Dissolved organic carbon distributions in the Bransfield and Gerlache Straits, Antarctica

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(revised version)

Deep-Sea Research, part II

October 1999

Abstract

During FRUELA'95 cruise, seawater samples were collected at the Bransfield and Gerlache Straits for the analysis of dissolved organic carbon (DOC) profiles throughout the water column. An excess of DOC probably derived from phytogenic material was observed in the upper mixed layer (UML; average: $+22 \pm 13 \mu\text{mol C l}^{-1}$), compared to the constant concentration of refractory DOC below 400 m ($44 \pm 4 \mu\text{mol C l}^{-1}$). The average excess DOC concentration was higher than the particulate organic carbon concentration, indicating the major contribution of DOC to carbon export in this area. However, large spatial variability of DOC in the upper mixed layer ($52\text{--}102 \mu\text{mol C l}^{-1}$) was observed: excess DOC contributed from 15 to 57% to the actual DOC concentration. Maximum average DOC concentrations in the UML were recorded in the Gerlache Strait ($71 \mu\text{mol C l}^{-1}$) and in the Gerlache-Bransfield confluence ($80 \mu\text{mol C l}^{-1}$), whereas minimum values were recorded in the Bransfield Strait ($61 \mu\text{mol C l}^{-1}$). Several shelf and slope stations showed a slight increase of DOC ($5\text{--}10 \mu\text{mol C l}^{-1}$) in the deep layer, which might be related to organic matter release from the underlying sediments. Considering the net DOC release from phytoplankton, the low bacterial biomass and the reduced vertical DOC export, the DOC excess could build up in about 6 days for most of the sampling stations. The probable fate of the DOC excess is the eastwards horizontal transport by the Bransfield Current out the study area.

Keywords: Dissolved Organic Carbon, Particulate Organic Matter, Bransfield and Gerlache Straits, Antarctica, Southern Ocean

1. Introduction

A dissolved organic matter (DOM) excess in surface ocean waters compared to deep waters is a commonly observed worldwide trend (Thingstad et al. 1997, and references therein). The contribution of this amount of DOM to the export of primary production is a subject of discussion nowadays (e.g. Legendre and Le Fèvre, 1995; Hansell and Carlson 1998a). The excess surface DOM can be: 1) consumed by heterotrophic bacteria; 2) exported downwards by turbulent diffusion or during deep winter convection (Copin-Montégut and Avril, 1993; Carlson et al., 1994); or 3) transported out of the production area by horizontal circulation (Legendre and Le Fèvre, 1995; Hansell and Waterhouse, 1997). This excess DOM has been hypothesized to be composed of semi-labile and labile material with recycling time of days to months. However, deep DOC is composed mostly of refractory material with recycling time of $\sim 10^{1-3}$ years (Copin-Montégut and Avril, 1993; Carlson and Ducklow, 1995). In agreement with the most recently studies, refractory DOC is not constant for all deep waters around the world; deep DOC concentrations decrease about 14 $\mu\text{M-C}$ from the northern North Atlantic Ocean to the northern North Pacific Ocean (Hansell and Carlson, 1998b).

There exists a wide range of measured DOC concentrations in the Southern Ocean: from 6 to 1000 $\mu\text{mol C l}^{-1}$ (Dafner, 1992; Dafner and Solin, 1995; Karl et al., 1996, and references therein). More realistic values between 40 and 100 $\mu\text{mol C l}^{-1}$ were measured in the Weddell Sea (Skoog and Wedborg, 1994; Wedborg et al., 1998), from 38 to 60 $\mu\text{mol C l}^{-1}$ along 6°W between 47° and 60°S (Kähler et al., 1997), from 33 to 105 $\mu\text{mol C l}^{-1}$ along 62°E between 49° and 66°S (Wiebinga and Baar, 1998), from 40 to 72 $\mu\text{mol C l}^{-1}$ in the Ross Sea (Carlson et al., 1998) and from 40 to 70 $\mu\text{mol C l}^{-1}$ along 170° E and 170°W between 50° and 67°S (Doval and Hansell, 2000). The wider

ranges in the earlier papers were related to analytical difficulties or special marine environments (Dawson et al., 1985).

Antarctic waters range from oligotrophic regions to productive coastal embayments (Karl, 1991). The Bransfield and Gerlache Straits, located in the coastal zone of the Antarctic Peninsula, are characterized by a complex circulation pattern, involving waters from the surrounding Weddell Sea, Bellingshausen Sea and Drake Passage (Niiler et al., 1991). This coastal zone shows a wide spatial and temporal range of phytoplankton production (Priddle et al., 1986; Holm-Hansen and Mitchell, 1991; Karl et al., 1991a).

A mesoscale study in this area was carried out during the RACER program (November 1986-March 1987; Karl, 1991; Huntley et al., 1991) with the main objective of studying the physical and biological processes causing the high productivity observed in coastal waters of the Antarctic Peninsula (Huntley et al., 1991). Despite DOC was not measured, outputs from the RACER carbon model suggested production of a large amount of labile DOC (Karl et al., 1991a). Aristegui and Montero (1995) and Aristegui et al. (1996) suggested large exudation of DOC in the same area to explain their measurements of community respiration and the discrepancy between primary production measured by the ^{14}C and O_2 methods.

Another three main conclusions from the RACER program will be specially considered in this work: 1) the upper mixed layer (UML) depth controlled the development of the spring bloom (Mitchell and Holm-Hansen, 1991); 2) a microbial food web dominated by phytoplankton was characteristic during the initial phase of the bloom (Karl et al., 1991b); and 3) the Bransfield Current could be important for transporting and redistributing biogenic material from eutrophic regions of the northern Gerlache Strait to the Drake Passage in a period of 15-30 days (Niiler et al., 1991).

The main objective of the FRUELA project is the study of carbon fluxes in an area of elevated productivity in the Antarctic Ocean: the Gerlache and Bransfield Straits. The present work deals with the spatial and vertical variability of DOC. The origin and fate of the observed excess surface DOC is studied as well as the relationship of DOC with other water masses tracers.

2. Material and Methods

The results presented here correspond to a grid of four transects in the western basin of the Bransfield Strait and one transect along the Gerlache Strait, occupied from 10 to 18 December 1995 during the FRUELA'95 expedition, aboard the Antarctic R/V 'Hespérides'. The positions of the sampling stations are shown in Fig. 1.

Salinity and temperature were recorded by means of a conductivity-temperature-depth (CTD) Mark IIIC probe. Water samples were collected with a General Oceanic rosette sampler (24 Niskin bottles of 10 l) attached to the CTD system.

Seawater samples for DOC analysis were collected on 27 stations spaced 5-10 miles at selected depths: surface, fluorescence maximum, 100 m, bottom and three more depths depending on the bathymetry. Samples were collected with 100 ml polyethylene syringes with teflon plunger tips and filtered by hand through Whatman Puradisc GF/F disposable filter devices (0.7 μ m pore size) on polypropylene housing. The filtrate was drawn eventually into 50 ml polyethylene containers. The filtering system and the containers used for DOC had been previously soaked on 0.1 N HCl, and rinsed with Milli-Q water. In addition, the containers were rinsed three times with 50 ml of sample. Samples were immediately stored at -70°C until analysis in the base laboratory, eight months later. This storage technique has demonstrated no artefactual results on the micromolar scale (Hansell and Carlson, 1998b).

DOC determination was performed by high temperature catalytic oxidation (HTCO) with a commercial Shimadzu TOC-5000. The combustion quartz tube was filled with a 0.5% Pt on Al₂O₃ catalyst. Three to 5 replicate injections of 200 µl were performed per sample. The concentration of DOC was determined by subtracting the average peak area from the instrument blank area and dividing by the slope of the standard curve. The instrument blank is the system blank plus the filtration blank. The system blank was determined by subtracting the DOC in UV-Milli-Q to the total blank. Measurements made with the high sensitivity catalyst (Pt on silica wool) produced values <2 µmol C l⁻¹ for fresh UV-Milli-Q water. The filtration blank (determined by filtering UV-Milli-Q water through the filtration system) was <2 µmol C l⁻¹. Before sample analyses, the catalyst was washed by injecting UV-Milli-Q, for at least 12 h, until the system blank was low and stable. The system blank was <8 µmol C l⁻¹. The device was standardized with Potassium Hydrogen Phthalate (KHP). The coefficient of variation (C.V.) of the peak area for the 3-5 replicate analyses of each sample was ~1%. The accuracy of our HTCO system has been tested within the international intercalibration exercise conducted by J. Sharp (Univ. of Delaware), with very satisfactory results (within ±10%; J. Sharp, pers. com.).

Seawater samples for particulate organic matter (POM), chlorophyll *a* (chl *a*), nutrients and oxygen were also collected. Sampling depths for POM were the same as DOC analysis; every 10 m between the surface and 100 m depth for chl *a* and surface, every 20 m between 20 m and 100 m, 200, 250, every 100 m between 300 m and 600 m, 800 m, 1000 m and every 300 or 500 m between 1000 m and bottom depending on bathymetry for nutrients.

A volume of 1 l of sample was filtered through an oilless vacuum filtration system. Particulate organic carbon (POC) and nitrogen (PON) were collected on

Whatman GF/F filters, which were dried on silica gel and frozen to -70°C until analysis in the base laboratory. Measurements were carried out with a Perkin Elmer 2400 CHN analyzer. Combustion to CO_2 and NO_x was performed at 900°C and reduction of NO_x to N_2 at 640°C . Chlorophyll *a* was determined fluorometrically, with a Turner Designs 10000R fluorometer, after 90% acetone extraction (Yentsch and Menzel, 1963). Samples for nutrients analyses were collected on 100 ml polyethylene syringes and filtered by hand through Whatman Puradisc 25 disposable filters (polypropylene filter media: $0.45\mu\text{m}$ pore size) on polypropylene housing. The filtrate was drawn into 50 ml polyethylene containers and analyzed immediately using standard segmented flow analysis procedures (Castro et al., this volume).

3. Results and Discussion

3.1 Hydrographic conditions

According to García et al. (this volume) silicate is a very good discriminator of water masses in the FRUELA area. To study the spatial variability of DOC, Chl *a* and POC in relation to water masses, we have displayed the silicate distributions at two reference levels: the upper mixed layer (UML) and 200 m (Fig. 2b,c).

Figure 2a shows the UML depth (Z_{UML}), calculated following Castro et al. (this volume). Shallower UMLs ($\leq 20\text{m}$) were found in the southeastern corner of the Bransfield Strait and in the Gerlache Strait, with the exception of station 40. Stratification in the northeastern part of the Gerlache Strait was due to the presence of a warm ($T > -1.0^{\circ}\text{C}$) and diluted ($S < 33.5$) water layer. In the southeastern part of the Gerlache Strait and in the southeastern sector of the Bransfield Strait, melting ice favored the strong water column stratification (García et al., this volume).

The horizontal distribution of silicate integrated over the UML (Fig. 2b) discerns between the Transition Zonal Water with Bellingshausen influence (TBW) and the Transitional Zonal Water dominated by Weddell Sea influence (TWW) in the Bransfield Strait (García et al., this volume). The silicate isopleth of $79 \mu\text{mol kg}^{-1}$ coincides with the isohaline of 34.1 and can be considered the limit between TBW ($\text{SiO}_2 \leq 79 \mu\text{mol kg}^{-1}$) and TWW. The northeast advection of surface water from the Gerlache Strait is discerned by the highest silicate levels in the area ($\geq 84 \mu\text{mol kg}^{-1}$). At 200 m depth (Fig. 2c), the Bransfield Front separates the intrusion of Lower Circumpolar Deep Water (LCDW) with high silicate concentrations ($>85 \mu\text{mol kg}^{-1}$) from TWW with lower levels (García et al., this volume). In the Gerlache Strait, the high silicate levels ($>94 \mu\text{mol kg}^{-1}$) correspond to LCDW warmer and saltier ($T = 0.7 \pm 0.1 \text{ }^\circ\text{C}$, $S = 34.50 \pm 0.01$) than LCDW in the northwestern part of the Bransfield Strait ($T = 0.07 \pm 0.3 \text{ }^\circ\text{C}$; $S = 34.41 \pm 0.06$; $\text{SiO}_2 = 87 \pm 4 \mu\text{mol} \cdot \text{kg}^{-1}$). In the Bransfield-Gerlache confluence lower silicate levels corresponds to the TWW. Below 400 m, TWW fills the entire Bransfield Strait with a mean silicate concentration of $86 \pm 3 \mu\text{mol kg}^{-1}$ and salinity of 34.56 ± 0.02 .

3.2 Vertical DOC profiles

The average DOC profile for the study area (mean $\pm$ SD) decreased from $66 \pm 13 \mu\text{mol C l}^{-1}$ in the UML to $44 \pm 4 \mu\text{mol C l}^{-1}$ in deep waters ($>400 \text{ m}$). Selected DOC profiles at stn 40, in the Gerlache Strait; stn 74, in the Gerlache-Bransfield confluence; stn 103, in the Bransfield Strait; and stn 121, at the Bransfield Front (Fig. 3), cover all the observed vertical variability.

The correlation of DOC with density was low ($r^2 < 0.1$) in the whole water column, indicating the low control of hydrography on the distribution of DOC.

Stations 74 and 121 showed a DOC maximum at the base of UML (*i.e.* in the bottom layer of UML) as well as most of the sampling stations (70%). Despite the similar Chl *a* levels, DOC concentrations were very different between these stations. Concentration at the DOC maximum was higher in the Gerlache-Bransfield confluence (stn 74; 120 $\mu\text{mol C l}^{-1}$) than in the Bransfield Front (stn 121; 75 $\mu\text{mol C l}^{-1}$). The Chl *a* maximum at these stations ($>4 \text{ mg m}^{-3}$) was apparently shallower than the DOC maximum in agreement with the distributions of TOC found by Wedborg et al. (1998) at productive stations in the Weddell Sea.

Conversely, in other stations the DOC maximum can be located within the UML. This is the case of stn 40, where the DOC maximum was at 20 m, coinciding with the subsurface Chl *a* maximum ($\sim 4 \text{ mg m}^{-3}$). This station in the Gerlache Strait showed the highest DOC values in the study area, although the average DOC value in the upper mixed layer (102 $\mu\text{mol C l}^{-1}$) was similar to that obtained in the Gerlache-Bransfield confluence (stn 72: 99 $\mu\text{mol C l}^{-1}$; Fig. 4c).

Despite the relatively high Chl *a* levels at stn 103 ($>2 \text{ mg m}^{-3}$), DOC was low in the UML ($\sim 55 \mu\text{mol C l}^{-1}$). Chl *a* and DOC were homogeneously distributed within the UML, as well as in most of the stations with low DOC and Chl *a*. This station showed the typical profile for the Bransfield Strait. The average DOC in the UML for this area varied between 52 and 63 $\mu\text{mol C l}^{-1}$, except in a few stations located near the islands (Fig. 4c). On the contrary, most of the stations with high average values of DOC (ex.: stns 40, 72, 121), showed no uniform profiles within the UML, which points to net production processes being quicker than the time for homogenization.

Below the UML, DOC concentration decreases monotonically with depth, although several shelf and slope stations showed a slight increase of 5-10 $\mu\text{mol C l}^{-1}$ in the bottom layer (stations: 39, 97, 99, 103 and 117). Several authors have obtained the

same behavior for slope and abyssal stations (Williams et al., 1980; X. A. Álvarez-Salgado and A. E. J. M. Miller, unpubl.) which can be related to diffusion from the sediments of DOM younger than that in the overlying water (Bauer et al., 1995).

3.3 Organic matter below the upper mixed layer

A constant DOC concentration of $44 \pm 4 \mu\text{mol C l}^{-1}$ ($n=15$) was found below 400 m, as a result of the homogeneous water mass there and the low bacterial activity at this depth range (Pedrós-Alió et al., this volume). This can be considered refractory DOC. It was similar to the DOC levels found by Kähler et al. (1997) in 6°W, between 47° to 60°S and Carlson et al. (1998) in the Ross Sea. This concentration is intermediate between the low levels recorded in the deep Pacific Ocean ($34\text{--}40 \mu\text{mol C l}^{-1}$) and the higher levels measured in the deep Atlantic Ocean ($\sim 44\text{--}48 \mu\text{mol C l}^{-1}$; Hansell and Carlson, 1998b). Our baseline DOC is very close to the values reported by these authors for the Southern Ocean (about $42 \mu\text{mol C l}^{-1}$).

Following the distribution of silicate at 200 m depth (Fig 2c), DOC concentrations were studied to check the influence of the different water masses. The values of DOC at this depth showed an average concentration of $52 \pm 7 \mu\text{mol l}^{-1}$, *i.e.* only $8 \mu\text{mol C l}^{-1}$ higher than the mean refractory DOC below 400 m. DOC values were not significantly different between LCDW and TWW (t ($df=14$) = 0.62, $p=0.55$). The correlation between DOC and silicate was only $r^2=0.25$ ($p<0.001$).

The fact that the DOC concentration at 200 m depth was mainly independent of water mass, indicate that the amount of DOC seems to be essentially refractory, although a minor fraction of semi-labile DOC (15% of the total) was also present at this depth.

3.4 Organic matter in the upper mixed layer. The excess DOC

The distributions of average Chl *a* and POC (Fig. 4a, b) in the UML were quite similar. Maximum values of Chl *a* and POC were found in the Gerlache Strait (4-6 mg Chl *a* m⁻³ and 22-25 µmol C l⁻¹), and at several stations in the Bransfield Strait: at the Bransfield Front (>3.0 mg Chl *a* m⁻³, >12 µmol C l⁻¹) and at stratified stations (119 and 140 :3 mg Chl *a* m⁻³, 16 µmol C l⁻¹). Minimum values corresponded to stations located north of the Bransfield Front (1.5 mg Chl *a* m⁻³, <9 µmol C l⁻¹). Although not all POC and Chl *a* maxima coincided, the direct correlation (Model II; Sokal and Rohlf, 1995) between these variables for all samples (in the UML) of the study area was:

$$\text{POC } (\pm 3.9) = 2.5 (\pm 0.3) + 4.3 (\pm 0.3) \text{ Chl } a \quad (1)$$

$$r^2 = 0.75, \quad n = 50, \quad p < 0.001$$

The high correlation between POC and Chl *a* (eq. 1) allow us to estimate the percentage of autotrophs by multiplying the slope of the regression by the average chlorophyll *a* and dividing by the average POC. Autotrophs represent ~80% of POC in the UML. The slope of equation 1, 4.3 mol C g Chl *a*⁻¹ (51.6 g C g Chl *a*⁻¹) was similar to the ratio used in the RACER program and it was considered typical for Antarctic phytoplankton (Mitchell and Holm-Hansen, 1991). The range of POC/Chl *a* ratios found in this layer (32-192 g C g Chl *a*⁻¹) was within the values reported for Antarctic waters (between 11 and 416 g C g chl *a*⁻¹; Palmisano et al. 1985; El Sayed and Taguchi, 1981).

POC and PON were obviously coupled throughout the entire water column, and the direct correlation (Model II) was very high ($r^2 = 0.95$; $p < 0.001$). If we considered the UML, the direct correlation (Model II) between POC and PON for the study area was:

$$\text{POC } (\pm 0.6) = 0.35 (\pm 0.17) + 5.1 (\pm 0.1) \text{ PON} \quad (2)$$

$$r^2 = 0.97, \quad n = 54, \quad p < 0.001$$

The slope of equation 2 is lower than the Redfield ratio and similar to that found in Antarctic waters (Copin-Montégut and Copin-Montégut, 1983; Pérez et al., 1994). This low C/N ratio suggests that the environmental conditions were favorable for phytoplankton growth, as bacterial biomass (low C/N ratios) made a little fraction of particulate organic matter (Pedrós-Alió et al., this volume). The direct C/N ratio of POM was 5.3 ± 0.5 within the UML. These low POC/Chl *a* and POC/PON ratios are typical of autotrophic systems (Holm-Hansen et al., 1989; Nelson et al., 1989).

The horizontal distribution of average DOC in the UML (Fig. 4c) showed maximum values in the Gerlache Strait (82 and $102 \mu\text{mol C l}^{-1}$) and in the Gerlache-Bransfield confluence (86 and $99 \mu\text{mol C l}^{-1}$) coinciding with relative high Chl *a* maximum values ($>3 \text{ mg m}^{-3}$). Minimum values of average DOC were measured within the Bransfield Strait, especially at stations far from the islands shelf (52 - $63 \mu\text{mol C l}^{-1}$). The direct correlation (Model II) between DOC and POC or Chl *a* was only significant ($r^2=0.25$) in the Gerlache Strait and Gerlache-Bransfield confluence. In these two areas a higher correlation was found between total organic carbon ($\text{TOC} = \text{DOC} + \text{POC}$) and POC ($r^2=0.45$).

An excess of DOC was observed in surface waters as compared to bottom waters (background DOC: $44 \pm 4 \mu\text{mol C l}^{-1}$). The great variability of the average DOC in the UML lead to a large range of excess DOC (8 - $58 \mu\text{mol C l}^{-1}$) with a mean value of $+22 \pm 13 \mu\text{mol C l}^{-1}$ (average integrated DOC excess in the UML: $6.7 \pm 7.0 \text{ gC m}^{-2}$) for the whole study area. So, 15 to 57% of the observed DOC in this layer was semilabile and labile DOC. The average excess DOC for the three contrasting regions: Gerlache

Strait, Gerlache-Bransfield confluence and Bransfield Strait, varied between 17 and 36 $\mu\text{mol C l}^{-1}$ (6 and 10 gC m^{-2} ; Table 1).

The great variability of the excess DOC is larger than recently found in other systems as: the Mediterranean Sea (0-40 $\mu\text{mol C l}^{-1}$; Copin Montégut and Avril, 1993) or the Pacific Ocean (20-40 $\mu\text{mol C l}^{-1}$; Peltzer and Hayward, 1996; Hansell and Waterhouse, 1997) and similar to that found in coastal upwelling areas as the NW Iberian coast (10-60 $\mu\text{molC l}^{-1}$; Doval et al., 1997) or the Arabian Sea (20-60 $\mu\text{molC l}^{-1}$; Hansell and Peltzer, 1998). We can group the DOC data in two different areas: A) Gerlache and Gerlache-Bransfield confluence (8 stations): relative high DOC concentrations and B) Bransfield Strait (18 stations): low DOC concentrations. The behavior of DOC was different in the recent study of Kähler et al. (1997) using the same HTCO method, in the eastern Weddell Sea. He did not find any variability of surface DOC concentration because DOC was not dependent of biological activity. The range of DOC in the Bransfield Strait was similar to that found by Carlson et al., (1998) in the Ross Sea where the low but labile surface DOC seems quickly recycling by bacterioplankton.

The average POC in the UML was $13.6 \pm 5.1 \mu\text{mol C l}^{-1}$. Therefore, the average excess DOC / (excess DOC + POC) was 0.59; *i.e.* 59% of the 'potentially' degradable organic matter is in the dissolved form and 41% as suspended particles (Table 1). The average percentage was close to the 40-50% reported for the NW Iberian upwelling system (Doval et al., 1997), and far from a oligotrophic system as the Mediterranean Sea (89% after seasonal accumulation; Copin-Montégut and Avril, 1993).

3.5 Origin and fate of the DOC excess

The main sources of the excess DOC in the study area could be: extracellular release by phytoplankton, sloppy-feeding by zooplankton and dissolution of fecal pellets, egestion by microzooplankton and cell lysis from viral infection (Carlson and Ducklow, 1995).

Melting ice did not seem to affect the DOC levels in the study area: although stns 94 and 115 at the Bransfield Strait and stns 34 and 43 at the Gerlache Strait showed lower salinity values (<33.8), they did not show high DOC levels in contrast with the results found by Kahler et al., (1997) in other areas of the Southern Ocean.

In agreement with studies made during the RACER program, phytoplankton seems to be the dominant microplankton community during this cruise (Varela et al., this volume). Integrated zooplankton biomass between the surface and 200 m ranged from 0.19 to 0.99 gC m⁻². Although there is no direct correlation between the integrated zooplankton biomass and integrated DOC in the UML in the study area, maximum integrated zooplankton biomass were located in the Gerlache Strait coinciding with maximum values of DOC (Anadón et al., this volume). Bacterial biomass was low compared to phytoplankton biomass ($<25\%$; Pedrós-Alió et al., this volume) probably due to the low temperature and virus lysis (Pedrós-Alió et al., this volume).

Average DOC production from phytoplankton at 5 m was between 0.4 to 4.1 mg C m⁻³ h⁻¹ for the whole study area (Morán and Estrada, this volume). The average values for the three selected regions (assuming they are similar throughout the UML) were: Gerlache Strait (2.33 mg C m⁻³ h⁻¹), Gerlache-Bransfield confluence (0.85 mg C m⁻³ h⁻¹) and Bransfield Strait (1.33 mg C m⁻³ h⁻¹). The average excess DOC could be produced from phytoplankton in about 6, 21 and 6 days, respectively, if losses were negligible. The estimated average geostrophic velocity in the Bransfield Current was 0.085 m s⁻¹ during this cruise (Gomis et al., this volume), *i.e.* a flushing time of ~15

days within the sampling area. If the UML is maintained during the flushing time, the excess DOC of most of the stations sampled (regions A and C, 89% of the total stations) could be net produced by phytoplankton. The higher DOC found at Gerlache Strait and Gerlache-Bransfield confluence seems to be the result of a rapid biological production. A slow production but large flushing time favored DOC accumulation in the oceanic oligotrophic gyres (Copin-Montégut and Avril, 1993). The large time necessary to produce DOC within the Gerlache-Bransfield confluence from phytoplankton (21 days), suggest that the advection from Gerlache is quite important.

Low bacterial biomass contributed to the observed DOC accumulation in the UML. This accumulated DOC can be coagulate and aggregate to POC as suggested Karl et al. (1991a) or can be exported horizontally and/or vertically. Turbulent diffusion is the major mechanism for the downward transport of DOC from surface to deep waters although stratification maintains the UML. The eddy diffusion flux of DOC from the UML to the waters below 400 m depth can be roughly estimated from $F = -K_Z \cdot \Delta DOC / \Delta Z$ (Copin-Montégut and Avril, 1993). K_Z is the turbulent diffusion coefficient, which can be calculated by the equation $K_Z = \varepsilon \cdot N^2 \cdot R / (1 - R)$. The dissipation rate (ε) and the Richardson number (R) have been set to constant values of $10^{-8} \text{ m}^2 \text{ s}^{-3}$ and 0.2 respectively, for the open ocean (Copin-Montégut and Avril, 1993). Consequently, K_Z mainly depends on the square of the Brunt-Väisälä frequency, $N^2 = (g/\rho) \cdot (d\rho/dZ)$. Values of K_Z ranged from $5.5 \text{ m}^2 \text{ d}^{-1}$ to $19.7 \text{ m}^2 \text{ d}^{-1}$. $\Delta DOC / \Delta Z$ was simply calculated as $-(DOC_{\text{UML}} - DOC_{\text{UML-400}}) / [(400 - Z_{\text{UML}})/2 - (Z_{\text{UML}}/2)]$ and varied from 0 to 11.8 mg C m^{-4} . Finally, the resulting eddy diffusion fluxes ranged from $0 \text{ mg C m}^{-2} \text{ d}^{-1}$ to $155 \text{ mg C m}^{-2} \text{ d}^{-1}$ (average: $30.3 \text{ mg C m}^{-2} \text{ d}^{-1}$). These numbers are extremely low when compared with the average excess DOC observed in the UML (6.7 gC m^{-2}), confirming that stability although small, keep the DOC within the UML indicating that

turbulent diffusion is not an important route to inject semilabile DOC in subsurface waters. Therefore, horizontal export seems to be the main fate of the excess DOC in the study area.

Acknowledgements. The authors wish to thank all the participants in the cruise FRUELA'95 and the crew of the 'BIO Hesperides' for their valuable help. We specially thank R. Anadón, M. Estrada, J. A. Morán, and C. Pedrós-Alió for providing zooplankton biomass, phytoplankton exudation and bacterial biomass data. A fellowship from the EC MAST2 project CT93-0065 allowed M.D.D. to carry out this work. X.A.A.-S. was funded by a 'Contrato de Incorporación' of the Spanish 'Ministerio de Educación y Ciencia'. C.G.C. was funded by a contract from the EC MAS3-CT96-0060 project. This work was financed by CICYT contract no. ANT94-1168-E.

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Table 1.

Average and standard deviation of the depth-integrated excess DOC ($\text{DOC}_{\text{ex}} = \text{DOC}_{\text{UML}} - 44; \mu\text{mol C l}^{-1}$), POC ($\mu\text{mol C l}^{-1}$) and excessDOC / (excessDOC + POC) ratio in the UML; DOC production from phytoplankton ($\text{DOC}_{\text{pr}}; \text{mg C m}^{-3} \text{ h}^{-1}$) and percentage of extracellular release (PER) at 5 m (taken from Moran and Estrada, this volume) for the three areas considered: Gerlache Strait (Gerlache S.); Gerlache-Bransfield confluence (Gerl.-Bransf. conf.) and Bransfield Strait (Bransfield S.).

Region	DOC_{ex} ($\mu\text{mol C l}^{-1}$)	POC ($\mu\text{mol C l}^{-1}$)	$\text{DOC}_{\text{ex}}/$ ($\text{DOC}_{\text{ex}} + \text{POC}$)	DOC_{pr} ($\text{mg C m}^{-3} \text{ h}^{-1}$)	PER %
Gerlache S.	27 ± 18	17.8 ± 4.7	0.55 ± 0.16	2.33	13
Gerl.-Bransf. conf.	36 ± 13	17.4 ± 5.0	0.64 ± 0.11	0.85	17
Bransfield S.	17 ± 6	11.9 ± 4.1	0.57 ± 0.10	1.33	26

Note: The stations sampled for DOC within the three regions were:

Gerlache Strait: 34, 37, 39, 40, 43,

Gerlache-Bransfield confluence: 47, 72, 74

Bransfield Strait: 52, 76, 79, 81, 94, 97, 99, 101, 103, 115, 117, 119, 121, 123, 138, 140, 142, 144

Figure Captions

Figure 1. Map of the DOC sampling grid consisting of four transects in the western basin of the Bransfield Strait and one transect along the Gerlache Strait, during the FRUELA'95 cruise. Open circles marked selected stations presented in Figure 3

Figure 2. Spatial distribution of a) upper mixed layer depth (Z_{UML} , m), b) averaged depth-integrated silicate ($\mu\text{mol kg}^{-1}$) in the upper mixed layer and c) silicate at 200 m depth ($\mu\text{mol kg}^{-1}$). TBW: Transition Zonal Water with Bellingshausen Sea influence; TWW: Transition Zonal Water with Weddell Sea influence; LCDW: Lower Circumpolar Deep Water; B.F.: Bransfield Front

Figure 3. DOC ($\mu\text{mol l}^{-1}$), sigma theta (γ ; Kg m^{-3}) and chl *a* (mg m^{-3}) vertical profiles at selected stations in the studied area: a) stn 40, b) stn 74, c) stn 103 and d) stn 121

Figure 4. Spatial distribution of depth-integrated in the upper mixed layer a) chlorophyll *a* (mg m^{-3}), b) POC ($\mu\text{mol l}^{-1}$) and c) DOC ($\mu\text{mol l}^{-1}$)

(Figura 1)

(Figure 3)

(Figure 2)