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Sources of dissolved organic carbon and nitrogen in Otsuchi Bay on the Sanriku ria coast of Japan in the spring

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Abstract —We examined the interannual variation in the concentrations of dissolved organic carbon and nitrogen (DOC and DON, respectively), inorganic nutrients, phytoplankton biomass (concentration of chlorophyll *a*), and bacterial biomass in Otsuchi Bay, on the Sanriku ria coast of northeast Japan, opening to the east onto the Pacific Ocean. The variation in DOC was correlated with both phytoplankton biomass ($R=0.427$, $n=64$, $p<0.05$) and physical parameters (salinity: $R=-0.376$, $n=65$, $p<0.01$; log-temperature: $R=0.294$, $n=65$, $p<0.01$), suggesting that both DOC released from organisms and DOC introduced from outside of the bay by river runoff and water exchange with off-shore water affect its dynamics in the bay. In contrast, DON concentrations were correlated with Chl *a* but not with salinity or temperature, suggesting that the fluctuation of DON is less affected by the introduction of DON from outside of the bay. A temperature–salinity diagram suggested that inflow from the Oyashio Current lowers the C : N molar ratio of dissolved organic matter in the bay, whereas inflow of riverine water and the Tsugaru Warm Current raise the C : N molar ratio. These results suggest that the origin of water mass introducing to the bay is as important as the frequency of water exchange with waters from outside of the bay in determining the variation and chemical composition of dissolved organic matter in Otsuchi Bay.

Key words: dissolved organic matter (DOM), dissolved organic carbon (DOC), dissolved organic nitrogen (DON), material cycle, C : N ratio, marine bacteria, western Pacific

Introduction

The accumulation in surface waters and subsequent transportation of dissolved organic carbon (DOC) and dissolved organic nitrogen (DON) into deeper layers may have a large effect on global material cycling (Hedges 1992, Ogawa and Tanoue 2003). Annual fluctuations in DOC and DON concentrations are closely coupled with biological events such as spring blooms of phytoplankton (Carlson et al. 1994, Carlson et al. 1998, Ogawa and Tanoue 2003). In coastal areas, however, mixing with river water and exchange with off-shore water interrupt the accumulation of phytoplankton biomass (Winter et al. 1975, Furuya et al. 1993). Annual fluctuations in phytoplankton biomass and DOC and DON levels in coastal areas are controlled by highly complicated systems where mixing and advection result from the interplay of land topography, river inflow, currents, and weather conditions.

The introduction of allochthonous DOC and DON into coastal areas via river inflow and exchange with offshore water may affect microbial and classical grazing food-web dynamics. The marine bacterial community can use not only the available dissolved organic matter (DOM) released from autochthonous phytoplankton, but also DOM introduced by river runoff or materials transported from other oceanic regions (Hedges et al. 1997, Opsahl and Benner 1997, Williams 2000). Because the chemical properties of DOM as bacterial substrates, such as the C : N ratio, affect the rate of uptake of inorganic nutrients by bacteria, the change of DOM could affect the competition for nutrient uptake between phytoplankton and bacteria (Kirchman 2000, Hasegawa et al. 2005). Thus, qualitative and quantitative changes in DOC and DON levels could have a key role in determining material flow in coastal areas.

Here, we present data on DOC and DON, chlorophyll *a* (Chl *a*) concentrations, bacterial abundance, and environmental parameters, including nutrient levels (NO_3^-, NO_2^-, NH_4^+, and PO_4^{3-}), obtained inter-annually in spring at three different sampling stations in Otsuchi Bay. Otsuchi Bay is a semi-enclosed small bay on the Sanriku ria coast of northeast Japan, opening onto the Pacific Ocean (Fig. 1), and is fed by the Otsuchi, Kotsuchi, and Unosumai Rivers, which produce a river plume with an approximate influx of 3–10 m s^{-1} (Hi-

rano and Hayakawa 1976). The river inflow has a key role controlling water exchange with oceanic water and nutrient concentrations within the bay (Anbo et al. 2005, Otobe 2005). We examined the relationship between DOC and DON dynamics and plankton community metabolism. Our results suggest that two exogenous sources of DOC and DON, i.e., riverine and off-shore water, together with autonomous phytoplankton-derived sources, are important in DOM dynamics in the bay.

Materials and Methods

Study site and sample collection

Water samples were collected from stations M, N, and H, located at the mouth of Otsuchi Bay (39°21′30″N, 141°59′31″E; water depth: 73.3 m), near the center of the bay (39°20′22″N, 141°57′05″ E; water depth: 43 m), and in the vicinity of the Unosumai River mouth (39°20′04″N, 141°55′23″E; water depth: 27 m), respectively (Fig. 1). Sampling dates and depths, water temperature, and salinity at 0 m water depth are summarized in Table 1. Samples were collected using a 5-l Van Dorn sampler. Subsamples for determining bacterial abundance were fixed with formaldehyde (final concentration 2% v/v) and stored at 4°C in the dark until the preparation of slides for microscopic observation. Subsamples for determining concentrations of inorganic nutrients (NH_4^+, NO_2^-, NO_3^-, and PO_4^{3-}) were stored at −20°C. To measure Chl *a*, phytoplankton were immediately collected on a GF/F filter (Whatman International Ltd.) and stored at −20°C in the dark after soaking in 6 ml of N, N-dimethylformamide (Suzuki and Ishimaru 1990). For determination of DOC and DON concentrations, subsamples were immediately filtered through a Whatman GF/F filter with slightly reduced pressure (>700 mmHg) using a hand-operated vacuum pump. The filtrate was stored at −20°C in a glass ampoule.

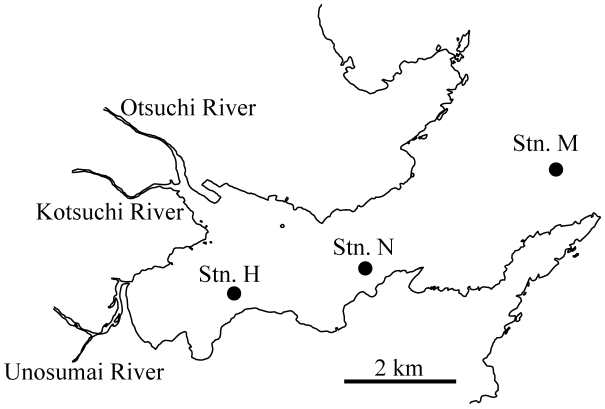

Fig. 1. Locations of sampling stations in Otsuchi Bay, Japan.

Table 1. Sammary of date of survey, sampling site, temperature and salinity at 0 m water depth.

Date of survey	Sampling site	Sampling depth (m)	Temprature (°C)	Salinity
17 May 96	Stn. N	0, 5,10, 17, 25 and 40	8.23	32.01
20 May 96	Stn. N	0, 5, 10, 15, 25 and 40	9.42	28.55
26 August 96	Stn. N	0, 2, 5, 10, 25 and 40	20.50	31.06
27 August 96	Stn. N	0, 2, 5, 10, 30 and 40	20.72	31.99
22 November 96	Stn. N	0, 5, 15, 30 and 40	13.00	32.66
27 November 96	Stn. N	0, 5, 10, 20 and 40	13.21	33.53
7 April 97	Stn. M	0, 5, 10, 20, 50 and 70	7.30	23.45
	Stn. N	0, 5, 10, 20, 30 and 40	8.60	26.16
10 April 97	Stn. N	0, 5, 10, 20, 30 and 40	7.18	23.96
9 June 98	Stn. N	0, 5, 10, 25 and 40	14.56	27.63
11 June 98	Stn. M	0, 5, 10, 20, 30, 50 and 70	11.70	33.44
24 May 00	Stn. N	0, 6, 13, 23, 33 and 42	14.15	23.14
22 May 01	Stn. M	1, 7.5, 25 and 50	10.35	33.44
	Stn. N	1, 7.5, 20 and 35	12.07	32.29
	Stn. H	1, 5 and 20	12.32	32.45
28 May 02	Stn. M	1, 5, 20 and 50	12.09	33.31
	Stn. N	1, 5, 20 and 35	13.41	32.74
	Stn. H	1, 10 and 22	14.28	31.70
21 May 03	Stn. M	1, 10, 20, 40 and 65	11.80	32.44
	Stn. N	1, 10, 20 and 40	12.24	31.66
25 May 04	Stn. M	0, 10, 30 and 65	12.21	28.45
	Stn. N	0, 5, 20 and 40	12.80	20.60
	Stn. H	0, 5 and 22	12.76	22.05
24 May 05	Stn. M	1, 20, 40 and 75	9.84	33.60
	Stn. N	1, 5, 20 and 35	11.68	31.74
	Stn. H	1, 5 and 20	11.75	29.69

Determination of biological parameters and concentrations of DOC, DON, and nutrients

Bacterial abundance was counted directly using epifluorescent microscopy after DAPI staining (Porter and Feig 1980). Bacterial carbon biomass was estimated by assuming the carbon content of a bacterium to be 30×10^{-15} g of carbon, which is the mean carbon content of coastal bacteria (Fukuda et al. 1998). Chl *a* concentrations were determined using fluorometry (Fluorometer 10-AU, Turner Designs; Holme-Hansen et al. 1965) after extraction with N, N-dimethylformamide (Suzuki and Ishimaru 1990) at −20°C for more than 2 days. Phytoplankton carbon biomass was estimated by assuming the carbon : chlorophyll *a* weight ratio to be 50, which is approximately the geometrical mean between the lower- and upper end of the observed range in literature (Laws et al. 2000).

Concentrations of inorganic nutrients (NO_3^-, NO_2^-, NH_4^+, and PO_4^{3-}) were determined colorimetrically using an autoanalyzer (Technicon AA-2 or AACS II or AACS III; Armstrong et al. 1967). DOC and total dissolved nitrogen (TDN) were analyzed using a high-temperature catalytic oxidation (HTCO) system consisting of a commercial unit, the Shimadzu TOC-5000 (Shimadzu Co.), connected to a total nitrogen micro-analyzer, the Yanaco TN-7 (Yanagimoto Co.; Ogawa et al. 1999). The concentration of DON was obtained by subtracting the sum of the concentrations of inorganic nitrogen (NO_3^-, NO_2^-, and NH_4^+) from TDN (Ogawa et al. 1999).

Integrated standing stock of carbon, nitrogen or phosphorus in each chemical and biological component in the water column, *I*, are given by

$$I = q_1\times z_1+\sum_1^{n-1}\left\{\frac{(q_i+q_{i+1})}{2}\times(z_{i+1}-z_i)\right\}+z_n\times(Z-d_n) \quad (1)$$

where q_i is amount of substance at depth z_i, z_i is the *i*th sampling depth from the surface ($i=1, 2, \ldots n$) and Z is water depth at sampling station.

Statistical analysis

All of the statistical analyses were conducted using SPSS (SPSS version 11.0; SPSS Japan Inc.). Before calculations of Pearson's correlation coefficients, normality of variables was tested by the Kolmogorov-Smirnov test. When the log-transformation shorten their Kolmogorov-Smirnov distance, log-transformed variables were used to calculations of Pearson's correlation coefficients.

Results

Physical properties of Otsuchi Bay in the spring

The water temperature at 0 m water depth in April–June varied from 7.30 to 12.21°C, 7.30 to 14.56°C, and 11.75 to 14.28°C at stations M, N, and H, respectively (Table 1). The surface temperatures at station H were higher than at the other two stations, except on 25 May 2004. Salinity in the surface layer varied from 23.45 to 33.60, 26.16 to 32.74, and 22.05 to 32.45 at stations M, N, and H, respectively (Table 1). Although station H was located closer to the mouths of the Otsuchi, Kozuchi, and Unosumai Rivers than was station N, the surface layer salinity at station N was lower than that at station H on 21 May 2001 and 25 May 2004. Hirano and Hayakawa (1976) reported that runoff from the Unosumai River mixed vertically with high salinity water upwelled from lower layers near the mouth of the Unosumai River. They also reported that the mixed water flowed under the river plume from the Otsuchi and Kozuchi Rivers toward the bay mouth. Thus, the contribution of the plume from the three rivers to the surface water may differ between stations H and N.

Spatial distribution of DOC and DON and biological and environmental parameters

The average concentrations (±SD) of dissolved inorganic nitrogen (DIN; $NO_3^-+NO_2^-+NH_4^+$) and phosphate (PO_4^{3-}) at the surface (0−1 m), subsurface (5−20 m), and below (22 m−bottom) at stations M, N, and H for April–June were 1.57±1.77 (n=21), 1.57±1.85 (n=45), and 3.81±2.59 (n=34) μM for DIN and 0.09±0.06 (n=18), 0.16±0.14 (n=39), and 0.34±0.20 (n=34) μM for phosphate, respectively (see Appendix). The average concentrations of DIN and phosphate in the water column in the bay were lower than those in the three river water (Anbo et al. 2005). Concentrations of inorganic nitrogen and phosphate in the surface layer (0−1 m) tended to be higher at stations H and N and decrease with distance off-shore, suggesting the loading of riverine nutrients (Fig. 2C, D). A negative correlation between nitrate concentrations and salinity in the surface layer (0–1 m) (r=−0.698, n=21) confirmed this suggestion.

The Chl *a* concentration fluctuated greatly, as with inorganic nutrient concentrations, whereas levels of bacterial abundance remained within a narrow range (see Appendix). The average (±SD) concentrations of Chl *a* and bacterial abundance at the surface (0–1 m), subsurface (5–20 m), and below (22 m–bottom) obtained at stations M, N, and H in April–June were 3.23±3.15 (n=21), 3.91±3.60 (n=45), and 2.74±2.87 (n=33) $\mu g\,l^{-1}$ for Chl *a* and $1.30\pm0.47\times10^6$ (n=19), $1.25\pm0.52\times10^6$ (n=41) and $0.89\pm0.27\times10^6$ (n=31) cells ml^{-1}, respectively (see Appendix). Chl *a* concentrations in the surface layer (0–1 m) followed a trend similar to that observed in nutrients, i.e., higher at stations H and N, but below the surface layer, their vertical profiles had subsurface peaks at all stations except station M in May 2005, station N in April 1997, June 1998, and May 2001 and station H in May 2001 and May 2004 (Appendix). This accu-

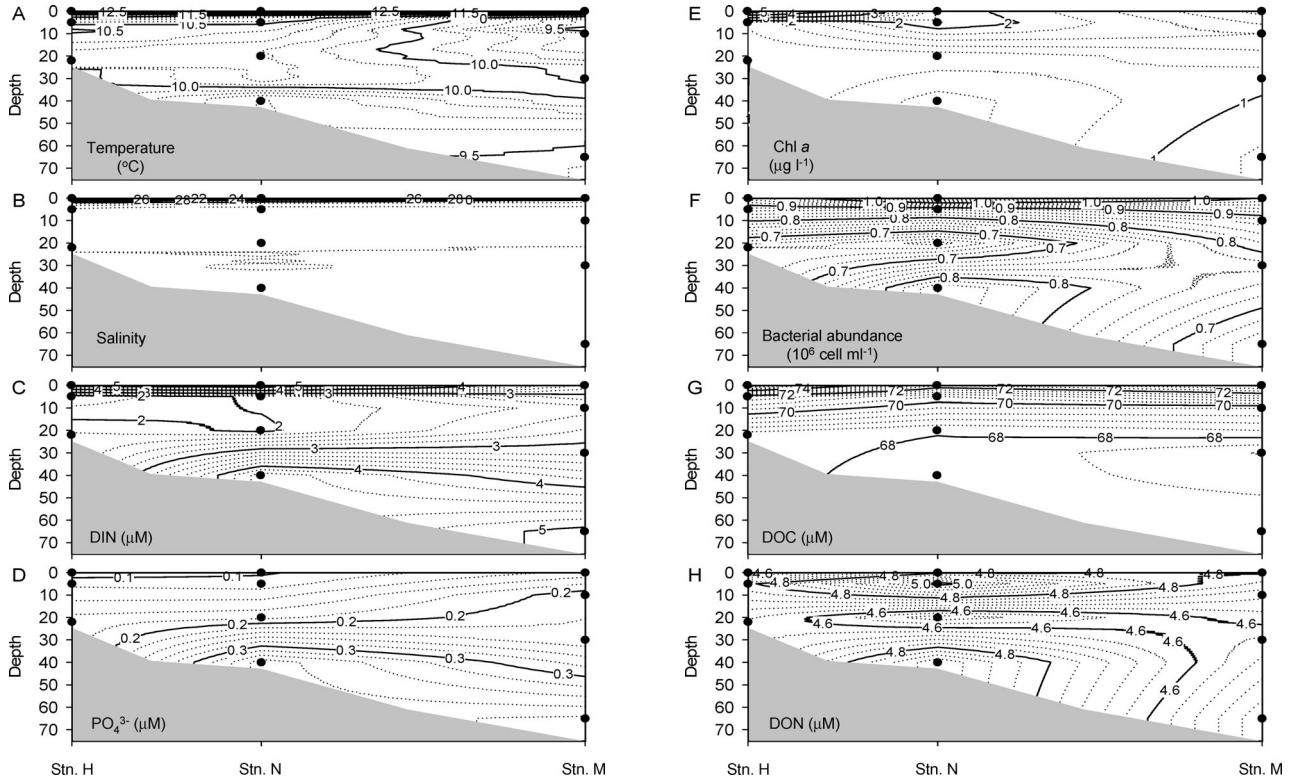

Fig. 2. Vertical and horizontal profiles of (A) temperature, (B) salinity, concentrations of (C) dissolved inorganic nitrogen (DIN: $NO_3^-+NO_2^-+NH_4^+$) and (D) phosphate (PO_4^{3-}), (E) concentration of chlorophyll *a*, (F) bacterial abundance and concentrations of (G) dissolved organic carbon (DOC) and (H) nitrogen (DON) in Otsuchi Bay on 25 May 2006.

mulation of Chl *a* in deeper layers suggests that spring blooms were already in decay periods, in which phytoplankton cells and phytodetritus sink below the subsurface layer. However, the horizontal and vertical variations of bacteria were less than those of Chl *a* concentrations. Because of this low level of variation in bacterial abundance, the effects of river water and subsurface peaks in bacterial abundance were not distinctive (Fig. 2F and Appendix).

DOC concentrations were higher in the surface layers (0−1 m) at three sampling station compared with those in the below depth, except station M in June 1998 and May 2005, station N in May 2005 and station May 2001 (Fig. 2G and Appendix). In addition, DOC concentrations in the surface layer (0–1 m) tended to be higher at stations H and N and decrease with distance off-shore (Fig. 2G and Appendix). These results suggest that a potential source of DOC is the river inflow. On the other hand, the vertical profiles of DOC had the peak in the subsurface layer (5–20 m) in the above exceptional cases, suggesting that another potential source of DOC is autochthonous, possibly of phytoplankton origin. However, DOC concentrations varied within a much narrower range than did the biological parameters (Fig 2E–G and Appendix).

In DON concentration, horizontal and vertical profiles had similar trends with that of DOC (Appendix). However, the increase of DON concentration in the surface layer at the river mouth was not distinctive (Fig. 2H and Appendix). The vertical profiles of DON had the peak in the subsurface layer (5–20 m) similar to that of DOC, suggesting that the DON also released from biological processes within the bay. Although DON concentration varied less than that of DOC, the coefficients of variation (CVs) were almost the same (6.2 and 6.8% for DOC and DON, respectively).

Interannual variation in biological and chemical properties at station N

The integrated standing stock of DIN and PO_4^{3-} in the water column varied from 20.6 to 239 mM m^{-2} and from 5.10 to 27.7 mM m^{-2}, respectively (Fig. 3A). However, there were no significant correlations between the variation in DIN or phosphate and that in phytoplankton carbon or bacterial carbon (Fig. 3A, B). The phytoplankton carbon and bacterial carbon varied from 173 to 2000 and 33.2 to 1.12 mM m^{-2}, respectively (Fig. 3B). The correlation between variations in phytoplankton biomass and bacterial biomass, which is supposed to be linked to phytoplankton activity through the release of dissolved and particulate organic matter (Cole et al. 1988), was not statistically significant ($p>0.05$).

The integrated stocks of DOC and DON (2820–3180 mM m^{-2} and 188–229 mM m^{-2}, respectively) varied within a narrower range than did nutrients and biological parameters. The integrated standing stock of DON increased

over the study period (R=0.882, n=6, $p<0.05$), whereas that of DOC showed no significant trend ($p<0.05$). However, DOC increased gradually after May 2001 (R=0.887, n=5, $p<0.05$). The C : N molar ratio of dissolved organic matter from 9 June 1998 was higher (16.9) than the ratios from other dates (13.8–15.4).

Long-term variation in the integrated standing stock of DIN, PO_4^{3-}, and bacterial biomass tended to decrease during this decade (R=−0.704, n=11, $p<0.05$; R=−0.763, n=11, $p<0.01$; and R=−0.653, n=10, $p<0.05$, respectively), whereas that of Chl *a* did not follow a significant trend ($p<0.05$). However, the integrated standing stocks of nutrients and Chl *a* exhibited higher short-term fluctuation.

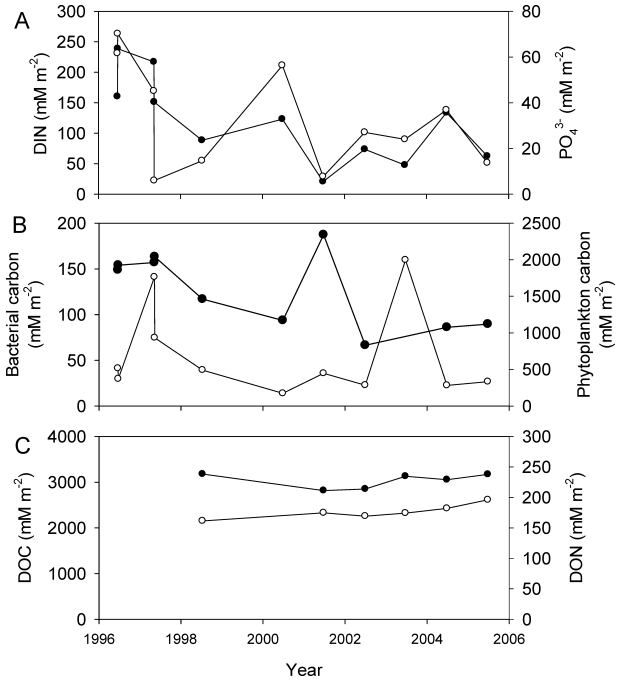

Fig. 3. Changes in the integrated stocks of (A) dissolved inorganic nitrogen (DIN: $NO_3^-+NO_2^-+NH_4^+$; closed circles) and dissolved reactive phosphate (open circles), (B) bacterial carbon (closed circles) and phytoplankton carbon (open circles), and (C) dissolved organic carbon (DOC; closed circles) and dissolved organic nitrogen (DON; open circles) at station N from 17 May 1996 to 24 May 2005.

Correlations among DOC and DON concentrations and biological and environmental parameters in Otsuchi Bay during the spring

Pearson correlation coefficients between components, calculated using a consolidated dataset obtained during the spring period (April–June) from three sampling stations, are presented in Table 2. The DOC concentrations were positively correlated with temperature and Chl *a* concentrations and negatively correlated with salinity. The DON concentrations were only positively correlated with Chl *a* concentrations. There was a significant relationship between DOC and DON. Chl *a* was negatively correlated with temperature, whereas the correlation between Chl *a* and nitrate was insignificant. Correlation between bacterial abundance and Chl *a* suggests that bacterial assemblages were controlled by the supply of dissolved substrates derived from photosynthesis by the phytoplankton assemblage. However, significant relationships between bacterial abundance and DOC and DON were not observed. Bacterial abundance was negatively correlated with salinity and temperature.

Discussion

Previous studies of the dynamics of the phytoplankton assemblage in Otsuchi Bay have indicated that the distribution of phytoplankton in spring is controlled mainly by a combination of water exchange, with subsurface inflow from outside the bay and vertical mixing with or without induction by strong westerly winds (Furuya et al. 1993, Kawamiya et al. 1996). The current of oceanic water with high nitrate and low Chl *a* concentrations washes the phytoplankton population toward the outside of the bay during spring blooms (Furuya et al. 1993, Kawamiya et al. 1996). In the winter, this outflow in the upper layer occurs almost constantly, but occasionally warm water masses originating from the Kuroshio Current intrude into the upper layer and result in outflow in

Table 2. Summary of correlation coefficient among salinity, log-transformed water tenperature (Log Temp: °C), concentrations of dissolved organic carbon (DOC: μM) or nitrogen (DON: μM), log-transformed concentration of nitrate (Log NO_3^-: μM) or chlorophyll *a* (Log Chl *a*: μg L^{-1}) and log-transformed bacterial abundance (Log BA: cells mL^{-1}). Correlation coefficient was calculated using consolidated dataset obtained from three sampling stations during spring (from April to June). N. S. indicates that correlation wasnot statitically significant ($p>0.05$).
(Number of samples)

	Salinity	Log Temp	Log NO_3^-	DOC	DON	Log Chl *a*
DOC	−0.376** (65)	0.294* (65)	N. S. (65)			
DON	N. S. (65)	N. S. (65)	N. S. (65)	0.451** (65)		
Log Chl *a*	N. S. (100)	−0.307** (100)	N. S. (100)	0.427** (64)	0.314* (64)	
Log BA	−0.242* (92)	−0.317** (92)	N. S. (92)	N. S. (56)	N. S. (56)	0.490** (91)

*: $p<0.05$, **: $p<0.01$.

the lower layers (Shikama 1990). In the summer, alteration of the current direction in the upper layer occurs periodically on a cycle of a few days (Shikama 1990).

DOC and DON are released from various metabolic processes including grazing of heterotrophic organisms in marine environments (Nagata 2000). Because the release process for DOC and DON is closely coupled with the activities of organisms, the dynamics of DOC and DON should correlated with primary productivity. The correlations between concentrations of DOC and DON and that of Chl *a* in Otsuchi Bay (Table 2) suggest that biological processes act important role to control the dynamics of DOC and DON in the bay. However, high amounts of refractory DOC and DON in the water column and rapid incorporation of labile DOC and DON by heterotrophic bacteria reduce the seasonal fluctuations of DOC and DON (Ogawa and Tanoue 2003). Correspondently, the variations of DOC and DON in Otsuchi Bay are much fainter than those of bacterial and phytoplankton carbons (Fig. 3). In addition, the inflow of riverine DOC and DON complicates the DOC and DON dynamics in costal areas.

Pearson correlation coefficients for DOC and each parameter indicated that the DOC concentration was significantly correlated not only with Chl *a*, but also with salinity and temperature (Table 2, Fig. 4A, B). The negative correlation between DOC and salinity in the surface layer suggests that inflow of riverine DOC is a dominant factor controlling DOC concentrations in the surface layer (0–1 m) in Otsuchi Bay (Table 2, Fig. 4A). To evaluate the derivation of DOC and DON in the surface layer (0–1 m) and below two layers (5–20 m and 22 m–bottom), we examined the origin of water masses in the bay using the relationship between temperature and salinity because there is frequent exchange of water between Otsuchi Bay and the ocean (Shikama 1990). Hanawa and Mitsudera (1986) categorized, on the temperature–salinity (T–S) plane, the origin or source of waters in the Sanriku coastal area as follows: the water of the Tsugaru Warm Current has temperatures >5°C and a salinity range of 33.7 to 34.2 (Fig 5). Waters with high salinity can be regarded as Kuroshio Water. Oyashio Water has temperatures <7°C and salinity lower than that of the Tsugaru Warm Current.

Using the T–S diagram, most water was categorized as belonging to the surface-layer water system (Fig. 5), which appears in spring and summer and in the upper layers in the Sanriku coastal area (Hanawa and Mitsudera 1986). However, the low temperature and low salinity of bay water suggest that the mixing water mass originated from the Oyashio Current with the surface-layer water in the bay occurred. Hasegawa et al. (unpublished) reported a decrease in the C : N molar ratio of dissolved organic matter in the Oyashio Current in spring. A positive correlation between the C : N molar ratio of dissolved organic matter and temperature is consistent with their results (Fig. 6B). Temperatures >5°C

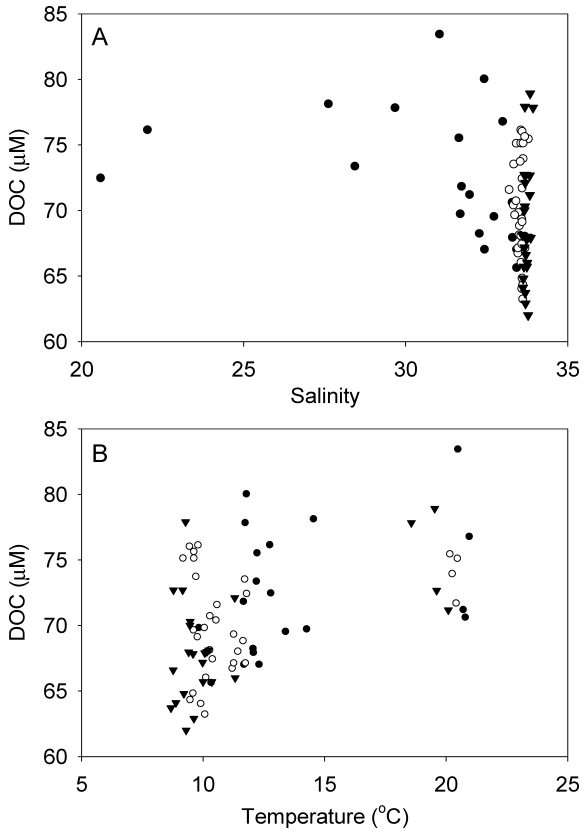

Fig. 4. Relationships between concentration of dissolved organic carbon (DOC) and (A) salinity, and (B) temperature at three different water levels in Otsuchi Bay. Closed circle, opened circle and closed reverse triangle indicate data obtained from 0–2 m, 5–20 m and >22 m at depth, respectively.

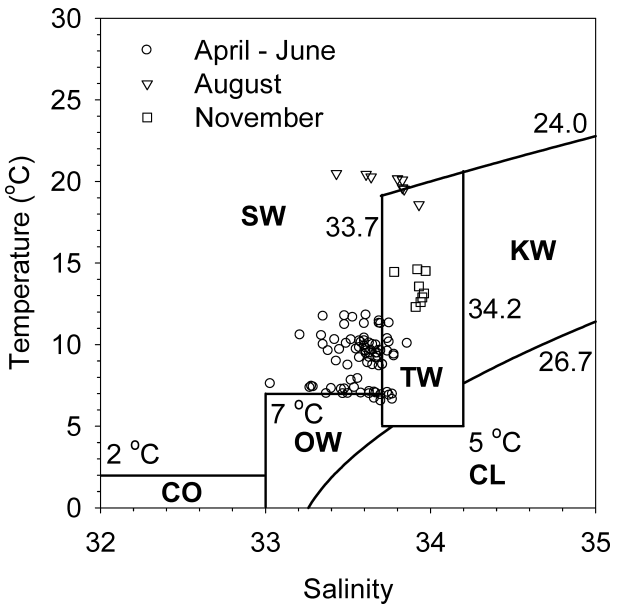

Fig. 5. Temperature–salinity scatter diagram based on the consolidated dataset and classification of six water systems in the Sanriku coastal area in Hanawa and Mitsudera (1987): surface-layer water system (SW); coastal Oyashio water system (CO); Oyashio water system (OW); Tsugaru Warm Current water system (TW); Kuroshio water system (KW); and cold lower-layer water system (CL).

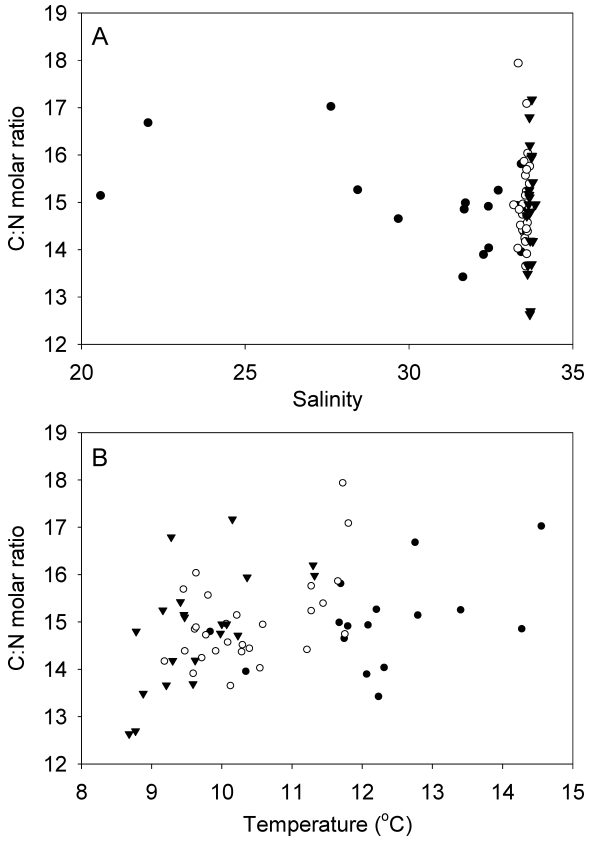

Fig. 6. Relationships between C : N molar ratio of dissolved organic matter and (A) salinity and (B) temperature at three different water levels in Otsuchi Bay. Closed circle, opened circle and closed reverse triangle indicate data obtained from 0–2 m, 5–20 m and >22 m at depth, respectively.

and salinity >33.7 suggest that inflow from the Tsugaru Warm Current occurred, especially in August and November (Fig. 5). Hanawa and Mitsudera (1986) reported that the Tsugaru Warm Current often goes southward along Sanriku ria from July to November. The high DOC and low Chl *a* levels in August 1996 (Appendix) are consistent with the inflow of a water mass of subtropical gyre origin (Ogawa et al. 2003).

In contrast, DON concentrations were not correlated with salinity or temperature (Table 2). With the exception of DOC concentration, DON concentration was only correlated with Chl *a* (Table 2). These results suggest that riverine DON was a minor portion of the autochthonous DON derived from phytoplankton photosynthesis, and that the release of DON, unlike that of DOC, was not stimulated by increased temperature. The high C : N molar ratio in the river water and warm waters are consistent with this speculation (Fig. 6A).

Previous studies of the dynamics of biological and chemical parameters in Otsuchi Bay during spring blooms have indicated the importance of water exchange with water masses from outside the bay and the attending vertical advection (Furuya et al. 1993, Kawamiya et al. 1996). Our results show that the origin of water masses flowing into the bay is also a prevailing factor in the spatial distribution of DOC, DON, nutrients, and plankton. During periods of water mixing in the bay, the differences in water mass origin cause the rapid alteration of physical and chemical properties of microenvironments for planktonic organisms. Our future research will evaluate the effect of these microenvironmental changes on the population dynamics of planktonic organisms.

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Appendix. Summary of samling date, sampling site, sampling depth, water temprature (Temp.), salinity, concentration of chlorophyll *a* (Chl *a*), bacterial abundance, nitrate concentrations of dissolved inorganic nitrogen (NO_3^-, NO_2^- and NH_4^+) and phosphate (PO_4^{3-}), concenrtation of dissolved organic carbon (DOC) and nitrogen (DON) and C : N molar ratio (DOC/DON) of dissolved organic matter.

Date	Sampling site	Depth (m)	Temp. (°C)	Salinity	Chl. *a* ($\mu g\,L^{-1}$)	Bacteria (10^6 cells mL^{-1})	NO_3^- (μM)	NO_2^- (μM)	NH_4^+ (μM)	PO_4^{3-} (μM)	DOC (μM)	DON (μM)	DOC/DON
17 May 96	Stn. N	0	8.23	32.01	2.59	1.4	1.52	0.11	0.36	0.16			
		5	7.60	33.03	3.18	1.4	0.83	0.15	0.37	0.19			
		10	7.44	33.28	4.25	1.3	0.66	0.12	0.36	0.24			
		17	7.36	33.27	4.35	1.6	0.93	0.08	0.61	0.27			
		25	6.99	33.37	2.77	1.3	1.89	0.16	1.53	0.42			
		40	6.99	33.50	0.940	1.2	4.32	0.21	2.90	0.59			
20 May 96	Stn. N	0	9.42	28.55	1.65	1.8	16.7	0.13	0.90	0.16			
		5	7.40	33.29	3.87	2.1	2.79	0.07	0.00	0.16			
		10	7.30	33.40	4.40	1.6	1.61	0.17	0.99	0.31			
		15	7.91	33.56	2.52	1.4	2.44	0.14	1.01	0.33			
		25	7.81	33.52	1.37	1.2	2.89	0.17	1.30	0.38			
		40	6.98	33.47	0.610	1.1	3.69	0.13	3.29	0.64			
26 August 96	Stn. N	0	20.50	31.06	5.97	1.8	0.91	0.04	0.05	0.05	83.4		
		2	20.97	33.01	2.07	1.6	0.16	0.04	0.04	0.05	76.8		
		5	20.48	33.43	1.53	1.2	0.28	0.03	0.02	0.05	75.1		
		10	20.27	33.64	0.903	1.5	0.19	0.04	0.11	0.05	73.9		
		25	20.09	33.83	0.725	1.6	0.10	0.03	0.10	0.05	71.2		
		40	19.61	33.83	1.00	1.5	1.57	0.11	0.64	0.06	72.7		
27 August 96	Stn. N	0	20.72	31.99	0.956	1.3	4.31	0.28	0.55	0.06	71.2		
		2	20.81	33.30	1.32	1.6	2.08	0.14	0.42	0.06	70.6		
		5	20.43	33.61	0.777	1.7	0.20	0.03	0.06	0.05	71.7		
		10	20.17	33.80	0.822	1.8	0.18	0.04	0.10	0.05	75.4		
		30	19.53	33.84	1.59	1.4	0.13	0.03	0.03	0.05	78.9		
		40	18.57	33.93	1.86	1.5	0.15	0.03	0.12	0.05	77.8		

Appendix. Continued.

Date	Sampling site	Depth (m)	Temp. (°C)	Salinity	Chl. *a* (μg L^{-1})	Bacteria (10^6 cells mL^{-1})	NO_3^- (μM)	NO_2^- (μM)	NH_4^+ (μM)	PO_4^{3-} (μM)	DOC (μM)	DON (μM)	DOC/DON
22 November 96	Stn. N	0	13.00	32.66	0.857	1.0	2.40	0.73	0.75	0.28			
		5	14.46	33.78	1.17	0.87	2.10	0.77	0.95	0.27			
		15	14.62	33.92	1.41	0.68	1.76	0.83	0.48	0.24			
		30	14.51	33.97	0.850	0.57	2.17	0.82	0.70	0.29			
		40	12.31	33.91	0.283	0.59	6.60	0.50	0.56	0.58			
25 November 96	Stn. N	0	13.21	33.53	1.61	1.2	2.69	0.60	0.55	0.31			
		5	13.57	33.93	1.72	0.82	2.62	0.60	0.79	0.33			
		10	13.14	33.96	1.88	0.71	3.02	0.58	0.34	0.32			
		20	12.90	33.95	0.741	0.55	4.83	0.47	0.21	0.45			
		40	12.61	33.94	0.316	0.48	6.44	0.44	0.85	0.67			
7 April 97	Stn. N	0	8.60	26.16	3.60	1.7	1.58	0.08	0.22	0.19			
		5	7.36	33.54	8.08	1.5	0.11	0.06	0.25	0.20			
		10	7.12	33.63	6.37	1.7	4.71	0.24	0.31	0.59			
		20	6.70	33.66	11.6	1.6	0.34	0.05	0.08	0.56			
		30	6.89	33.75	7.92	1.1	5.18	0.31	0.13	0.67			
		40	6.54	33.70	13.9	1.2	7.31	0.24	4.15	1.01			
	Stn. M	0	7.30	23.45	3.85	2.1	0.04	0.04	N. D.				
		5	7.26	33.46	2.76	1.8	1.76	0.10	0.47				
		10	7.08	33.66	4.58	1.9	5.84	0.20	0.43				
		20	7.07	33.74	3.79	1.6	7.66	0.19	0.78				
		50	6.96	33.77	2.62	0.95	7.89	0.20	0.29				
		70	6.64	33.77	2.34	0.64	8.03	0.25	0.86				
10 April 97	Stn. N	0	7.18	23.96	3.94	1.9	0.19	0.12	N. D.	0.17			
		5	7.28	33.48	5.32	1.8	1.53	0.23	0.74	0.29			
		10	7.02	33.58	4.10	2.5	2.51	0.29	0.09	0.32			
		20	6.98	33.63	3.14	1.8	5.58	0.17	N. D.	0.50			
		30	7.03	33.67	4.92	0.87	3.88	0.22	0.03	0.50			
		40	6.92	33.70	8.08	0.65	1.64	0.07	0.13	0.49			
9 June 98	Stn. N	0	14.56	27.63	4.40	1.2	0.96	0.03	0.02	0.01	78.1	4.59	17.0
		5	11.73	33.35	2.54	1.1	0.29	0.01	N.D.	0.03	73.5	4.10	17.9
		10	11.81	33.61	1.10	0.86	0.24	0.02	N.D.	0.03	72.4	4.24	17.1
		25	11.30	33.69	4.02	1.0	0.96	0.09	0.40	0.17	72.1	4.45	16.2
		40	10.15	33.75	1.91	1.2	4.07	0.25	0.72	0.42	68.0	3.96	17.2
11 June 98	Stn. M	0	11.70	33.44	4.32	1.2	0.25	0.01	N.D.	0.03	67.0	4.24	15.8
		5	11.66	33.53	7.30	0.98	0.25	0.01	N.D.	0.03	68.8	4.34	15.6
		10	11.45	33.69	5.19	1.1	0.27	0.01	N.D.	0.03	68.0	4.42	15.4
		20	11.28	33.70	5.04	1.2	0.68	0.06	N.D.	0.08	67.1	4.26	15.8
		30	11.32	33.75	3.24	0.94	1.15	0.08	0.04	0.14	66.0	4.13	16.0
		50	10.36	33.74	2.16	0.77	3.55	0.19	0.04	0.31	65.7	4.12	15.9
		70	10.07	33.86	0.670	0.56	4.50	0.24	0.02	0.37	67.9	4.54	15.0
24 May 00	Stn. N	0	14.15	23.14	1.67	1.4	3.23	0.06	0.94	0.12			
		6	10.00	33.35	0.846	1.5	0.29	0.02	0.44	0.06			
		13	9.70	33.45	1.33	0.59	0.22	0.05	0.50	0.14			
		23	8.98	33.43	1.06	0.80	1.17	0.14	1.44	0.25			
		33	8.74	33.50	0.731	0.73	1.68	0.18	1.60	0.51			
		42	8.75	33.65	0.325	0.53	2.87	0.27	2.44	0.49			

Appendix. Continued.

Date	Sampling site	Depth (m)	Temp. (°C)	Salinity	Chl. *a* (μg L^{-1})	Bacteria (10^6 cells mL^{-1})	NO_3^- (μM)	NO_2^- (μM)	NH_4^+ (μM)	PO_4^{3-} (μM)	DOC (μM)	DON (μM)	DOC/DON
22 May 01	Stn. M	1	10.35	33.44	1.18	2.1	0.18	0.02	0.18	0.12	65.6	4.70	13.9
		7.5	9.92	33.60	1.77	1.2	0.32	0.03	0.38	0.19	64.0	4.45	14.4
		25	9.21	33.63	2.33	1.0	0.32	0.03	0.38	0.19	64.8	4.74	13.7
		50	8.68	33.69	1.68	0.99	1.39	0.13	0.70	0.28	63.7	5.04	12.6
	Stn. N	1	12.07	32.29	2.42	1.7	0.23	0.06	0.03	0.07	68.2	4.91	13.9
		7.5	10.13	33.58	2.06	1.9	0.16	0.06	0.11	0.14	66.0	4.84	13.6
		20	9.48	33.63	2.01	1.9	0.28	0.04	0.21	0.17	64.3	4.47	14.4
		35	8.88	33.62	3.09	1.5	0.28	0.04	0.21	0.17	64.1	4.75	13.5
	Stn. H	1	12.32	32.45	1.77	1.7	1.08	0.09	0.31	0.13	67.0	4.78	14.0
		5	10.29	33.52	1.58	1.6	0.32	0.09	0.14	0.10	68.1	4.74	14.4
		20	9.60	33.61	1.65	1.8	0.15	0.05	0.40	0.15	64.8	4.66	13.9
28 May 02	Stn. M	1	12.09	33.31	0.16	0.73	0.00	0.03	0.05	0.02	67.9	4.55	14.9
		5	11.22	33.48	0.10	0.45	0.00	0.04	0.04	0.03	66.7	4.63	14.4
		20	10.09	33.63	1.92	0.49	0.93	0.18	0.39	0.17	63.2	4.34	14.6
		50	9.30	33.78	N. D.	0.49	3.24	0.33	1.11	0.32	62.0	4.37	14.2
	Stn. N	1	13.41	32.74	0.39	0.78	0.00	0.07	0.12	0.06	69.5	4.56	15.2
		5	11.76	33.48	0.20	0.58	0.02	0.11	0.06	0.10	67.1	4.55	14.7
		20	10.40	33.60	4.31	0.56	0.04	0.10	0.04	0.09	67.4	4.67	14.4
		35	9.62	33.70	0.06	0.66	2.25	0.30	1.51	0.29	62.9	4.43	14.2
	Stn. H	1	14.28	31.70	0.32	0.94	0.05	0.08	0.17	0.07	69.7	4.70	14.8
		10	11.28	33.60	1.40	0.73	0.00	0.03	0.08	0.02	69.3	4.55	15.2
		22	10.00	33.65	1.00	0.90	0.98	0.21	0.66	0.21	65.7	4.39	15.0
21 May 03	Stn. M	1	11.80	32.44	10.3		0.04	0.00	0.12	0.09	80.0	5.37	14.9
		10	9.81	33.57	10.2		0.06	0.17	0.09	0.04	76.1	4.89	15.6
		20	9.46	33.61	10.6		0.05	0.04	0.17	0.08	76.0	4.85	15.7
		40	9.16	33.67	7.64		0.57	0.11	0.83	0.18	72.7	4.77	15.2
		65	8.78	33.71	3.33		1.42	0.32	1.48	0.28	72.7	4.91	14.8
	Stn. N	1	12.24	31.66	12.8		0.18	0.03	0.10	0.01	75.5	5.63	13.4
		10	9.72	33.55	6.62		0.03	0.01	0.07	0.05	73.7	5.18	14.2
		20	9.19	33.57	19.6		0.09	0.02	0.16	0.11	75.1	5.30	14.2
		40	8.77	33.71	4.48		1.24	0.21	1.43	0.28	66.6	5.25	12.7
25 May 04	Stn. M	0	12.21	28.45	1.12	1.0	2.17	0.47	0.69	0.15	73.3	4.81	15.3
		10	9.62	33.38	1.60	0.87	1.62	0.51	0.38	0.21	69.6	4.69	14.8
		30	9.98	33.67	1.07	0.77	2.30	0.32	0.52	0.23	67.2	4.55	14.8
		65	9.41	33.78	0.752	0.64	3.78	0.43	0.90	0.38	68.0	4.41	15.4
	Stn. N	0	12.80	20.60	2.16	1.1	4.75	0.24	0.58	0.10	72.4	4.79	15.1
		5	10.55	33.34	2.21	0.86	1.54	0.20	0.32	0.11	70.4	5.02	14.0
		20	10.22	33.57	1.06	0.61	1.01	0.15	0.78	0.17	68.0	4.49	15.1
		40	9.59	33.74	1.49	0.86	2.86	0.39	1.28	0.37	67.8	4.95	13.7
	Stn. H	0	12.76	22.05	5.56	0.95	4.57	0.48	0.30	0.09	76.1	4.57	16.7
		5	10.59	33.21	1.25	0.87	1.02	0.38	0.26	0.12	71.5	4.79	14.9
		22	10.23	33.60	0.999	0.64	1.13	0.32	0.79	0.17	68.1	4.63	14.7

Appendix. Continued.

Date	Sampling site	Depth (m)	Temp. (°C)	Salinity	Chl. *a* (μg L^{-1})	Bacteria (10^6 cells mL^{-1})	NO_3^- (μM)	NO_2^- (μM)	NH_4^+ (μM)	PO_4^{3-} (μM)	DOC (μM)	DON (μM))	DOC/DON
24 May 05	Stn. M	1	9.84	33.6	1.74	0.63	0.30	0.02	0.24	0.05	69.8	4.72	14.8
		20	9.64	33.64	1.65	0.66	0.46	0.01	0.36	0.06	75.1	4.69	16.0
		40	9.47	33.68	1.36	0.61	0.74	0.06	0.45	0.09	70.3	4.66	15.1
		75	9.46	33.67	1.27	0.61	1.06	0.07	0.48	0.12	70.0	4.62	15.2
	Stn. N	1	11.68	31.74	1.89	0.69	1.37	0.07	0.45	0.11	71.8	4.79	15.0
		5	10.07	33.49	1.97	0.84	0.63	0.03	0.23	0.06	69.8	4.67	15.0
		20	9.78	33.61	2.29	0.94	0.46	0.01	0.32	0.09	69.1	4.70	14.7
		35	9.28	33.68	1.36	0.73	1.78	0.12	0.34	0.18	77.9	4.64	16.8
	Stn. H	1	11.75	29.69	1.66	1.5	2.13	0.09	1.02	0.16	77.8	5.31	14.6
		5	10.30	33.42	2.05	0.78	1.04	0.12	0.34	0.11	70.7	4.87	14.5
		20	9.64	33.69	2.05	0.77	1.24	0.06	0.22	0.15	75.6	5.08	14.9

N. D.: Not detectable.