Supplement of Ocean Sci., 16, 1559–1576, 2020
https://doi.org/10.5194/os-16-1559-2020-supplement

Ocean Science
Open Access

Supplement of

Variability and stability of anthropogenic CO_2 in Antarctic Bottom Water observed in the Indian sector of the Southern Ocean, 1978–2018

Léo Mahieu et al.

Correspondence to: Léo Mahieu (leo.mahieu@liverpool.ac.uk) and Claire Lo Monaco (claire.lomonaco@locean.upmc.fr)

Quality control

A careful quality control was performed for all the data used in this study. This exercise consists in comparing data collected in the deep ocean (where minimum variability is expected). In the Southern Ocean, the bottom layer is generally excluded for quality control since AABW is a relatively young water mass that accumulated anthropogenic CO_2 (e.g. Lo Monaco et al., 2005b; van Heuven et al. 2011; Pardo et al., 2017; Murata et al., 2019) and that can be impacted by recent climate changes (e.g. McKee et al., 2011; Purkey and Johnson, 2012; Gordon et al., 2015; Menezes et al., 2017; Gruber et al., 2019b).

Most of the data used in our study (up to 2011) underwent a secondary quality control performed by a group of experts (following a first quality control by the data provider) in the framework of the international data syntheses GLODAPv1 (Key et al., 2004) , CARINA (Key et al., 2010; Lo Monaco et al., 2010) and GLODAPv2 (Olsen et al., 2016). The objective of the secondary quality control is to ensure the consistency of the dataset at the global scale. To this aim, the deep measurements from two cruises are compared at crossovers, then a global inversion is used in order to suggest adjustments that minimize the differences. The data collected after 2011 did not go through a secondary quality control, but they were qualified by the data provider by comparison to the most recent international data synthesis. In order to ensure the consistency of the data used in this study, we detailed below the comparison of measurements obtained in old deep waters characterized by a maximum in C_T (approximately 2000 m-3000 m). Note that the data were compared as a function of neutral density.

OISO dataset

The adjustments applied to the OISO dataset (Table S1) are those recommended in GLODAPv2 (https://glodapv2.geomar.de/). Figure S1 shows the consistency of our dataset at the two OISO stations where samples were collected down to the bottom: the OISO-ST11 in the Antarctic Zone (56.5° S-63° E, station investigated in this study) and the OISO-ST17 in the Subtropical Zone (30° S-66° E). This figure shows a limited number of measurements that are out of the range of tolerance, but one has to keep in mind that interannual (or multi-annual) variations may occur and this calls for great care before applying an adjustment. This is the case for A_T data that did not get an adjustment in GLODAP because this could not be argued safely due to the limited number of data in this region. Adding new data over the period 2012-2018, A_T values obtained between late 1998 and 2004 appear clearly lower than those collected since 2009 both in the Antarctic zone and the Subtropical zone (Figure S1). This is surprising, but there is no reason to believe that the data are biased since Certified Reference Materials (CRMs) were used during all OISO cruises, and the instrument and data processing were the same during the first OISO cruise in January/February 1998 (showing A_T values close to the mean in Figure S1) and the following cruises. For these reasons, no adjustment was applied to the A_T data from OISO (Table S1).

Table S1. Adjustments applied to the data

Cruise name	Expocode	C_T (+)	A_T (+)	S (+)	O_2 (x)	NO_3 (x)
GEOSECS	318M19771204	-23	0	0	1	1
INDIGO I	35MF19850224	-10	-10	0	1	1
INDIGO III	35MF19870114	-6	-4	0	1	1.02

OISO-1	35MF19980121	0	0	0	1	1
OISO-3	35MF19981205	0	0	0	0.99	1
OISO-5	35MF20000719	0	0	0	1	1.06
OISO-6	35MF20010103	0	0	-0.009	1	1
OISO-8	35MF20020104	6.6	0	0	1	1
OISO-11	35MF20040103	0	0	-0.022	1.01	1
OISO-18	35MF20091219	0	0	0	1	1
OISO-19	35MF20110114	0	0	0	1	1
OISO-21	35MF20120125	0	0	0	1	1
OISO-23	35MF20140106	0	0	0	1	1
OISO-26	35MV20161008	0	0	0	1	1
OISO-27	35MV20170105	0	0	0	1	1
OISO-28	35MV20180105	0	0	0	1	1

The adjustment is either additive (+) or multiplicative (x)

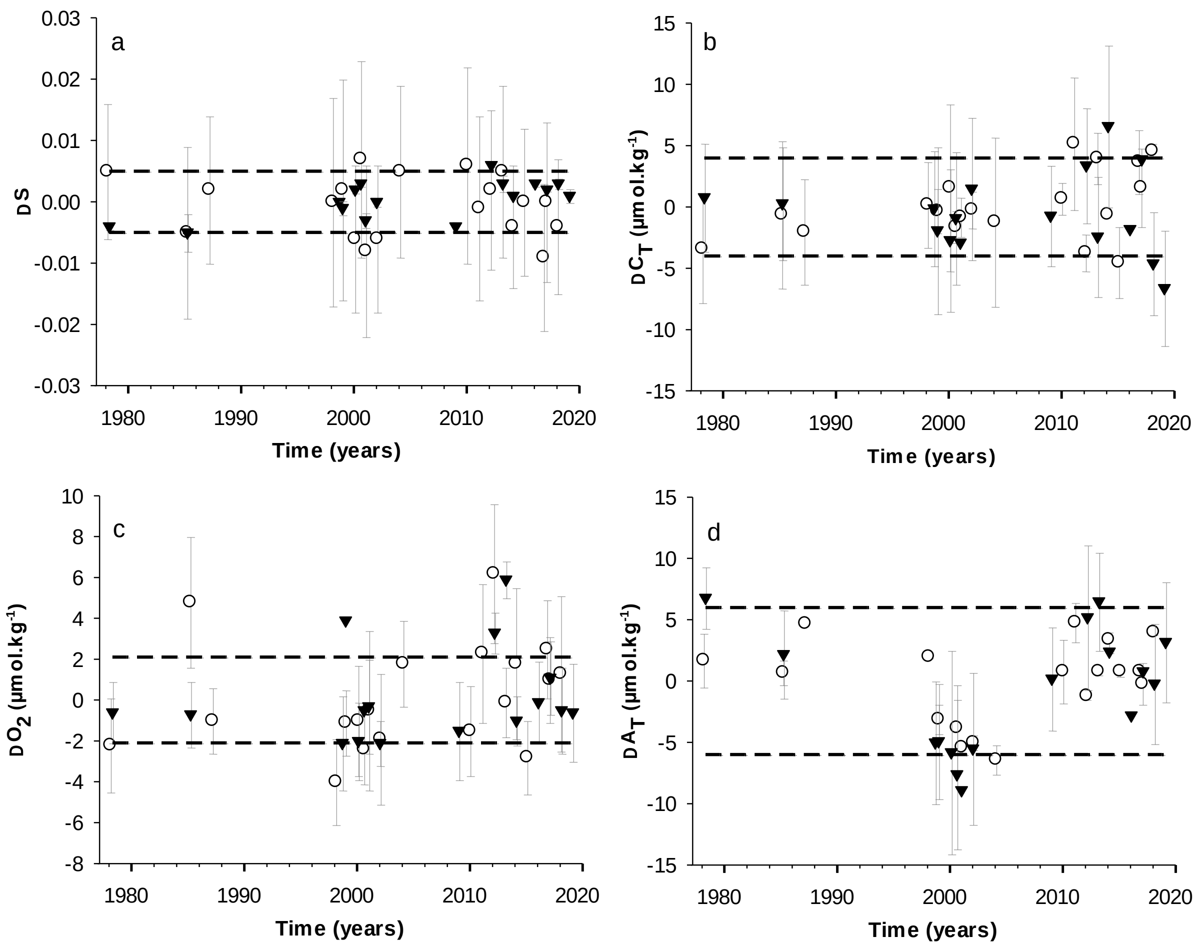

Figure S1. Mean differences observed in deep waters between the measurements obtained during one cruise and the mean value calculated over the full period at the two sites where samples were collected down to the bottom: the OISO-ST11 in the Antarctic Zone (black triangles) and the OISO-ST17 in the Subtropical Zone (open circles). The dashed lines indicate the limits for considering an adjustment (as defined in the CARINA and GLODAP syntheses).

The data plotted here are adjusted as recommended in the GLODAPv2 synthesis (for cruises in 1978-2011), except for A_T in 1987 (INDIGO-3 cruise) that was adjusted by -4 µmol.kg^{-1}. The OISO data for 2012-2019 were not adjusted (Table S1).

Historical datasets GEOSECS and INDIGO

The historical data from GEOSECS and INDIGO were first qualified in GLODAPv1 (Key et al., 2004), then in CARINA (Lo Monaco et al., 2010) and GLODAPv2 (Olsen et al., 2016). Biases are common in historical datasets because no reference material was used, notably for A_T and C_T. The offsets evaluated for the Indian leg of GEOSECS (conducted in 1977-1978) in the framework of the first international data synthesis GLODAP were further confirmed with the following syntheses CARINA and GLODAPv2. For the INDIGO cruises, a good agreement also exists among the three data syntheses, with the exception of the adjustment recommended for A_T data. For the INDIGO-1 cruise (conducted in 1985), we applied the A_T correction recommended in GLODAPv2 (-10 µmol.kg^{-1}) because the corrected data appear consistent with our dataset (Fig. S1d). Note that this adjustment is close to the one applied in GLODAPv1 (-6 µmol.kg^{-1}), while the A_T correction in CARINA (-16 µmol.kg^{-1}) was probably biased due to the comparison with the OISO cruises conducted between 1998 and 2004 (Fig. S1d). For the INDIGO-3 cruise (conducted in 1987), we believe that the adjustment recommended for A_T in GLODAPv2 (-8 µmol.kg^{-1}) could be biased due to a possible decrease in A_T in the deep ocean at high latitudes. Indeed, the original A_T data from the INDIGO-3 cruise in 1987 appear consistent with data from the 1970s (south of 61° S) and until 1996 for data collected north of 61° S (Fig. S2, Table S2, Fig. S3), then the difference increase with time. For this reason, the former recommendation from GLODAPv1 and CARINA for no adjustment (in reason of the lack of available observations in this region for robust comparison) is consistent with most of the data until 1996, whereas the GLODAPv2 adjustment is mainly consistent with data collected since 1998. In order to reduce the potential bias that could result from either over-adjusting the data (GLODAPv2 recommendation) or not adjusting the data (GLODAPv1 and CARINA recommendations), and because most of the crossovers collected north of 61° S before 1998 suggest a small positive offset, we applied an intermediate adjustment of -4 µmol.kg^{-1} (the impact on C_{ant} is +2 µmol.kg^{-1}).

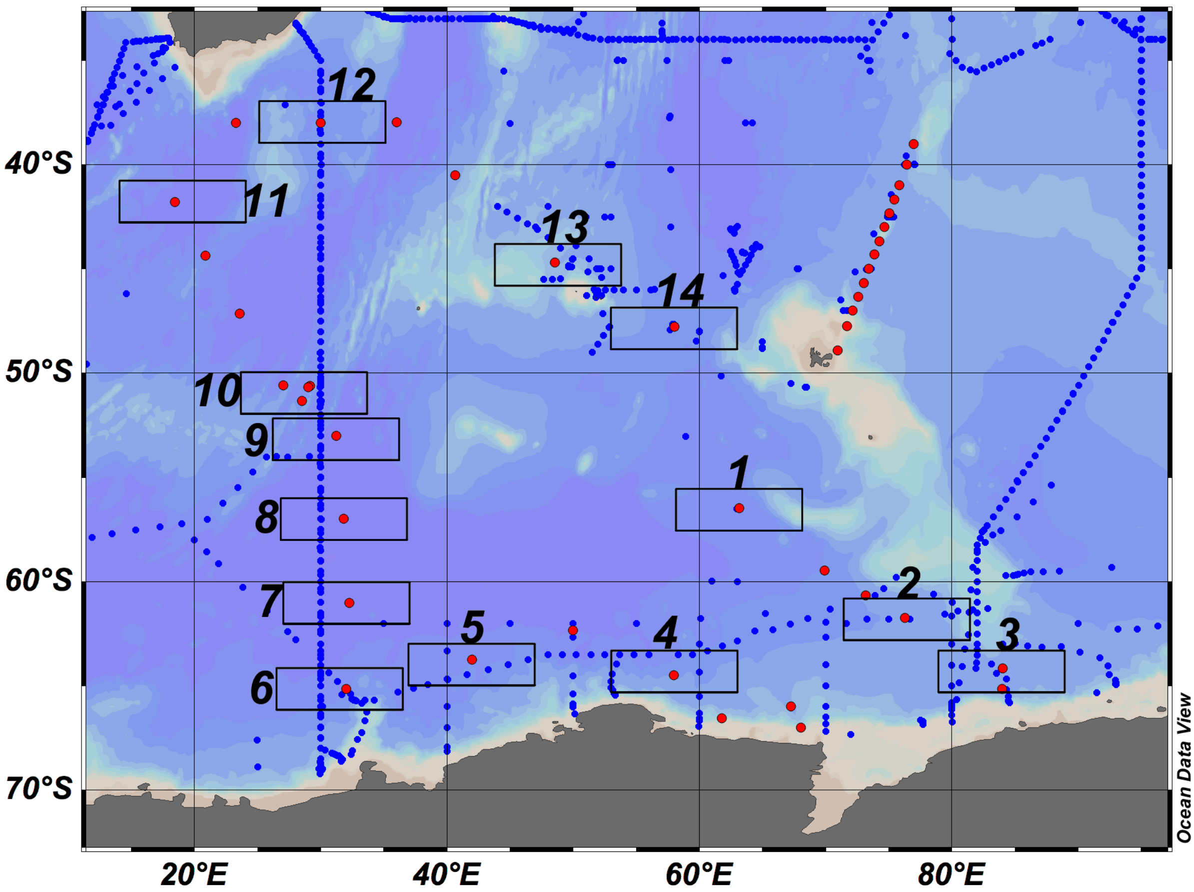

Figure S2. Map locating the 14 crossovers with the INDIGO-3 cruise used for the quality control of A_T data. INDIGO-3 stations are in red, the other cruises are in blue.

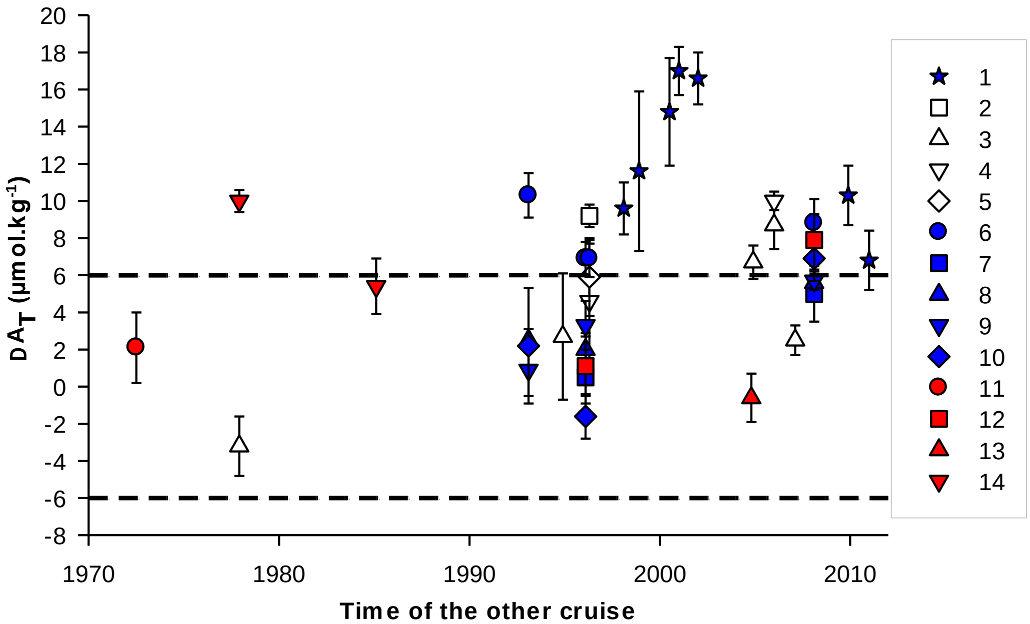

Figure S3. Differences in A_T observed in deep waters at the 14 crossovers with the INDIGO-3 cruise (Figure S2, Table S2). A positive difference means that A_T from INDIGO-3 (uncorrected data) is higher than A_T from the other cruise (corrected data). The color code indicates the latitude range: north of 50° S in red, 50° S-61° S in blue, south of 61° S in white.

Table S2. Mean differences (and standard deviation) in A_T (µmol.kg^{-1}) observed in deep waters (2000 m-4000 m) at the 14 crossovers with the INDIGO-3 cruise shown in Figure S3.

Expocode	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
316N19720718											**+2.1** (±1.9)			
318M19771204			**-3.2** (±1.6)											**+10.0** (±0.6)
35MF19850224														**+5.4** (±1.5)
35MF19930123						**+10.3** (±1.2)		**+2.5** (±0.6)	**+0.9** (±1.4)	**+2.2** (±3.1)				
316N19941201			**+2.7** (±3.4)											
35MF19960220						**+6.9** (±0.9)	**+0.5** (±1.4)	**+2.0** (±0.9)	**+3.3** (±1.3)	**-1.6** (±1.2)		**+1+1** (±1.6)		
320619960503		**+9.2** (±0.6)		**+4.6** (±3.1)	**+5.9** (±2.1)	**+6.9** (±1.0)								
35MF19980121	**+9.6** (±1.4)													
35MF19981205	**+11.6** (±4.3)													
35MF20000719	**+14.8** (±2.9)													
35MF20010103	**+17.0** (±1.3)													
35MF20020104	**+16.6** (±1.4)													
74DI20041103													**-0.6** (±1.3)	
09AR20041223			**+6.7** (±0.9)											
09AR20060102			**+8.7** (±1.3)	**+10.0** (±0.5)										
33RR20070204			**+2.5** (±0.8)											
33RR20080204						**+8.8** (±0.5)	**+5.0** (±1.5)	**+5.6** (±0.4)	**+5.7** (±0.5)	**+6.9** (±0.6)		**+7.9** (±2.2)		
35MF20091219	**+10.3** (±1.6)													
35MF20110114	**+6 .8** (±1.6)													

Data are from GLODAPv2 with adjustments applied, except for INDIGO-3 (uncorrected data). The differences are calculated following the CARINA and GLODAPv2 procedures (Key et al., 2010, Olsen et al., 2016). A positive difference means that A_T from INDIGO-3 is higher than A_T from the other cruise.

References

Gordon, A. L., Huber, B. A. and Busecke, J.: Bottom water export from the western Ross Sea, 2007 through 2010, Geophys. Res. Lett., 42(13), 5387–5394, https://doi.org/10.1002/2015GL064457, 2015.

Gruber, N., Landschützer, P. and Lovenduski, N. S.: The Variable Southern Ocean Carbon Sink, Annu. Rev. Mar. Sci., 11(1), 159–186, https://doi.org/10.1146/annurev-marine-121916-063407, 2019b.

Key, R. M., Kozyr, A., Sabine, C. L., Lee, K., Wanninkhof, R., Bullister, J. L., Feely, R. A., Millero, F. J., Mordy, C. and Peng, T. H.: A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), Glob. Biogeochem. Cycle, 18(4), GB4031, https://doi.org/10.1029/2004GB002247, 2004.

Key, R. M., Tanhua, T., Olsen, A., Hoppema, M., Jutterström, S., Schirnick, C., van Heuven, S., Kozyr, A., Lin, X., Velo, A., Wallace, D. W. R. and Mintrop, L.: The CARINA data synthesis project: introduction and overview, Earth System Science Data, 2(1), 105–121, https://doi.org/10.5194/essd-2-105-2010, 2010.

Lo Monaco, C., Metzl, N., Poisson, A., Brunet, C. and Schauer, B.: Anthropogenic CO2 in the Southern Ocean: Distribution and inventory at the Indian-Atlantic boundary (World Ocean Circulation Experiment line I6), J. Geophys. Res. Oceans, 110(C6), https://doi.org/10.1029/2004JC002643, 2005b.

Lo Monaco, C., Álvarez, M., Key, R. M., Lin, X., Tanhua, T., Tilbrook, B., Bakker, D. C., Van Heuven, S., Hoppema, M. and Metzl, N.: Assessing the internal consistency of the CARINA database in the Indian sector of the Southern Ocean, Earth Syst. Sci. Data, 2(1), 51–70, https://doi.org/10.5194/essd-2-51-2010, 2010.

McKee, D. C., Yuan, X., Gordon, A. L., Huber, B. A. and Dong, Z.: Climate impact on interannual variability of Weddell Sea Bottom Water, J. Geophys. Res. Oceans, 116(C5), https://doi.org/10.1029/2010JC006484, 2011.

Menezes, V. V., Macdonald, A. M. and Schatzman, C.: Accelerated freshening of Antarctic Bottom Water over the last decade in the Southern Indian Ocean, Sci. Adv., 3(1), e1601426, https://doi.org/10.1126/sciadv.1601426, 2017.

Murata, A., Kumamoto, Y. and Sasaki, K.: Decadal-Scale Increase of Anthropogenic CO2 in Antarctic Bottom Water in the Indian and Western Pacific Sectors of the Southern Ocean, Geophys. Res. Lett., 46(2), 833–841, https://doi.org/10.1029/2018GL080604, 2019.

Olsen, A., Key, R. M., van Heuven, S., Lauvset, S. K., Velo, A., Lin, X., Schirnick, C., Kozyr, A., Tanhua, T., Hoppema, M., Jutterström, S., Steinfeldt, R., Jeansson, E., Ishii, M., Pérez, F. F. and Suzuki, T.: The Global Ocean Data Analysis Project version 2 (GLODAPv2) – an internally consistent data product for the world ocean, Earth Syst. Sci. Data, 8(2), 297–323, https://doi.org/10.5194/essd-8-297-2016, 2016.

Pardo, P. C., Tilbrook, B., Langlais, C., Trull, T. W. and Rintoul, S. R.: Carbon uptake and biogeochemical change in the Southern Ocean, south of Tasmania, Biogeosciences, 14(22), 5217–5237, https://doi.org/10.5194/bg-14-5217-2017, 2017.

Purkey, S. G. and Johnson, G. C.: Global Contraction of Antarctic Bottom Water between the 1980s and 2000s, J. Clim., 25(17), 5830–5844, https://doi.org/10.1175/JCLI-D-11-00612.1, 2012.

van Heuven, S. M. A. C., Hoppema, M., Huhn, O., Slagter, H. A. and de Baar, H. J. W.: Direct observation of increasing CO2 in the Weddell Gyre along the Prime Meridian during 1973–2008, Deep Sea Res. Part II Top. Stud. Oceanogr., 58(25), 2613–2635, https://doi.org/10.1016/j.dsr2.2011.08.007, 2011.