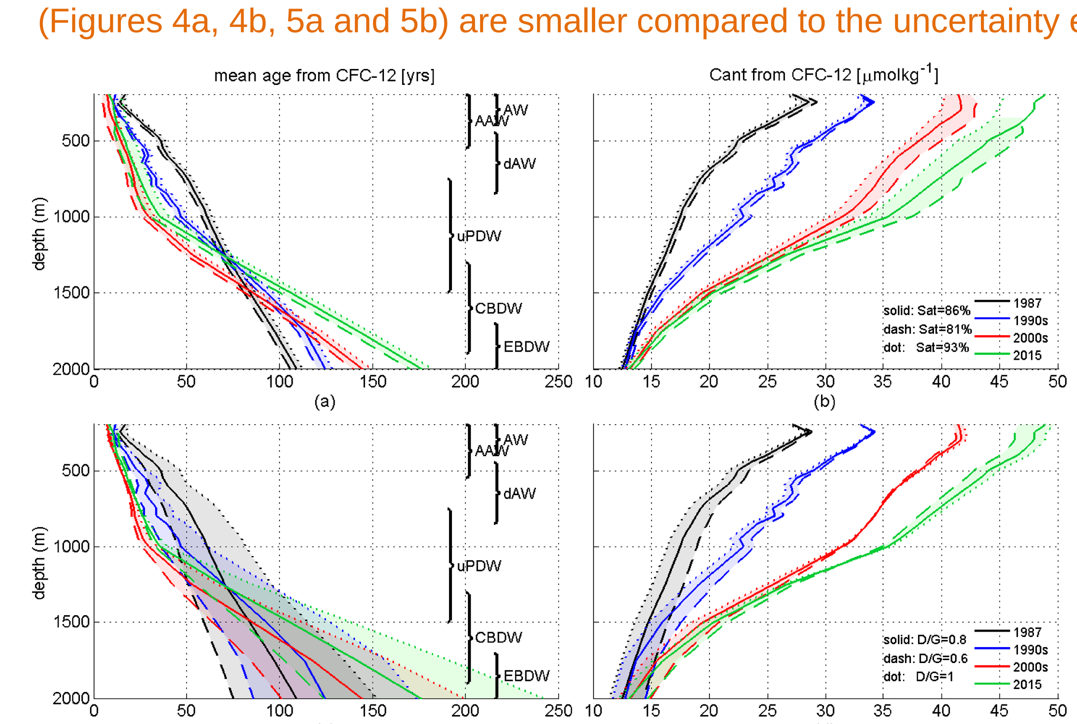

Figure 4: Decadal mean profiles of mean age (a,c) and anthropogenic carbon (b,d) in the Eurasian basin similar to Figures 2a and 3a. Additional shaded areas represent uncertainty estimates. 81% and 93% saturation estimates are shown in dashed and dotted lines (a, b) while Δ/Γ ratio of 0.6 and 1 are shown in dashed and dotted lines (c, d).

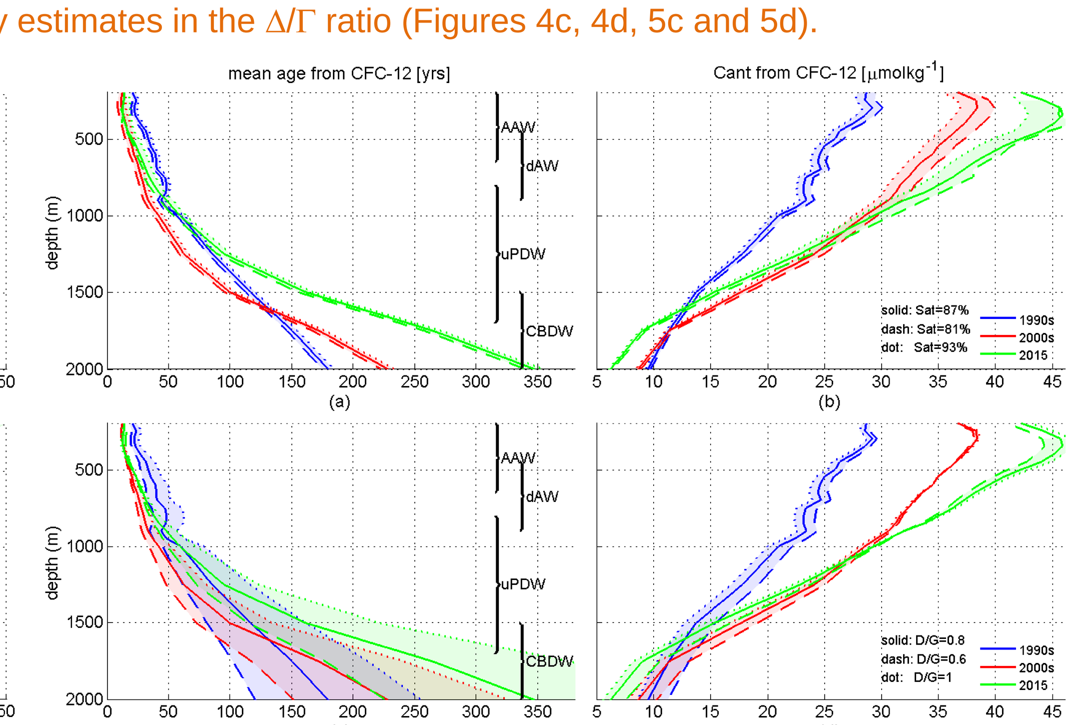

Figure 5: Decadal mean profiles of mean age (a,c) and anthropogenic carbon (b,d) in the Amerasian basin similar to Figures 2b and 3b. Additional shaded areas represent uncertainty estimates. 81% and 93% saturation estimates are shown in dashed and dotted lines (a, b) while Δ/Γ ratio of 0.6 and 1 are shown in dashed and dotted lines (c, d).

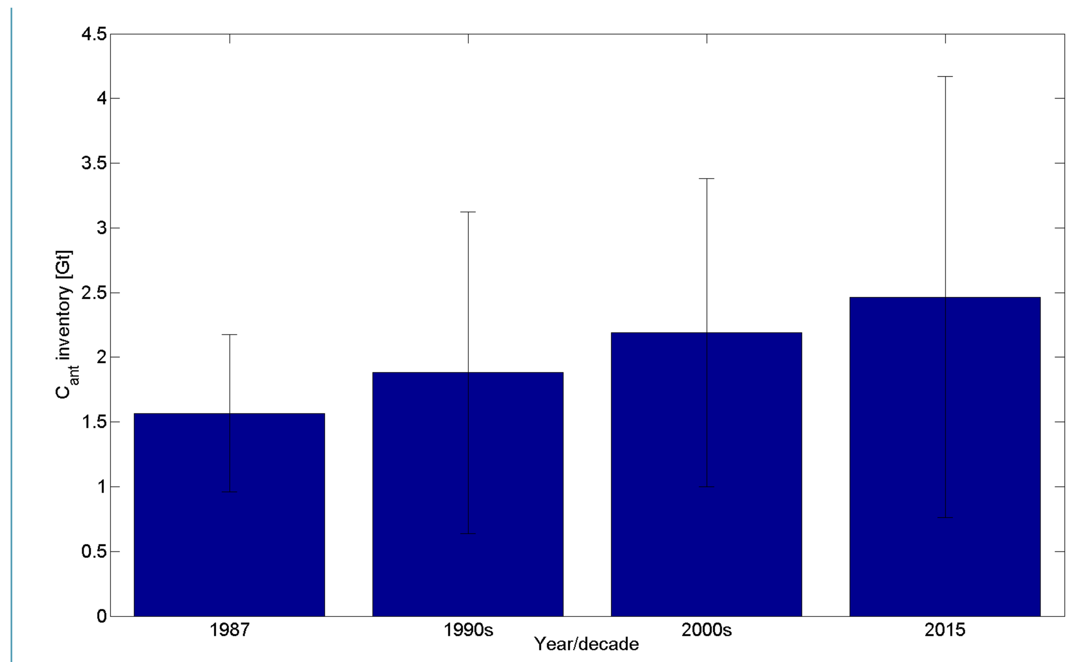

Figure 6: Inventory of anthropogenic carbon in the intermediate waters of the Arctic Ocean with standard deviation as error bars.

C_{ant} Inventory

It is not possible to calculate C_{ant} inventories of Amerasian and Eurasian basins separately, due to the lack of volume knowledge on these basins.

C_{ant} inventory in the intermediate waters of the Arctic Ocean is increasing (Figure 6) at a decadal rate of about 0.3 Gt C $decade^{-1}$. The rate of increase is 20%, 16% and 13% from 1987 – 1990s, 1990s – 2000s and 2000s – 2015 respectively.

C_{ant} Specific Inventory

For the specific inventory, a statistically significant increase of about 0.6 ± 0.3 mol C m^{-2} yr^{-1} (p-value < 0.01) was found. This range agrees with 0.6 – 0.9 mol C m^{-2} yr^{-1} given by Ericson et al., (2014).

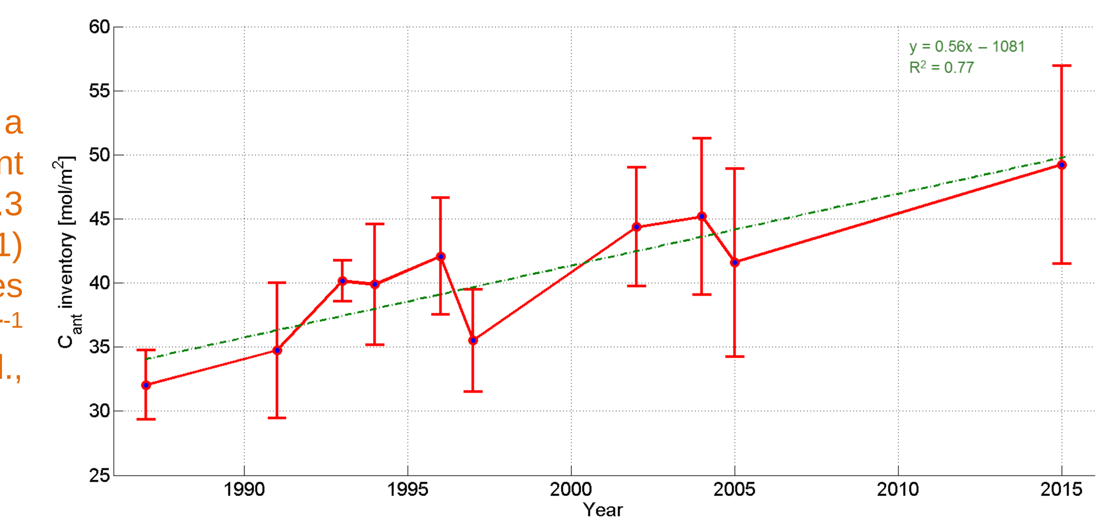

Figure 7: Specific Inventory of anthropogenic carbon in the intermediate waters of the Arctic Ocean with standard deviation as error bars. Line of best linear fit is drawn in green.

Summary

1. There is increased ventilation in the upper 1600 m from 1987 to the 2000s in the Eurasian basin. Changes in particular are seen in the dAW and uPDW water masses becoming younger, likely connected to (Fram Strait Branch Water and) Barents Sea Branch Water. 2015 seems to show constant age/older waters.
2. There is increased ventilation in the upper 1600 m from 1990s to 2000s in the Amerasian basin (possibly ventilation from Eurasian basin and Pacific waters from Bering Strait) while 2015 seems to show constant age/older waters.
3. Anthropogenic carbon has increased in the intermediate waters of both the Eurasian and Amerasian basins from 1987/1990s to the 2000s and to 2015.
4. Increasing ventilation in the intermediate waters has lead to a similar C_{ant} increase as expected from atmospheric CO_2 rise alone as a result of decreasing water mass age in the 1990s and 2000s. However, a smaller C_{ant} increase than expected from atmospheric CO_2 rise alone was observed in 2015.
5. C_{ant} inventory has increased through the decades in the intermediate waters of the Arctic but the rate of change has decreased from 1987 to 2015.

References

- Bluhm, B.A., Kosobokoba, K.N. and Carmack, E.C. (2015), A tale of two basins: An integrated physical and biological perspective of the deep Arctic Ocean, Progress in Oceanography, 139, 89–121.
- Ericson, Y., Ulfsbo, A., van Heuven, S., Kattner, G. and Anderson, L.G. (2014). Increasing carbon inventory of the intermediate layers of the Arctic Ocean. Journal of Geophysical Research Oceans, 119, 2312–2326.
- He, Y.-C., Tjiputra, J., Langehaug, H.R., Jeansson, E., Gao, Y., Schwinger, J., Olsen, A. (submitted). A model-based evaluation of the Transit-time Distribution (TTD) method for inferring anthropogenic carbon storage in the ocean.
- Karstensen, J., Schlosser, P., Wallace, D. W. R., Bullister, J.L. and Blindheim, J. (2005). Water mass transformation in the Greenland Sea during the 1990s, Journal of Geophysical Research,110, C07022.
- Key, R.M., Olsen, A., van Heuven, S., Lauvset, S.K., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishi, M., Pérez, F.F., and Suzuki, T. (2015). Global Ocean Data Analysis Project, Version 2 (GLODAPv2), ORNL/CDIAC-162, NDP-093, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee.
- McGuire, A.D., Anderson, L.G., Christensen, T.R., Dallimore, S., Guo, L., Hayes, D.J., Heimann, M., Lorenson, T.D., Macdonald, R.W. and Roulet, N. (2009). Sensitivity of the carbon cycle in the Arctic to climate change. Ecological Monographs, 79(4), 523–555.
- Olsen, A., Key, R.M., van Heuven, S., Lauvset, S.K., Velo, A. and others (2016). The Global Ocean Data Analysis Project version 2 (GLODAPv2) – an internally consistent data product for the world ocean, Earth System Science Data, 8, 297-323.
- Tanhua, T., Olsson, K.A. and Jeansson, E. (2005). Formation of Denmark Strait Overflow Water and its hydro-chemical composition, Journal of Marine Systems, 57, 264–288.
- Tanhua, T., Jones, E.P., Jeansson, E., Jutterström, S., Smethie Jr, W.M., Wallace, D.W. and Anderson, L.G. (2009). Ventilation of the Arctic Ocean: Mean ages and inventories of anthropogenic CO_2 and CFC-11, Journal of Geophysical Research,114, C01002.
- Waugh, D.W., Hall, T. M., McNeil, B. I., Key, R., and Matear, R. J. (2006). Anthropogenic CO_2 in the oceans estimated using transit time distributions, Tellus B, 58, 376–389.

CONTACT INFORMATION
Allégaten 70, NO-5007 Bergen | Tel: +47 55 58 98 03 | Fax: +47 55 58 43 30 | post@bjerknes.uib.no | **bjerknessenteret.no**

This work is supported by the Norwegian Research Council through the project VENTILATE (229791).

UNIVERSITY OF BERGEN | uni Research | NERSC Nansen Center, Bergen | HAVFORSKNINGSINSTITUTTET INSTITUTE OF MARINE RESEARCH