Reports

Indian-Atlantic Transfer of Thermocline Water at the Agulhas Retroflection

Abstract. *During November and December 1983, two anticyclonic eddies were observed west of the Agulhas Retroflection, apparently spawned at the retroflection. The western eddy, centered 300 kilometers southwest of Cape Town, has a winter cooled core encircled by warm Indian Ocean water. Between Cape Town and the "Cape Town Eddy" is a net geostrophic transport of Indian Ocean thermocline water (14 × 10^6 cubic meters per second) into the South Atlantic Ocean. This circulation configuration, similar to that observed by earlier researchers, suggests that Indian-Atlantic thermocline exchange is a common occurrence. Such a warm-water link between the Atlantic and Indian oceans would strongly influence global climate patterns. The Indian Ocean water is warmer than the adjacent South Atlantic water and thus represents a heat input of 2.3 × 10^13 to 47 × 10^13 watts into the Atlantic. The large uncertainty arises from the unknown partition between two possible routes for the return flow from the Atlantic to the Indian Ocean: cooler South Atlantic thermocline water or much colder North Atlantic Deep Water. In either case, interocean mass and heat exchange of thermocline water at the Agulhas Retroflection is a distinct likelihood.*

The major interocean link of the world ocean is the deepwater channel ringing Antarctica. Traditionally, research attention has been directed toward Antarctic Circumpolar Current, which carries relatively cold water from west to east. However, the circumpolar belt is particularly broad between Africa and Antarctica, providing opportunity for interocean exchange of the much warmer and saltier thermocline water. Such an exchange would significantly affect the heat and freshwater balance of the Atlantic Ocean, perhaps related to the anomalous condition of equatorward ocean heat flux across 30°S within the Atlantic (1). Because ocean heat and freshwater flux influences global climate patterns, the possible warmwater link between the Indian and Atlantic oceans might very well be an important climate factor (2). This linkage is explored in this study.

The Agulhas Current forms the western boundary current of the South Indian Ocean, from 27°S to 40°S. The source water at the northern end is derived from the East Madagascar Current and the Mozambique Current (3), although most of the transport [(60 to 70) × 10^6 m³/sec] of the Agulhas Current adjacent to Durban is part of a circulation gyre within the southwest corner of the Indian Ocean (4). The Agulhas Current turns westward as its path follows the southern terminus of the African continent, with separation occurring at the Agulhas Bank near 22°E. After separation the flow executes an abrupt anticyclonic turn to the east in what is referred to as the Agulhas Retroflection (5). Satellite infrared images indicate that the retroflection occurs in two spatial modes, more commonly at 19°E ± 1.5° and a secondary occurrence at 13°E ± 1° (6). The retroflection region is subject to active temporal variability (7). The Agulhas Current loop encloses a pool of Indian Ocean water south of Africa whose temperature is more than 5°C warmer than South Atlantic surface water at similar latitude. This feature supports a large heat flux into the atmosphere of 100 to 125 W/m² (8). Satellite and hydrographic data suggest an exchange of Indian and South Atlantic water at the retroflection, as filaments or eddies of the Agulhas Current are observed southwest of Cape Town (9). Model studies involving the Agulhas Retroflection indicate that interocean exchange would vary with the wind field (2).

From 13 November to 12 December 1983 a hydrographic survey was conducted from the R.V. *Knorr* (Fig. 1) with the objective of resolving thermohaline spatial characteristics of the Agulhas Retroflection (10). The depth of the 10°C isothermal surface is used as a proxy for the sea-surface dynamic height anomaly relative to 1500 dbar. This allows use of the XBT data for improved spatial definition of the thermocline baroclinity. The 1500-dbar surface is not horizontal, but the 1500-dbar dynamic topographic re-

lief relative to the 3000-dbar surface amounts to only 20 percent of the 0- to 1500-dbar relief; hence the 0- to 1500-dbar dynamic topography provides a reasonable depiction of the baroclinic field. There are three anticyclonic centers: (i) a center at 39°S, 24°E, around which is the Agulhas Retroflection; (ii) an elliptical feature at 39°S, 17°E, referred to as the Retroflection Eddy; and (iii) a center at 36°S, 15°E, referred to as the Cape Town Eddy.

The Cape Town Eddy is a cold-cored feature (Figs. 1 and 2) with the surface temperature of the central region 3.5°C colder than that within its high velocity rim. This condition is a consequence of the winter cooling of Indian Ocean water entrapped within an Agulhas ring. The eddy diameter, as defined by the 500-m isobath on the 10°C surface, is 275 Km (11), with a characteristic geostrophic velocity relative to 1500 dbar within the rim of 40 cm/sec, although speeds of over 50 cm/sec occur along the eastern edge. The Rossby number of the Cape Town Eddy is 0.04, representing an essentially geostrophic feature. The Retroflection Eddy has surface geostrophic speeds relative to 1500 dbar along its rim of 50 to 60 cm/sec, and the Agulhas axis within the main retroflection has speeds of about 100 cm/sec.

The net geostrophic volume transport relative to 1500 dbar across the Cape Town Eddy between stations 2 and 8 is 14 × 10^6 m³/sec from the Indian Ocean to the South Atlantic (12). The XBT data show that the warm surface-water rim of the Cape Town Eddy does not extend more than 10 km east of station 3 nor more than 20 km west of station 7, so the transport associated with the eddy rim is resolved by the data set. The 10°C topography and surface temperature patterns (Figs. 1 and 2) indicate that the warm water between the eddy and South Africa is a branch of the Agulhas Current.

The geostrophic volume transport of the Agulhas Current relative to 1500 dbar as resolved by stations 49, 50, and 51 is 47 × 10^6 m³/sec. However, the XBT data reveal that steeply sloped isotherms extend 40 km north of station 49, indicative of strong flux. Extending the same transport versus kilometer function found in the 49/50 station pair an additional 40 km to the north yields a total Agulhas transport of 67 × 10^6 m³/sec. About 20 percent of the Agulhas Current leaks into the South Atlantic.

The surface drifter trajectories are consistent with the circulation configuration represented by the 10°C topography (Fig. 2). One drifter was set out within the core of the Cape Town Eddy, three

within the warmwater–high-velocity rims of the Cape Town and Retroflection eddies, and a fifth within the core of the Retroflection Eddy (Fig. 1). The drifter within the Cape Town Eddy followed repeated anticyclonic turns with a slow westward migration amounting to one eddy diameter until the end of April 1984. At that point it abruptly altered its course and followed the trajectories of the three "rim" drifters to the northwest into the interior of the South Atlantic. Two of the latter executed one and two turns around the Cape Town Eddy before drifting into the South Atlantic, maintaining a surface temperature near 20°C. The drifter within the Retroflection Eddy was captured by the Agulhas Retroflection in early January 1984.

The configuration of the sea-surface dynamic anomaly observed as part of the 1983 *Knorr* cruise is surprisingly similar to that found in a March 1969 hydrographic data set (9). In addition, atlas dynamic topographic maps reveal a topographic high or crest southwest of Cape Town that can be associated with either or both of the South Atlantic or Indian subtropical gyres (13). I suggest that the circulation pattern observed in late 1983 represents a frequently occurring event, during which ~14 × 10⁶ m³/sec of warm Indian Ocean water enters the Atlantic Ocean. This flux represents as much as 50 percent of the Sverdrup transport of the South Atlantic subtropical gyre (14).

There is ambiguity in the heat flux calculations associated with this transfer. The introduction of Indian Ocean water (14 × 10⁶ m³/sec) must be matched by an export of similar magnitude, but at what temperature? Two choices are possible: by passage of colder South Atlantic thermocline water into the Indian Ocean south of the Agulhas Return Current, in which case the subtropical gyres of each ocean are partially linked, or by export of North Atlantic Deep Water (NADW) as the Indian Ocean water crosses the equator to feed the production of NADW (15). In the first case the heat flux from the Indian to the Atlantic amounts to 2.3×10^{13} W (16), whereas in the second case the value is 47×10^{13} W, based on a temperature of 2°C for NADW. The two routes are not mutually exclusive; a 50:50 split amounts to a transfer of 24×10^{13} W. The South Atlantic heat flux is unique in that it is directed toward the equator, in the range of 54 to 86×10^{13} W (1). Thus, it is likely that transfer of warm Indian Ocean water into the Atlantic contributes to the equatorward heat flux if it is frequent enough

and if a significant fraction crosses the equator to be converted eventually to NADW (17).

Thermohaline stratification within the South Indian and South Atlantic thermoclines as viewed in potential temperature–salinity space (θ/S) share a common θ/S curve in the interval from 7° to 15°C corresponding to a σ-t (water density)

range of 26.3 to 27.0 (Fig. 3). At colder temperatures the South Atlantic water is slightly fresher because of the presence of more concentrated Antarctic Intermediate Water (AAIW). Above 15°C the θ/S scatter displays branching. The common θ/S curve for the South Indian and South Atlantic thermoclines may be a consequence of exchange across the Agulhas
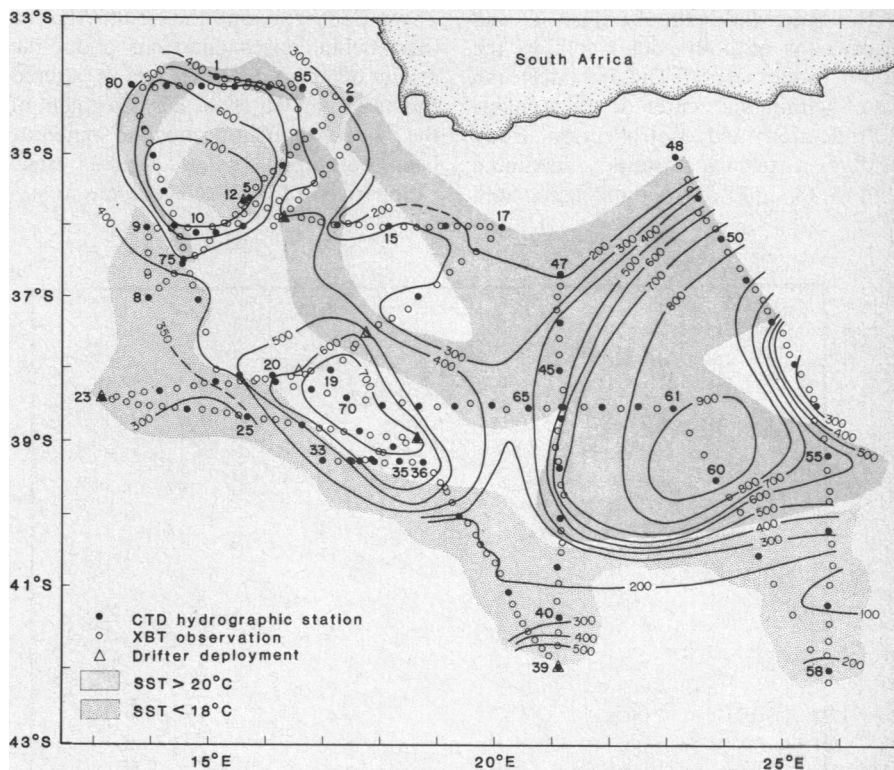

Fig. 1. Distribution of CTD hydrographic stations, XBT observations, and satellite-tracked drifter deployment sites during *Knorr* cruise 104-5, the Agulhas Retroflection cruise, November through December 1983. Sea-surface temperature (SST) above 20°C and below 18°C is shown by the patterned areas. The isopleths define the depth (in meters) of the 10°C surface. This surface depth bears a linear relation with the sea-surface dynamic topography relative to 1500 dbar. The relation is $D_{0/1500} = 1.1046 + 0.0014Z_{10°C}$, with D in dynamic meters and Z in meters. Eighty-five percent of the values are within 50 m of the linear fit along the $Z_{10°C}$ axis.

Fig. 2. Composite of three NOAA-7 (National Oceanic and Atmospheric Administration) infrared images, 7 through 9 December 1983, of the Agulhas Retroflection region. Warm surface water is in lighter tones. Some remnant signature of cold (dark) clouds remains in the southwest. Southwestern South Africa is in the upper right. The trajectories of five satellite-tracked drifters from launch in November 1983 to 6 January 1984 are shown. This image was made available by O. Brown and R. Evans of the University of Miami.

Retroflection. North of 18°S the eastern South Atlantic thermocline abruptly becomes saltier by 0.1 per mil relative to the common thermocline [as well as lower in oxygen, (18)]. This may mark the northern limit of direct contact with Indian Ocean water in the eastern South Atlantic, as also suggested by the drifter trajectories, which crossed the Greenwich meridian (in June 1984, 6 months after deployment) between 23° and 25°S.

The water within the Agulhas axis and warm rims of both eddies follows the South Indian curve. The Indian Ocean water within the center of the Agulhas Retroflection and Retroflection Eddy displays a subsurface salinity maximum (17° to 18°C, 35.57) per mil associated with reduced vertical temperature gradient and an oxygen saturation of 98 percent. This layer is believed to represent the remnant winter mixed layer and is thus called Subtropical Mode Water (STMW).

Within the Cape Town Eddy core is a thick homogeneous layer (16.46°C and 35.59 per mil) with 100 percent oxygen saturation extending from 20 to more than 250 m. The similarity of the Cape Town Eddy core and the South Atlantic thermocline raises questions about the origin of the eddy core. Is it altered Indian Ocean water, or has a segment of the South Atlantic thermocline somehow been entrapped by an Agulhas ring? Comparison of the water column at stations 63 (near the edge of the Agulhas Retroflection) and 70 (the center of the Retroflection Eddy) with station 5 (within the core of the Cape Town Eddy) indicates that the Cape Town Eddy core can be produced from Agulhas water in 1 year with an annual heat flux of 60 W/m² and an annual water loss of 30 cm (19). These values are less than annual values determined independently (8); hence it is likely that the Cape Town Eddy represents winter-modified Indian water. The Cape Town Eddy core has been effectively converted into South Atlantic water by local sea-air exchange processes south of Africa. Even if it eventually is incorporated into the South Atlantic, it would have little impact on interocean transfer of heat or mass (12). However, the flow between the eddy and South Africa does represent a large interocean exchange.

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10. Data were obtained from 85 hydrographic stations with a Neil Brown in situ recording conductivity-temperature-depth (CTD) instrument, with a 24-bottle rosette system for CTD calibration and chemistry; 243 expendable bathythermograph (XBT) T-7 probes were used; five satellite-tracked drifters using the Argos tracking system were deployed.
11. The 500-m isobath on the 10°C surface coincides with the high-velocity axis and with the ring of warm surface water.
12. The volume of water above 10°C within the Cape Town Eddy core is 15 × 10¹² m³ (determined by D. Olson, University of Miami, using the XBT and CTD data set). Hence, should the eddy eventually be incorporated into the South Atlantic gyre, it would contribute only 0.4 × 10⁶ m³/sec.
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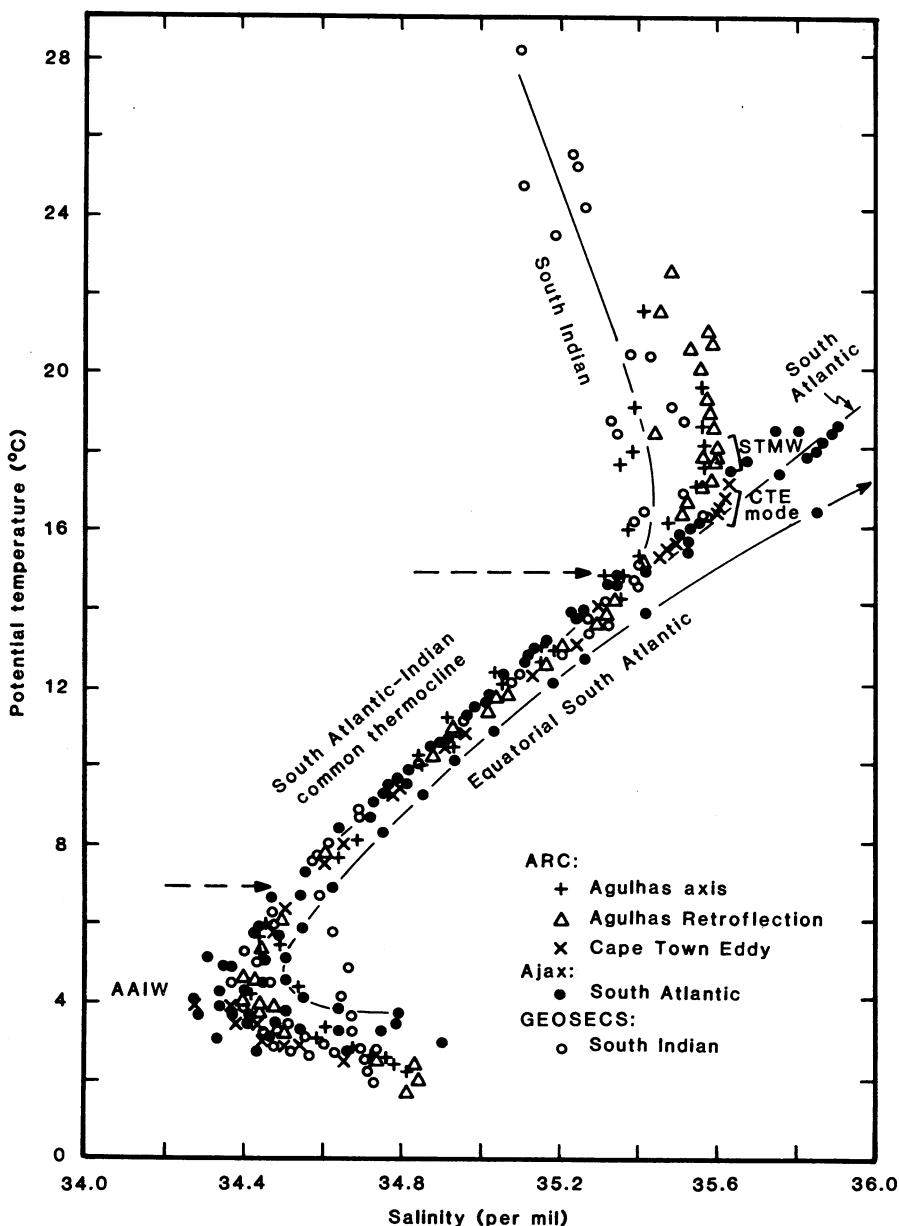

Fig. 3. Plot of potential temperature versus salinity for the eastern South Atlantic from the Ajax cruise aboard Knorr (Knorr cruise 104-4) (18), obtained just prior to the Agulhas Retroflection cruise (ARC), and for the western South Indian Ocean from the GEOSECS data set (18). Select stations from the ARC define three features discussed in the text; CTE, Cape Town Eddy.

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16. This is determined by differencing the transport-weighted temperatures of stations 3 and 4 from those of stations 7 and 8. The 3/4 and 7/8 station pairs represent, respectively, the axis of Indian Ocean water east of the Cape Town Eddy and of the South Atlantic water found west of the eddy.
17. The other source of interocean exchange that could balance NADW export from the Atlantic is the eastward flow of cold water in the Drake Passage. Since the contrast in temperature of that water with NADW is small, a large NADW production rate is required to support the northward heat flux in the South Atlantic.
18. The Ajax bottle data is supplied by J. Reid of Scripps Institute of Oceanography, prior to its complete processing. Similar θ/S structure is displayed in the Geochemical Ocean Sections Study (GEOSECS) data [A. E. Bainbridge, *GEOSECS Atlantic Expedition*, vol. 1, *Hydrographic Data, 1972–1973* (Government Printing Office, Washington, D.C., 1981]. The GEOSECS Indian Ocean data are from R. F. Weiss, W. S. Broecker, H. Craig, and D. Spencer [*GEOSECS Indian Ocean Expedition*, vol. 5, *Hydrographic Data, 1977–1978* (Government Printing Office, Washington, D.C., 1983)].
19. At these stations the 10°C isotherm is at similar depths. The thermal structure differs significantly only in the upper 300 m.
20. This work was supported by Office of Naval Research contract N000-14-84-C-0132. Lamont-Doherty Contribution No. 3763.

Volatile Halogenated Organic Compounds Released to Seawater from Temperate Marine Macroalgae

Abstract. Volatile halogenated organic compounds synthesized by various industrial processes are troublesome pollutants because they are persistent in terrestrial ecosystems and because they may be present in sufficient quantities to alter the natural atmospheric cycles of the halogens. Certain of these compounds, including polybromomethanes and several previously unobserved alkyl monohalides and dihalides, appear to be natural products of the marine environment. A variety of temperate marine macroalgae (the brown algae Ascophyllum nodosum *and* Fucus vesiculosis, *the green algae* Enteromorpha linza *and* Ulva lacta, *and the red alga* Gigartina stellata) *not only contain volatile halogenated organic compounds but also release them to seawater at rates of nanograms to micrograms of each compound per gram of dry algae per day. The macroalgae may be an important source of bromine-containing material released to the atmosphere.*

Volatile halogenated organic compounds (VHOC), including haloforms in drinking water (*1*), chlorinated solvents in ground water (*2*), and halogen-containing methanes, ethanes, and ethylenes in the atmosphere (*3*), have proven to be very bothersome pollutants. Such chemicals are biologically recalcitrant in terrestrial ecosystems, presumably because terrestrial organisms have not evolved with these or related organic compounds as common metabolites; thus their hazardous impacts are very slow to diminish. Furthermore, these halogenated volatiles may be dispersed globally in sufficient quantities to alter the natural geochemical cycles of halogens. If we are to appreciate the impact of such synthetic chemicals, they must be evaluated in the context of related natural compounds and processes, which are still poorly characterized for VHOC (*4*). Although it is recognized that various marine macrophytes (primarily tropical and subtropical rhodophytes) synthesize certain VHOC (*5,6*), the release of VHOC to seawater from such biological sources has not been assessed. If this marine capability is widespread, natural inputs of VHOC to the marine environment through the millennia may (i) have led to the development of marine, microbially mediated degradation pathways of VHOC and (ii) have contributed enormous quantities of volatile, organically bound halogens to the atmosphere, which would have important ramifications for the chemistry of transient species such as ozone and the hydroxyl radical.

In this report we demonstrate that a variety of temperate marine macroalgae (the brown algae *Ascophyllum nodosum* and *Fucus vesiculosis*, the green algae *Enteromorpha linza* and *Ulva lacta*, and a red alga, *Gigartina stellata*) not only contain VHOC (tens to hundreds of nanograms of VHOC per gram of dry weight) but also release these compounds to seawater at rates of nanograms to micrograms of each compound per gram of dry algae per day.

Intertidal macroalgae were collected between August 1983 and January 1984 from three sites around Cape Cod, Massachusetts. Heavily epiphytized plants were avoided, but it was not possible to exclude closely associated microscopic organisms. The algae were incubated for 1 day either in situ in 4-liter jars with Teflon-lined screw-cap lids or in a 34-liter laboratory aquarium maintained without headspace, with natural photoperiods, at the temperature of the water at the collection site. After incubation, a 2-liter sample of water was withdrawn, and the VHOC were concentrated by closed-loop stripping (*7*), with Tenax traps used to collect the VHOC. Our stripping and trapping parameters precluded recovery of extremely volatile compounds such as CH_3Cl and CH_3Br or relatively involatile compounds such as CBr_4 or CHI_3. We identified and quantified the VHOC on the Tenax traps using an HP 5995B benchtop gas chromatograph–mass spectrometer system (GCMS). Seawater and abiotic natural substrates collected at the same sites as the algae and used for controls showed no detectable VHOC production. After the incubations, we froze the algae with liquid nitrogen to disrupt the algal cells and then vacuum-extracted them at 30°C for 3 hours while trapping the released volatiles in a liquid-nitrogen trap (*8*). The VHOC recoveries were compared with and without tissue freezing; the polyhalomethanes were recovered at reduced levels (~20 percent) in the frozen specimens as compared with the fresh algae, whereas the monohalo compounds were recovered slightly more effectively (120 percent) after freezing. The VHOC concentrate was transferred to Tenax traps for GCMS analysis, and dry weights were determined (80°C) on the algal debris.

Five out of six temperate-zone representatives of the Phaeophyta, Chlorophyta, and Rhodophyta exhibited VHOC production and release (Table 1). In light

Table 1. Mean (and range) rates of release of the three major VHOC to seawater by temperate macroalgae (in nanograms per gram of dry algae per day); ND, not detected.

Algal species (Number of samples)	$CHBr_3$	$CHBr_2Cl$	CH_2Br_2
Brown algae			
Ascophyllum nodosum (8)	4,500 (150–12,500)	1,100 (ND–3,000)	680 (ND–2,100)
Fucus vesiculosis (7)	2,200 (140–4,700)	150 (ND–820)	84 (ND–590)
Green algae			
Enteromorpha linza (2)	(ND; 850)	(ND; ND)	(ND; 300)
Ulva lacta (2)	(1,700; 14,000)	(590; 4,300)	(ND; 250)
Red algae			
Chondrus crispus (2)	ND	ND	ND
Gigartina stellata (3)	(ND; 320; 2,100)	(ND; ND; 3,000)	(ND; ND; ND)