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Supplement of

Transport and storage of anthropogenic C in the North Atlantic Subpolar Ocean

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1 Supplement

2 S1. Evaluation of the proxy proposed by Zunino et al. (2014) in ORCA05-PISCES

3 Zunino et al. (2014) proposed a novel proxy to evaluate processes governing the long term
4 changes of Cant transport in the northern region of the North Atlantic subpolar gyre. This
5 proxy (T_{Cant}°) was computed from the intensity of the meridional overturning circulation
6 (MOC) times the difference of averaged-Cant concentrations between the northward flow of
7 warm and saline upper ocean waters, rich in Cant, and the southward return flow of colder
8 and fresher waters across a section (noted $\Delta[Cant]$, Eq. (S1)). In this region, the MOC
9 intensity was computed in density coordinates to remove depth overlaps between its upper
10 and lower limbs (Marsh et al., 2005; Lherminier et al., 2007). It was calculated as the
11 integration of volume transport from Greenland to Portugal and from bottom to each density
12 level. Maximum negative value corresponds thus to the net southward transport of the lower
13 MOC; the absolute value of this estimate corresponds to the intensity of the MOC (MOC_{σ} in
14 Eq. (S1)). In the model, the proxy (${}^mT_{Cant}^{\circ}$) was evaluated from monthly simulations over the
15 period 2002-2010.

16

$$17 \quad {}^mT_{CANT}^{\circ} = MOC_{\sigma} \Delta[C_{ANT}] \quad (S1)$$

18

19 T_{Cant}° was defined by Zunino et al. (2014) as the proxy of the diapycnal component of the
20 advective transport of Cant across the OVIDE section. It could be used in the model if (1) the
21 diapycnal transport of Cant (${}^mT_{Cant}^{diap}$) is the major mechanism driving changes in Cant
22 advective transport across the OVIDE section and if (2) T_{Cant}° is a good proxy of ${}^mT_{Cant}^{diap}$.

23

24 S1.1. Is ${}^mT_{Cant}^{diap}$ the major mechanism driving the ${}^mT_{CANT}^{adv}$ variability?

25 In the offline approach, the simulated advective transport of Cant ($[{}^mT_{Cant}^{adv}]^{offline}$) was
26 decomposed in three components along the Greenland-Portugal OVIDE section (Eq. (S2)) to
27 compare with results from Zunino et al. (2014). The approach was initially developed by
28 Bryden and Imawaki (2001) to study heat transport and was recently adapted by Zunino et al.
29 (2014) for Cant advective transport (${}^mT_{Cant}^{adv} = [{}^mT_{Cant}^{adv}]^{offline}$). Application of this approach to
30 monthly model output allowed to infer (i) the isopycnal transport of Cant across the OVIDE
31 section, noted ${}^mT_{Cant}^{iso}$, (ii) the diapycnal transport of Cant (${}^mT_{Cant}^{diap}$), related to the
32 overturning circulation and (iii) the net transport of Cant (${}^mT_{Cant}^{net}$), related to the arctic mass
33 balance (Lherminier et al., 2007).

34

$$35 \quad \left[{}^m T_{Cant}^{adv} \right]^{offline} = {}^m T_{Cant}^{adv} = {}^m T_{Cant}^{net} + {}^m T_{Cant}^{diap} + {}^m T_{Cant}^{iso} \quad (S2)$$

36

37 The decomposition of the advective transport of Cant across the Greenland-Portugal OVIDE
38 section yielded 2002-2010 mean values of diapycnal, isopycnal and net transport of Cant of
39 $178 \pm 42 \text{ kmol s}^{-1}$, $-97 \pm 24 \text{ kmol s}^{-1}$ and $13 \pm 9 \text{ kmol s}^{-1}$ respectively. The sum was equal to
40 ${}^m T_{Cant}^{adv}$ and amounts to $94 \pm 43 \text{ kmol s}^{-1}$. It's coherent with values computed online from 5
41 day averages ($90 \pm 44 \text{ kmol s}^{-1}$). Both estimates (online and offline) are strongly correlated
42 ($r=0.94$, $p\text{-value} = 0.00$; $r^2 = 0.89$, Fig. S1a). In general, the model results were lower than
43 those obtained from observation-based assessments (Table S1). However and as expected, the
44 diapycnal component drives a large northward transport of Cant-rich waters across the
45 section. It is partially compensated by the isopycnal component, yielding a negligible net
46 transport (Fig. S4a). Moreover, the correlation between ${}^m T_{Cant}^{adv}$ and each transport
47 component (${}^m T_{Cant}^{diap}$, ${}^m T_{Cant}^{iso}$ and ${}^m T_{Cant}^{net}$) was only significant with the diapycnal
48 component ($r = 0.75$, $p\text{-value} = 0.00$ from all simulations; $r = 0.89$, $p\text{-value} = 0.00$ from June
49 simulations; Fig.S1a). The diapycnal component explain from 60% (full model output over
50 OVIDE period) to 78% (June outputs) of ${}^m T_{Cant}^{adv}$ variability. These results attest that the
51 variability of the ORCA05-PISCES advective transport of Cant is controlled by those of the
52 diapycnal component, which validates the first condition to be satisfied in order to use the
53 proxy in the model.

54

55 SI.2. Is T_{Cant}° a good proxy of ${}^m T_{Cant}^{diap}$?

56 The mean value of T_{Cant}° derived from model output is higher by $155 \pm 57 \text{ kmol s}^{-1}$ compared
57 with ${}^m T_{Cant}^{diap}$, while the difference between the proxy and the diapycnal component estimated
58 by Zunino et al. (2014) is only of 22 kmol s^{-1} . In the model, T_{Cant}° is not equal to ${}^m T_{Cant}^{diap}$.
59 This curiosity is probably due to the parametrizations of the two quantities. ${}^m T_{Cant}^{\circ}$ is in fact a
60 proxy of diapycnal transport of Cant based on the assessments of the MOC magnitude times
61 ΔC_{ant} between both limbs of the MOC (Eq. (S1)) whereas ${}^m T_{Cant}^{diap}$ (Eq. (S2)) is a direct
62 estimation using Cant concentration times velocity of each grid level. The underestimation of
63 the MOC magnitude and ΔC_{ant} by the model is not as large as those detected on the volume
64 transport (Fig. 5) and the Cant concentration (Fig. 6) in Sect. 3.1. This implies that the
65 difference between T_{Cant}° from model output and T_{Cant}° from OVIDE data set (Table S1) is
66 not as large as the model-data differences obtained for T_{Cant}^{diap} . In the model, T_{Cant}° also

67 presents a seasonal cycle with an amplitude higher than 100 kmol s^{-1} , in phase (opposite) with
68 those observed on $\text{MOC}\sigma$ and on ΔCant (Figs. S1b to S1c). This seasonal organization is not
69 detected on ${}^m\text{T}_{\text{Cant}}^{\text{diap}}$ and ${}^m\text{T}_{\text{Cant}}^{\text{adv}}$ (Fig. S1). This is confirmed by the small correlation
70 obtained between the proxy and ${}^m\text{T}_{\text{Cant}}^{\text{diap}}$ ($r = 0.18$, $p\text{-value} = 0.04$) or between the proxy and
71 ${}^m\text{T}_{\text{Cant}}^{\text{adv}}$ ($r = 0.33$, $p\text{-value} = 0.00$) over the full period (2002-2010). It should be noted that the
72 correlation between ${}^m\text{T}_{\text{Cant}}^{\circ}$ and ${}^m\text{T}_{\text{Cant}}^{\text{diap}}$ from June simulations ($r=0.66$, $p\text{-value} = 0.03$) is
73 comparable with the observations. This is not observed for those estimated between ${}^m\text{T}_{\text{Cant}}^{\circ}$
74 and ${}^m\text{T}_{\text{Cant}}^{\text{adv}}$ ($r = 0.35$, $p\text{-value} = 0.29$). These comments refute thus the second condition to
75 use the estimator to disentangle the effect of both circulation and Cant accumulation
76 variability on the Cant transport variability.

77
78 **Table S1:** Model-data comparison over the period covered by OVIDE cruises (2002-2010).
79 Average and standard deviation (SD) for observation-based estimates (column 2) and model
80 outputs (columns 3 to 5). Model outputs: (1) June average with SD being a measure of
81 interannual variability, (2) average year with SD corresponding to the average seasonal
82 variability, or (3) average over the full period with SD being representative of total variability
83 (interannual + seasonal).

	OVIDE data set		ORCA05-PISCES	
		June only	Average year	Full period
$\text{T}_{\text{Cant}}^{\circ}$ (kmol s^{-1})	413.1 ± 70.4	332.0 ± 27.0	338.0 ± 19.2	333.5 ± 50.8
$\text{T}_{\text{Cant}}^{\text{diap}}$ (kmol s^{-1})	391.2 ± 79.2	201.5 ± 30.9	178.2 ± 9.2	178.1 ± 41.8
$\text{T}_{\text{Cant}}^{\text{iso}}$ (kmol s^{-1})	-164.5 ± 16.2	-112.7 ± 13.3	-97.0 ± 7.8	-96.5 ± 24.1
$\text{T}_{\text{Cant}}^{\text{net}}$ (kmol s^{-1})	21.0 ± 17.5	3.6 ± 6.3	13.9 ± 5.4	12.7 ± 8.8
$\text{T}_{\text{Cant}}^{\text{adv}}$ (kmol s^{-1})	247.7 ± 77.3	92.4 ± 32.4	95.1 ± 13.48	94.3 ± 42.6

84
85
86 Fig. S1 : 2002-2012 monthly evolution of (a) the diapycnal (blue), isopycnal (red), net (green)
87 and total (black) transport of Cant and $\text{T}_{\text{Cant}}^{\circ}$ (magenta) (kmol s^{-1}), of (b) the magnitude of the
88 MOC ($\text{MOC}\sigma$, Sv), and of (c) the Cant concentration in the upper (triangles) and the lower
89 (inverse triangles) MOC ($\mu\text{mol kg}^{-1}$) computed in offline either from model output
90 (continuous line) or from observation-based assessments (dotted line) for the Greenland-
91 Portugal OVIDE section. Colored dots symbolize the month June. On panel (a), time series in
92 grey represents the total transport of Cant computed in online by the model (including
93 advective, diffusive and eddies terms).

94

95 **S2. Description of section in the model**

96 The sections at 25°N, 36°N, OVIDE or at the sills were collocated in the model as a
97 continuous line between A and B defined by zonal (y) or meridional (x) grid segments.

98 Horizontal velocities (\vec{u} and \vec{v}) used to estimate mass transport across a section were towards
99 the North (for \vec{v}) if orthogonal to grid segment x and towards the East (for \vec{u}) if orthogonal to
100 grid segment y (Fig. S2).

101

102 Fig. S2: Schematic representation of section in the model

103

104 **S3. Online computation of transport of Cant across a section**

105 Fig. S3: Transport of Cant across (from top to bottom) 25° N, 36° N and OVIDE sections
106 computed online by ORCA05-PISCES over the period 2003-2011 (monthly resolution). In the
107 online approach, the transport of Cant (${}^mT_{\text{Cant}}^{\text{online}}$, black bold line) is the sum of the advection
108 (${}^mT_{\text{Cant}}^{\text{adv}}$, red fine line), the diffusion (${}^mT_{\text{Cant}}^{\text{lf}}$, blue fine line) and the eddy (${}^mT_{\text{Cant}}^{\text{eiv}}$, green
109 fine line) contributions. For each section, ${}^mT_{\text{Cant}}^{\text{adv}}$ is the major component of ${}^mT_{\text{Cant}}^{\text{online}}$.

110

111 **S4. Volume and Cant transported within water classes at 25°N, 36°N and at the**
112 **OVIDE section.**

113 Fig S4a: Simulated annual time series of Cant and volume transported (Pg yr^{-1}) by the
114 northward (full line) and southward (dashed line) following components of NACW (class 1)
115 through 25°N (green), 36°N (red) and OVIDE (black) over the period 1959-2011.

116

117 Fig S4b: Simulated annual time series of Cant and volume transported (Pg yr^{-1}) within IW
118 (class 2) through 25°N (green), 36°N (red), OVIDE (black) and the Greenland-Iceland-
119 Scotland sills (blue) over the period 1959-2011.

120

121 Fig S4c: Simulated annual time series of Cant and volume transported (Pg yr^{-1}) within
122 NADW (Class 3) through 25°N (green), 36°N (red), OVIDE (black) and the Greenland-
123 Iceland-Scotland sills (blue) over the period 1959-2011.

124

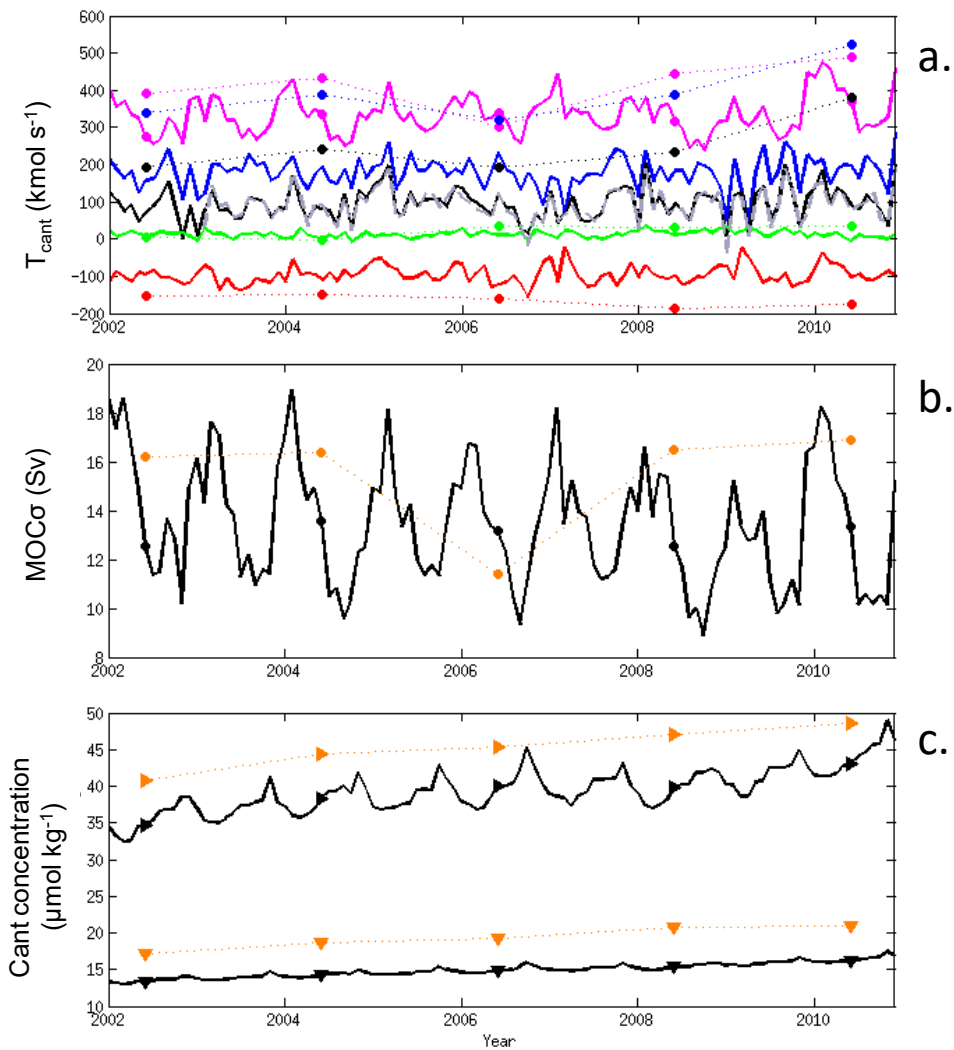


Fig. S1 : 2002-2012 monthly evolution of (a) the diapycnal (blue), isopycnal (red), net (green) and total (black) transport of Cant and T_{Cant° (magenta) (kmol s^{-1}), of (b) the magnitude of the MOC ($\text{MOC}\sigma$, Sv), and of (c) the Cant concentration in the upper (triangles) and the lower (inverse triangles) MOC ($\mu\text{mol kg}^{-1}$) computed in offline either from model outputs (continuous line) or from observation-based assessments (dotted line) for the Greenland-Portugal OVIDE section. Colored dots symbolize the month June. On panel (a), time series in grey represents the total transport of Cant computed in online by the model (including advective, diffusive and eddies terms).

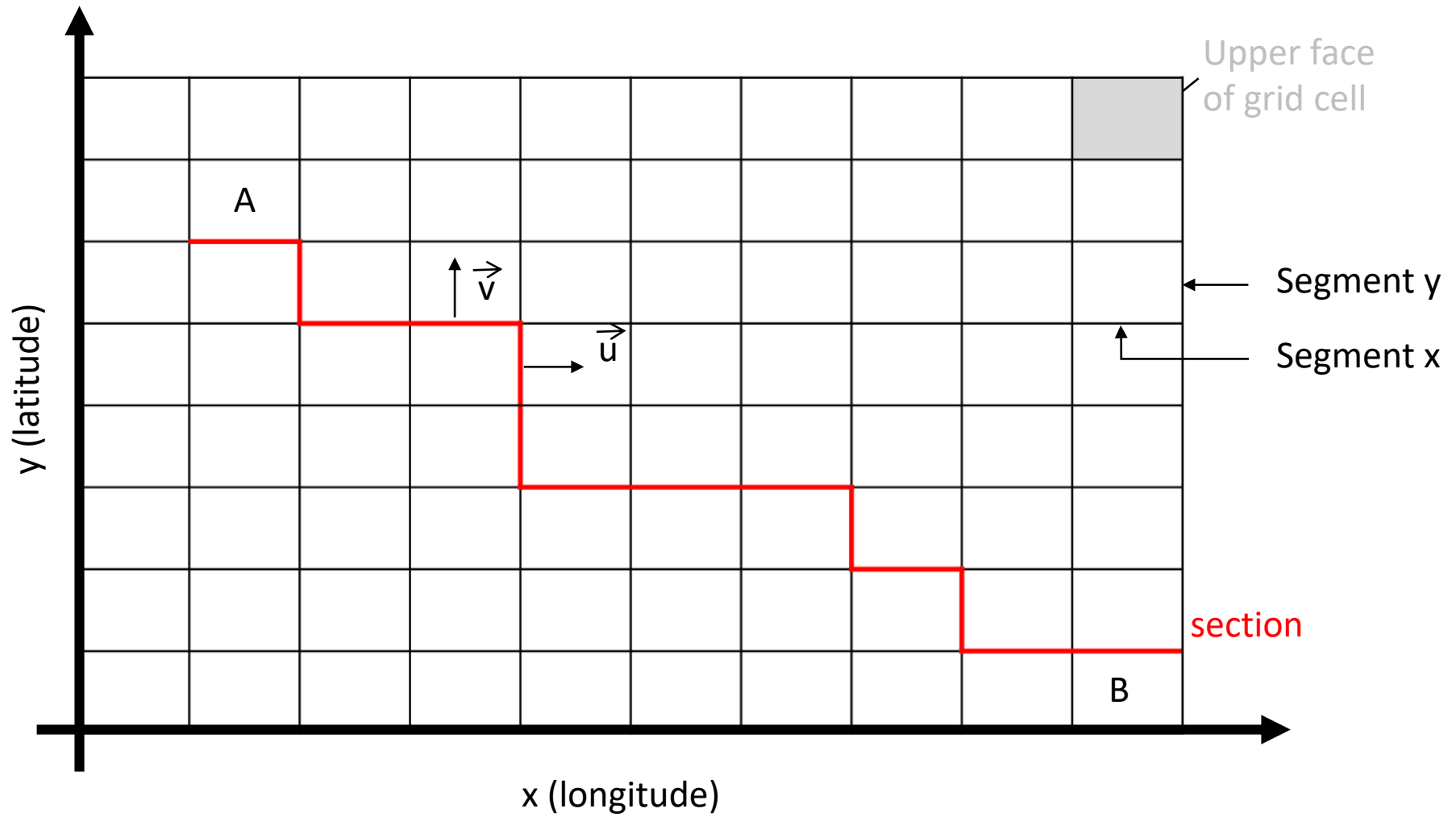


Fig. S2: Schematic representation of section in the model.

$$mT_{\text{Cant}}^{\text{adv}} + mT_{\text{Cant}}^{\text{lf}} + mT_{\text{Cant}}^{\text{eiv}} = mT_{\text{Cant}}^{\text{online}}$$

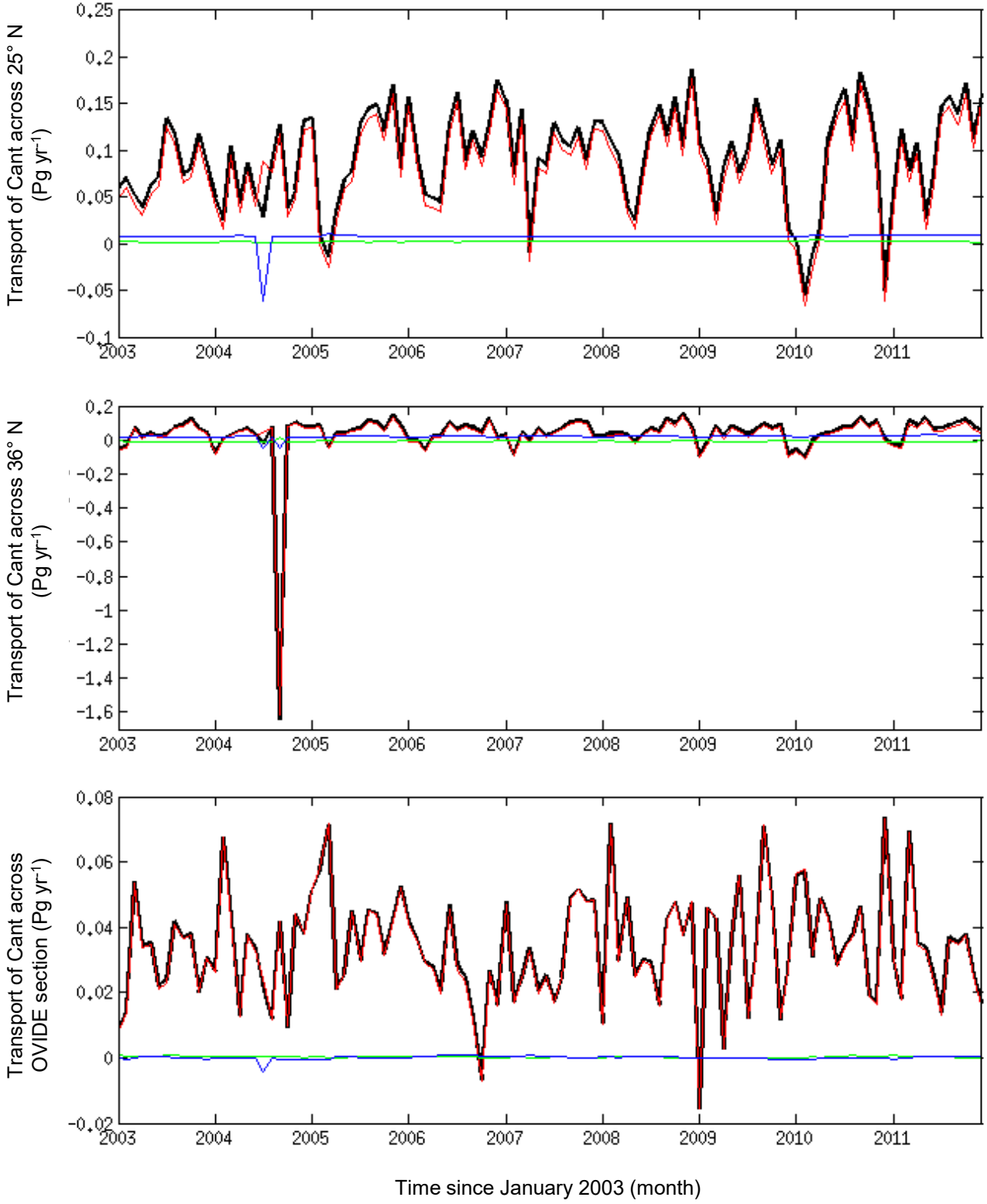


Fig. S3: Transport of Cant across (from top to bottom) 25° N, 36° N and OVIDE sections computed online by ORCA05-PISCES over the period 2003-2011 (monthly resolution). In the online approach, the transport of Cant ($mT_{\text{Cant}}^{\text{online}}$, black bold line) is the sum of the advection ($mT_{\text{Cant}}^{\text{adv}}$, red fine line), the diffusion ($mT_{\text{Cant}}^{\text{lf}}$, blue fine line) and the eddy ($mT_{\text{Cant}}^{\text{eiv}}$, green fine line) contribution. For each section, $mT_{\text{Cant}}^{\text{adv}}$ is the major component of $mT_{\text{Cant}}^{\text{online}}$.

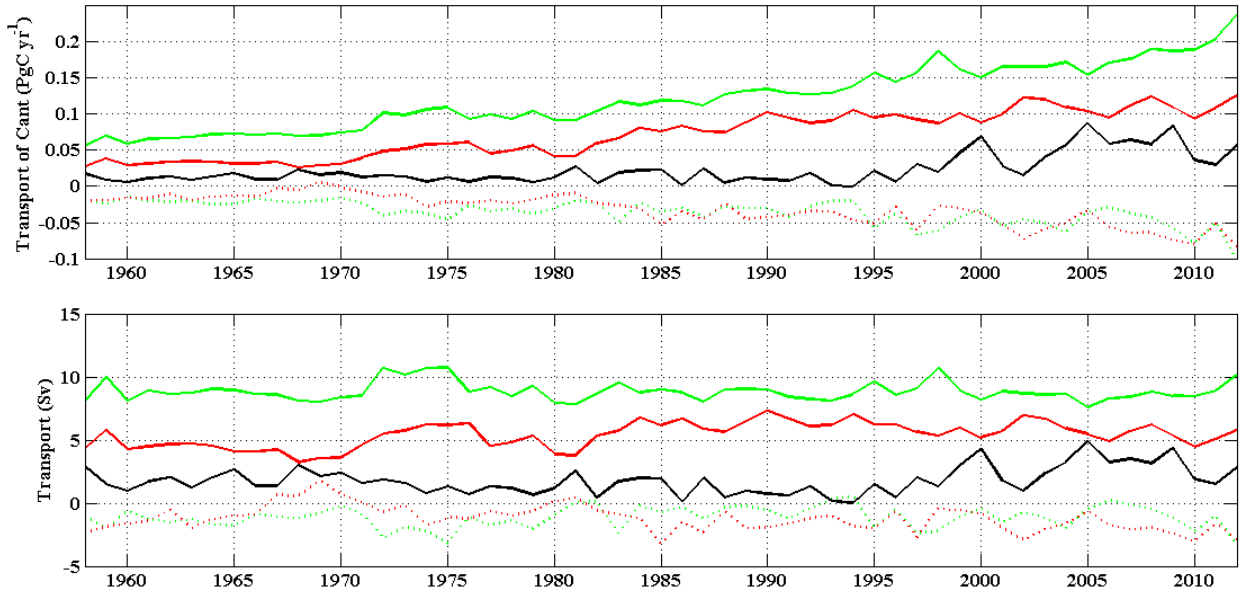


Fig S4a: Simulated annual time series of Cant and volume transported (Pg yr^{-1}) by the northward (full line) and southward (dashed line) following components of NACW (class 1) through 25°N (green), 36°N (red) and OVIDE (black) over the period 1959-2011.

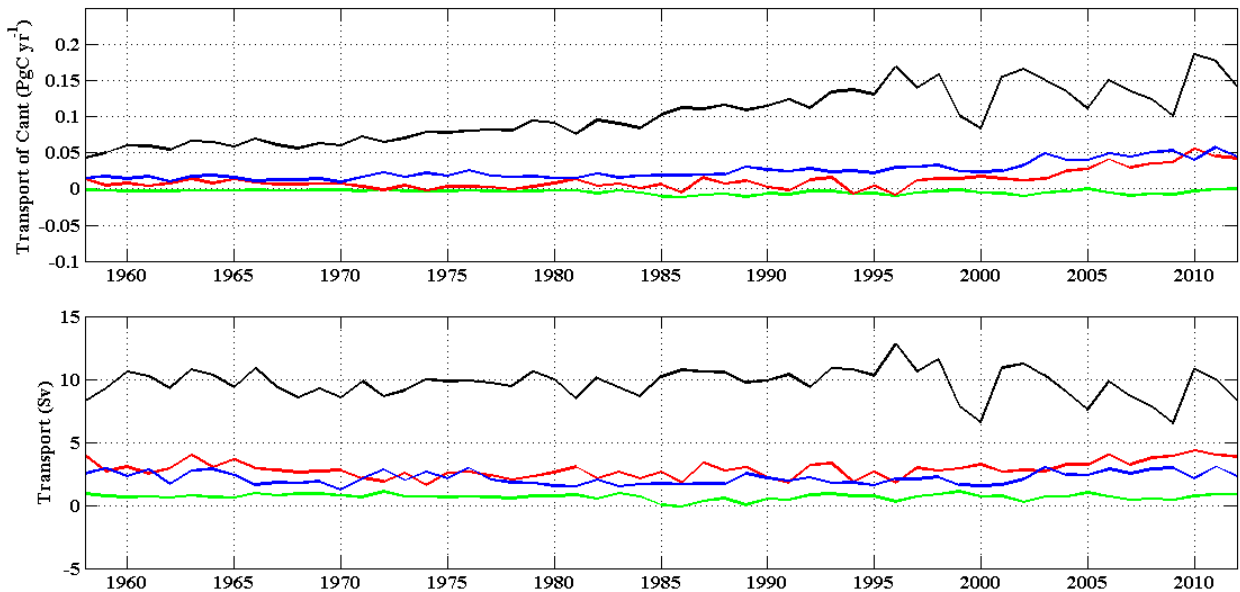


Fig S4b: Simulated annual time series of Cant and volume transported (Pg yr^{-1}) within IW (class 2) through 25°N (green), 36°N (red), OVIDE (black) and the Greenland-Iceland-Scotland sills (blue) over the period 1959-2011.

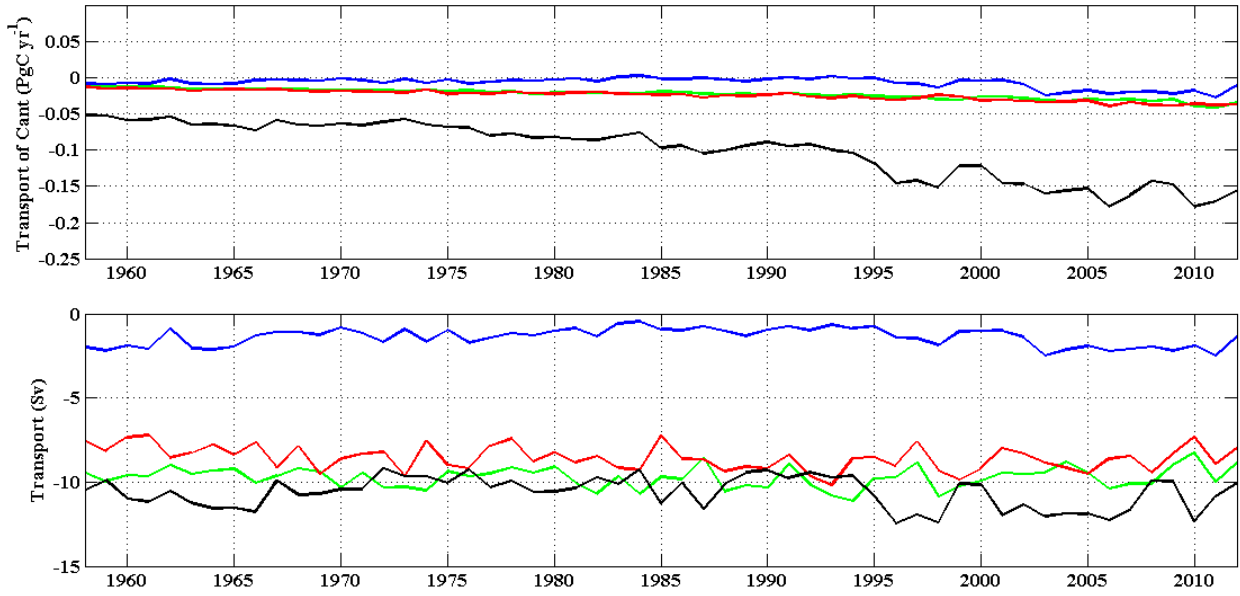


Fig S4c: : Simulated annual time series of Cant and volume transported (Pg yr⁻¹) within NADW (Class 3) through 25°N (green), 36°N (red), OVIDE (black) and the Greenland-Iceland-Scotland sills (blue) over the period 1959-2011.