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Lagrangian sediment traps for sampling at discrete depths beneath free-drifting icebergs

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Abstract

The recent proliferation of icebergs in the Southern Ocean and the chemical and biological enrichment recently identified in the surrounding water raise the question of whether these icebergs are major contributors to drawdown of CO_2 and the export of organic carbon to the deep ocean. The Lagrangian sediment trap (LST) was developed to measure the carbon export associated with these free-drifting icebergs. The core of the LST is a neutrally buoyant Sounding Oceanographic Lagrangian Observers (SOLO) float (Davis et al., 2001) that contains a variable-buoyancy engine, enabling it to sink to a set depth (600 m for the iceberg study), drift at that depth, then resurface on preset time intervals. Four sediment-trap funnels and opening/closing sample cups mounted around each SOLO float collect sinking particulate matter. Additionally, an upward-looking acoustic system mounted on the float detects the presence of ice cover above. In March/April 2009, three LSTs were deployed in the NW Weddell Sea for a total of five successful missions. Four of these LST deployments were made near or under a large iceberg. The fifth deployment was made at a control site 74 km from the nearest large iceberg. Sinking particulate matter was collected on each deployment. Despite the high-risk nature of the deployments, the LSTs successfully sampled particulate matter beneath drifting icebergs.

Key Words: Lagrangian Sediment Traps, Neutrally-buoyant sediment traps, Icebergs, Weddell Sea, Autonomous instrumentation, Carbon export

1. Introduction

The proliferation of icebergs originating from Antarctic ice shelves and glaciers over the past decade has raised questions about their potential impact on the surrounding pelagic ecosystem of the Southern Ocean. An earlier study suggested that free-drifting icebergs could serve as areas of enhanced production and export of organic carbon to the deep sea (Smith et al., 2007). One of the key issues yet to be resolved in evaluating the role of icebergs in the global carbon cycle is the production and export of particulate organic carbon associated with the surrounding pelagic community. The question remains whether these icebergs significantly influence the carbon cycle of the Southern Ocean.

Determining the amount of particulate matter associated with a large, unstable, chaotically drifting iceberg is a technical challenge. Due to their irregular and, at times, treacherous shapes and propensity to calve without warning, it is prohibitively dangerous to navigate around or beneath icebergs with traditional underwater vehicles such as remotely operated vehicles (ROVs) or autonomous underwater vehicles (AUVs). For an ROV, one considerable risk is entangling the tether connecting the vehicle to the ship on protrusions from the iceberg or on surrounding brash ice (Hobson et al., this issue). AUVs have been used successfully under ice shelves (McPhail et al., 2009**),** however with limited knowledge about the depth profile of the submerged portion of the iceberg (Dowdeswell and Bamber, 2007) it would be precarious to deploy these vehicles. Furthermore, AUVs are typically navigated around fixed targets, but the constant motion of the iceberg makes the frame of reference change for the AUV (Kimball and Rock, this issue). The risk of losing one of these expensive assets if it became trapped under the ice is too great.

Bottom-moored and surface-tethered sediment traps have been used routinely to collect particulate matter through the water column to estimate sinking particle flux. However, there have been serious biases of such designs due to turbulent flow across the collection surface (e.g. Gardner, 1980; Gust et al., 1994; Buesseler et al., 2007). Neutrally buoyant sediment traps were developed to drift with the surrounding water at discrete depths to collect sinking particulate matter while minimizing turbulent flow and contamination by “swimmers” (Buesseler et al., 2000; Lampitt et al., 2008). The neutrally buoyant sediment trap (NBST) was developed to sample upper-ocean particle fluxes at discrete pre-determined depths using an auto-ballasting controller and cylindrical collection tubes that close on recovery (Valdes and Price, 2000). A similar free-drifting sediment trap was designed around an Autonomous Profiling Explorer (APEX) buoyancy engine float with either isobaric or isopycnal capabilities for sampling at a predetermined depth or density surface using four collection funnels (Lampitt et al., 2008).

The more stringent criteria for sampling under free-drifting icebergs required a neutrally buoyant sediment trap that could be quickly deployed to depth in front of an on-coming iceberg, be acoustically tracked during sampling at depth, and be recalled when in open water. Here we describe the development of the Lagrangian sediment trap (LST) and the five deployments made under two icebergs in the NW Weddell Sea during March/April 2009.

2. Lagrangian sediment trap development

For this project, we required a low-cost vehicle that could be deployed autonomously to drift beneath an iceberg and collect sinking particulate matter. Following the collection period, the vehicle would drift clear of the iceberg and safely resurface. The LST consists of five critical components: a descent weight with a guillotine release, a buoyancy engine, an acoustic modem, sediment traps, and surface tracking devices.

2.1 Buoyancy engine

The LST was developed around an existing buoyancy control system, the Sounding Oceanographic Lagrangian Observers (SOLO) float (Davis et al., 2001). These floats have a variable-buoyancy engine and control system enabling them to change their density relative to the surrounding water. SOLO floats can perform over 200 conductivity-temperature-depth (CTD) profiles between 2000 m and the surface over a period of several years. In such missions, the SOLO float sinks to a set depth and drifts along within the surrounding water mass for a pre-programmed interval. At the end of the interval the buoyancy engine pumps oil out of the pressure hull to increase the vehicle's displacement and the float slowly rises to the surface, collecting CTD data on the ascent. On the surface, the SOLO float uses an Argo satellite transmitter to send data back to shore. An additional air bladder fills when the vehicle surfaces to ensure reliable communications to the Argo satellite network in rough seas. The SOLO float was incorporated into an autonomous vertical profiling instrument to estimate particulate organic carbon distribution to 100 m depth in the Southern Ocean (Bishop et al., 2004).

For the iceberg sampling mission, the SOLO floats met several requirements: the ability to sink well below a deep-draft iceberg and drift at a fixed depth for a programmable interval, a means of communicating its position to aid surface recovery, and a cost that did not prohibit deploying several of these instruments on risky missions. One of the technical challenges of this project was to modify the SOLO floats in such a way that they could sample particulate matter sinking beneath icebergs. Combining sediment traps with neutrally buoyant floats has been done for sampling in the open ocean (Valdes, and Price, 2000; Lampitt et al., 2008). The remaining challenge for our study was to use neutrally buoyant sediment traps to sample beneath free-drifting icebergs.

2.2 LST mechanical system

The SOLO float is encased in an anodized aluminum cylinder, 110 cm long and 17.3 cm in external diameter, with a hemispherical top end cap (Davis et al., 2001; Fig. 1). The LST, with all components mounted onto the vehicle, weighs 45 kg in air. The batteries, air valve, pumps, and ball-screw-driven piston are mounted on an internal frame. The oil-filled rubber bladder, located at the bottom of the internal chassis, is protected inside a plastic sleeve. During assembly the internal chassis slides into the cylindrical body and an O-ring provides a seal. The SOLO controller board set is mounted onto a snap ring at the top of the cylindrical housing. The electronics for the CTD (Seabird, SBE 41CP) are housed in the top end cap.

A ball-screw-actuated piston pushes oil in and out of a rubber bladder external to the pressure housing. As more oil is pushed into the bladder, the overall displacement of the vehicle increases, but since the weight remains the same, the vehicle becomes more buoyant. Reversing the process results in the internal void being filled with oil and thus the vehicle becomes denser. The piston is retracted at the commencement of a mission, drawing oil into the housing from the bladder, thus making the vehicle dense and minimizing the time it takes to sink to depth. Once at depth the float controller drives the piston in or out to maintain the programmed depth, allowing the SOLO float to drift with the current. After a preset interval the buoyancy engine pumps oil into the bladder for resurfacing.

In addition to the buoyancy control systems built into the SOLO float, we added two separate weight releases. Because our mission plan consisted of deploying the LST in the path of a drifting iceberg, it was important to have the vehicle sink very quickly to the target depth. To achieve this, a 7-kg descent weight was added to each LST. With the addition of the descent weight, the vehicle could reach 500 m, well below the iceberg, within 15 minutes. The descent weight was attached to the bottom of the vehicle with a piece of monofilament fishing line (45 kg test). The line was fed through a pressure-activated guillotine, which was calibrated to cut the line at 500 m. An ascent weight was also added to the system to increase the speed at which the vehicle resurfaced. The ascent weight was released by a burnwire as described in the electronics section below. The SOLO's buoyancy engine is mainly used to make small corrections in depth and not to change depth by significant amounts.

A conical sediment trap design was chosen for this study to increase the collection area on the neutrally-buoyant platform where turbulence would be minimized (Buesseler et al., 2007). The requirement for short-term collection of as much material as possible outweighed the concern of possible adherence of particles to the walls of the funnels. Four sediment-collecting funnels were mounted on a circular frame that encircles the upper portion of the SOLO float (Fig. 1). The compression rings of the frame were secured above and below the SOLO air bladder to eliminate any restrictions that would prevent filling. Each plastic funnel had a mouth diameter of 31.7 cm and a height of 30.5 cm with an interior surface slope of 25^{o} from vertical. The exit diameter at the bottom of each funnel was 3.8 cm. Four funnels yield a total collection surface area of 0.32 m^2. Each funnel is rigidly mounted on a Ultra-high-molecular-weight polyethylene (UHMW) plastic valve assembly. The valve assembly was designed to allow a 125-ml sample cup to move between three positions relative to the funnel opening. Each cup screws into a carriage that moves along a track between positions. The first and last positions are both "flush" positions, where the sample cup is covered and seawater freely flows through the funnel. The carriage begins the mission at the far left end of the track, held in position by a loaded spring attached to two burnwire releases. When the first burnwire releases, the cups shift from a “flush” position (to the left of center), to a “sample” position centered under the base of the funnel. This is where each cup will reside during the collection phase. When the second burnwire is fired, the cups shift from the “sample” position to a “flush” position (to the right of center). In this “flush” position, the sample cup is sealed to avoid sample loss and contamination by particulate matter during the ascent.

In addition to the two burnwires required to move the sample cup position relative to the opening of the funnel, a third burnwire was used to drop the ascent weight when it was time for the vehicle to resurface. Burnwire releases were chosen for these tasks as they were considered the simplest and most reliable actuators. The burnwires consisted of nylon-coated stainless-steel fishing line (1.4-mm diameter**)** crimped to the conductor wire of a rubber-molded wet cable (RMA-MP1, Impulse). The crimp was then sealed with liquid electrical tape and self-amalgamating tape. A small loop formed at the opposite end of the wire provided a place to tie the line restraining the sample-cup carriage or ascent weight. Finally a 2-mm section of the nylon insulation on the wire loop was removed, providing a small corrodible area that would dissolve when voltage was applied to the wire.

2.3 LST electrical system

The payload on the Lagrangian sediment trap (LST) consisted of electronics designed to communicate with the surface ship, to control burnwire actuators, and to detect the presence of ice above the instrument. Already contained in the chassis of the float was a SOLO controller board, which handled the control of the buoyancy engine, recording of the CTD data, and communication through the ARGO satellite link. To keep the system simple no additional computer was added beyond the SOLO float controller. The SOLO float controller operated independently from the LST electronics, using the original SOLO software. Because of the limited payload, it was important to find components that could satisfy multiple requirements. The two components used were an acoustic modem (ATM-885-4G, Teledyne Benthos, Inc.) and a serial datalogger (Databridge, Acumen). The acoustic modem provided the following functions: communication and ranging to the surface ship, upward acoustic detection of an iceberg, and electronic circuits to activate the burnwires. The modem received commands from acoustic signals and from the datalogger. The serial datalogger had the ability to log to a compact flash drive any data coming from the modem and, equally important, it transmitted commands serially to the modem on a periodic interval. After a command was sent to the modem, the datalogger monitored and recorded the response. The serial datalogger generated the following commands directed to the modem: fire burnwires 1 through 3, ping at 9 kHz, and change operating mode.

Energy for all the LST components was provided by non-rechargeable lithium battery packs. The SOLO controller was powered by a 7.8-V pack containing two DD lithium cells, with a combined capacity of 230 watt-hours. The other components (piston, modem, serial datalogger, etc.) were powered by two 15.6-V battery packs, with a total energy capacity of 940 watt-hours.

2.3.2 Upward-looking sonar

One of the design goals for this project was to build a system that could detect the presence of an iceberg overhead. The actual depths of the icebergs below the surface were unknown. The LST was designed to sink to 600 m, a depth well under the deepest iceberg we expected to encounter (Dowdeswell and Bamber, 2007). The initial expectation for the acoustic system was that it would detect the air-sea interface 600 m above. It was our further expectation that the ice would provide a stronger and closer acoustic reflection than the sea surface. However, evaluating how well this system would detect the presence of an iceberg above the float was not tested prior to deploying in the Antarctic.

The acoustic modem was capable of operating in a transponding mode. A tone burst was transmitted at a set frequency and then, after a short interval, the modem listened for acoustic returns at that same frequency. This mode was originally intended for ranging to other, distant acoustic transponders, but by listening for its own echoes, the modem was able to act as an echo sounder. The tone burst was transmitted every 5 minutes, and the listening period was set to last 2 seconds after each burst, which was long enough to detect a reflection 1500 m away from the sea surface or ice. During our first deployment (Sta. 27) the transponder frequency was set at 12 kHz. The initial data were difficult to interpret so the frequency was changed to 9 kHz to reduce attenuation through the water.

The additional electrical components, the acoustic modem board set, the custom burnwire board, and the serial datalogger were mounted to the internal chassis frame of the SOLO float. Additional space was made available by the removal of battery packs from the original float. Since our missions were only several days long, there was no need to carry the typical battery capacity of the SOLO floats, which can perform over 200 profiles.

2.3.3. Surface tracking

Two systems were in place to aid with surface relocation. The first was the ARGOS transmitter, which was an original component of the SOLO float. The second system used small VHF tracking transmitters. A custom VHF transmitter beacon (Sirtrack) was taped onto the mast of each of the three LSTs (frequencies of 160.720, 160.740, and 160.780 MHz, respectively). Both a portable radio with a Yagi antenna and the ship's radio direction finder were used to receive the transmission signals when the LST surfaced.

2.4 Test drones for LST

Due to the high-risk nature of our iceberg deployments, a low-cost drone unit was developed to initially test our deployment scenario without the risk of losing the more costly LST. The drone was a simple aluminum tube with a removable cap on one end and a plate welded onto the other. The drone was ballasted to be neutrally buoyant at 600 m, the target depth of the LST deployment. The bulk modulus of the 2000-m-depth-rated drone was greater than the surrounding water, so it gained buoyancy as it sank. As on the LST, a guillotine weight-release system was used to drop the descent weight at a depth of 500 m. The ascent weight was dropped by a magnesium release that corroded in seawater after approximately 24 hours. The drones had a VHF radio beacon installed to determine location during recovery. One of the drones was deployed on the iceberg expedition in 2008 (Smith, this issue). The drone's safe journey beneath a small drifting iceberg increased our confidence in deploying the first LST. The drone even survived surfacing in the pack ice, which had unexpectedly encroached during the 24-hour mission.

2.5 Field testing

One of the challenges with the LST was to correctly ballast the modified SOLO system. The variable buoyancy system can only change the vehicle displacement by ± 200 cc. Since we did not have a pressure chamber large enough to hold the float to correctly determine the ballast for each float, each LST was individually deployed on test dives from the R/V *Point Lobos* using the ROV *Ventana* in Monterey Bay. The LST was released autonomously and, with the help of a descent weight, sank quickly to 600 m depth. After the LST was deployed, the ROV was deployed in the same area. Prior to the mission, stainless steel nuts of various weights were secured on the front porch of the ROV. Once the ROV found the LST at its target drift depth (600 m), the float behavior was briefly observed. The LST was ballasted slightly buoyant prior to deployment and initially drifted slowly upward. Using the ROV's manipulator, nuts were dropped into the closed sediment collection funnels. In this fashion, the vehicle was made incrementally heavier until neutral buoyancy was achieved. The number and weights of the nuts were recorded and the final weight calculated for each LST.

2.5.1. Proposed mission scenario

Prior to arriving in the Antarctic, a mission scenario was conceived that started by using radar to track a target iceberg and determine its velocity. With the iceberg's trajectory and speed known, the LST would be deployed from the ship in the iceberg's path. The LST would quickly sink to its target depth with the aid of a disposable descent weight. After releasing the descent weight and reaching the target depth of 600 m, the LST would drift with the currents for a pre-programmed interval of time. The interval would be chosen to allow sufficient time for the iceberg to pass over the LST. Once the iceberg had cleared the LST, the instrument would be commanded acoustically to drop its ascent weight and return to the surface. On the surface the SOLO float controller in the LST would activate the ARGO satellite transmitter, sending a message every 45 sec. When a satellite passed within range of the LST, the signal would be received and an ARGO message would be generated with an estimate of the latitude and longitude of the instrument. Using these coordinates the LST could be located on the surface and recovered.

In practice, many of these steps were difficult to execute smoothly. The first problem was trying to predict the behavior of an iceberg. The motion of icebergs is very chaotic. In one instance an LST was placed in the path of a small iceberg whose course had been tracked for hours. Immediately after the LST deployment the iceberg stopped and abruptly changed course in the opposite direction, away from the instrument rather than towards it. The second unknown was how long to program the LST to drift. It was obviously not possible to estimate where an iceberg would be in a few hours, much less a few days. Surface currents, along with the wind, control the drift of the iceberg (Helly et al., this issue). The drift of the LST is controlled by subsurface currents, much deeper than those which influence the iceberg. The shipboard ADCP measurements were available to a depth of only 300 m and, thus, were not useful for predicting the drift of the LST at 600 m . Therefore, we were unable to predict the course of the LST or the iceberg. It was obvious, however, that if the LST began its ascent too early and the iceberg was still overhead it could easily be lost. In the end, we chose a period of 3.5 days for our deployments around the large icebergs.

3. Results

3.1 Iceberg deployments

The LSTs were deployed in the NW Weddell Sea and Scotia Seas during two cruises, one in June 2008 and a second in March/April 2009 (Smith, this issue). Only one LST was deployed on the 2008 expedition in the Scotia Sea. All indications were that the vehicle performed as expected: sinking, drifting, and resurfacing at the correct intervals. Unfortunately, the LST was damaged during a failed recovery effort and while pieces were sighted near the ship, the float was not seen or heard from (acoustically, ARGOS, or VHF) again. The spring 2009 cruise was far more successful. We deployed and recovered three different LSTs for a total of five deployments (Table 1). The first deployment (Sta. 27) was a very brief test with the LST being deployed in the path of a small iceberg. The LST sonar did not pick up any returns from the iceberg during this 6-hr drift period, indicating that the float was probably never directly beneath the ice.

Three of the following four deployments were under or near C-18a, a long tabular iceberg 35 km long and 6 km wide, with an aerial height of 28 m and a draft of between 150 - 200 m (Sherlock et al., this issue). Using low-resolution satellite images, the latitude and longitude of C-18a was determined. These positions were plotted along with the drop point and recovery point for each deployment (Fig. 3). The resolution was inadequate to determine the exact orientation of the iceberg, so in each case C-18a is plotted as an ellipse.

Although the final four deployments were of similar durations (approximately 3 days), there was a great deal of difference in the drift distances measured (Table 1). For example, deployment Sta. 96 lasted 3.5 days during which time the LST drifted 40.6 km. LST deployment at the control site (Sta. 142) was 3.7 days and drifted only 15.7 km. While LST deployment Stas. 43 and 95 drifted from 2.7 km/day to 8.5 km/day.

Another unpredictable factor was the change in the position and orientation of C-18a throughout each mission. During deployment Stas. 95 and 96, the goal was to put one LST in the path of C-18a and one some distance away. LST (Sta. 96) came very close to the iceberg after being deployed some distance away (Fig. 3c). Further, on deployment Sta. 95, the vehicle was only under the iceberg for a short time, indicating that C-18a probably rotated away from the path of the LST (Fig. 3b).

3.1.1 Summary of deployments

The LST depth profile was highly reliable. Using a descent weight attached to a pressure-activated guillotine, the floats repeatedly reached 500 m in approximately 14 minutes. Controlled by the SOLO float buoyancy engine, the LST sank from 500 m to 600 m in approximately 1.5 hrs. Once at the target depth, the SOLO float held depth with remarkable accuracy. The ascent of the vehicle was acoustically triggered once, and on every other deployment it was triggered internally by a pre-set watchdog timer. Data were recorded during only one ascent, with the duration of the ascent from 600 m lasting approximately 90 minutes. Data from the other ascents were not recorded because during those deployments the watchdog timer ended the mission — a condition under which the software stops recording CTD measurements.

During the drift phase, when the vehicle was hovering around 600 m, CTD data were recorded every 5 to 6 minutes. Figure 4 compares the salinity and temperature measurements recorded by the LST during deployment Sta. 96 with those taken from ship-based CTD casts over the same period. Data from the three concurrent CTD casts were averaged between 590 m and 610 m since the LST does not hover exactly at 600 m. The ship-based measurements were collected between 28 to 31 March. The distances between the CTD casts and the LST drop point were 22.2 km, 18.8 km, and 21.6 km, respectively. The LST measurements display little variation in either salinity (Fig. 4a) or temperature (Fig. 4b) over the 3.5-day drift period at 600 m depth. The ship-based CTD measurements correlate well with those collected on the LST. The LST CTD data salinities were within ± 0.1 PSU and temperatures were within 1^{o}C of the maximum and minimum CTD cast measurements, which revealed more variation in the upper water column (Fig. 4c, d).

3.2 Acoustic detection of iceberg above LST

Figure 5 shows the acoustic returns recorded during two concurrent deployments, Stas. 95 and 96. The drop points for these LSTs were selected in an attempt to get one instrument under C-18a and one in nearby open water. In Figure 5a and c, each acoustic return is plotted as a circle whose y-coordinate is the vertical distance between the LST and the target. The diameter of the circle is proportional to the strength of the signal. All acoustic returns that met the following criteria were plotted; the signal strength was at least half the maximum strength and the distance between the target and the LST was not greater than the drift depth of the LST. This eliminated noise and multiple reflections, and did not change the shape of the plot. The distance between the target and LST was calculated using the elapsed time between the transmission burst and the return signal.

Figure 5 a and b display data from deployment Sta. 95, in which the LST was deployed in the path of C-18a (Fig 3b). A shaded box highlights the drift phase of the deployment, when the LST had reached 600 m and was maintaining depth. The acoustic returns demonstrate that a target, presumably the iceberg, was detected between 450 m and 550 m above the LST for 7 hours during the first day of the mission. The remainder of the returns were centered slightly above 600 m, which would be the air-water interface.

Figure 5b, is a vertical expansion of the acoustic returns during the drift period (plotted as a line). The difference in depth between the air-water interface and the presumed iceberg target was between 108 m and 150 m. These values are in the range of the expected draft of C-18a. During this expedition, the depth of C-18a below the surface was observed during three ROV dives to be 138 m, 185 m, and 190 m (Sherlock et al., this issue). During deployment Sta. 43, the LST also went beneath C-18a for 30 hours of an 80-hour mission. The acoustic returns (not shown) from Sta. 43 indicated an iceberg draft of approximately 150 m.

Figure 5c and d show data from deployment Sta. 96, when the LST was deployed 18.5 km from C-18a (Fig. 3c). The sonar returns hover around 600 m and indicate that the LST was never underneath an iceberg. The depth of the LST recorded by the SOLO float depth-sensor during the drift phase was also 600 m. A scattering of returns were also recorded during the ascent phase as the vehicle approached the surface. About 2.5 days into the mission the sonar detected a strong return from a target 55 m above the float. It is not clear what the target was, although it is most likely one of the marine mammals commonly observed around C-18a.

3.3 Collections in sediment traps

The LSTs were very effective in collecting sinking particulate matter during four deployments beneath and in the vicinity of C-18a. Using deployment Sta. 43 as a representative collection, the particulate matter was dominated by diatoms, including *Corethron pennatum* (Fig. 6a); detrital aggregates formed around radiolarians (Fig. 6b); and fragments of euphausiids (Fig. 6c). Fecal material from euphausiids, smaller crustaceans, and fish were also abundant in the trap collections (Fig. 6d). Small mineral grains were also present in greater numbers in proximity to C-18a than at the “control” site, 74 km away in open water. Detailed descriptions of the structural and chemical composition of the LST collections are given by Smith and associates (this issue).

4. Discussion

4.1 Challenges

4.1.1 LST relocation

Our original deployment scenario was very difficult to execute in the ever-changing conditions of the Southern Ocean. Another unanticipated difficulty was finding the LST once it had surfaced. Several factors combined to make this challenging. The expectation was that once the LST reached the surface and began transmitting to the ARGO system, an electronic message with the approximate latitude and longitude would be received shortly and then location of the LST from the ship would be straightforward.

The first complicating issue was that there were far fewer satellite passes than originally anticipated. Sometimes the passes could be hours apart at our location in the NW Weddell Sea. A further complication was that the ship's electronic mail system retrieved messages only intermittently three times a day. Ultimately a colleague ashore would call the ship's satellite phone to report the position information. The difficulty receiving positive transmissions may have been in part due to the position of the LST in the water. The SOLO float air bladder was found to be empty on some recoveries. A defect in the air valves now has been discovered since our LST deployments, which may explain the erratic messages.

Although we also had a radio (RF) beacon on the LST, with an expected range of ~ 13 km, in reality we only received a radio signal when the instrument was within 5.5 km. Without ARGOS coordinates or a radio signal, the only information available to estimate the LST location was the deployment position and surface current velocity. Unfortunately, none of the shipboard instruments could measure current flow as deep as 600 m, so only the surface currents were used to estimate the direction of LST drift. These drift estimates, we discovered later, had no bearing on the drift of the LST. The relocation process often took many hours.

To improve LST relocation, a higher quality RF beacon will be integrated into the instrument. In addition, a shipboard directional satellite antenna system has been acquired. Direct ARGOS communication will eliminate the need for electronic mail access, which is often unavailable on the ship. The biggest improvement, however, will be achieved by adding an Iridium transmitter and a GPS receiver to the SOLO float. The Iridium transmissions can send the GPS locations to an Iridium phone on the ship. Using the combination of Iridium and GPS, we hope to resolve the position of the LST to within 10 m.

4.1.2 Acoustic communications

Although we were able to range to the LST immediately after deployment, it was not possible to establish an acoustic link with the instrument after one to three days. Probably the LST had drifted much further than estimated ro the ship's noise made acoustic communication difficult.

Overall, using the acoustic modem in a transponder mode to detect the presence of an iceberg overhead was promising (Fig. 5). One upgrade would be to run the modem from a higher voltage battery pack. The standard SOLO float battery pack voltage was close to the lower cutoff of the modem, hence the modem did not transmit at the maximum output power.

4.2 Comparison of LST to other neutrally buoyant sediment traps

Two other neutrally buoyant sediment traps have been developed to collect sinking particulate matter in open ocean situations (Table 2). The design of Valdes and Price (2000) uses four acrylic cylinders (Vertex-style; Knauer et al., 1979) to collect sinking particles with a total collection surface area of 0.017 m^2. These collection tubes are closed across the top when the ballast weight is released for ascent to the surface. The NBST sediment traps have been used very successfully in the North Atlantic and North Pacific (Buesseler et al., 2000, 2007). The PELAGRA sediment trap is similar in design to the LST with four collection funnels constructed around a central APEX float (Lampitt et al., 2008). The collection cups at the base of the funnels are closed upon release of the ballast weight. Unlike these previous designs, the LST was developed specifically to sample under free-drifting ice masses while acoustically monitoring the overlying water and ice conditions. Another unique feature of the LST is that sample cups can be both opened and closed at depth to avoid contamination during descent from and ascent to the surface.

4.3 Future directions

The development of the LSTs to operate under extreme conditions was very successful and provided critical information concerning the export of particulate matter associated with free-drifting icebergs. The LSTs performed the crucial tasks of maintaining depth beneath the iceberg, detecting the iceberg overhead, and sampling sinking particulate matter. Although the LSTs provide a snapshot of the carbon input from drifting icebergs into the Southern Ocean, the difficulty of deploying these vehicles in the path of the icebergs limits the number of data points that can be collected. Ultimately we envision pairing the LSTs with long-term moored observatories that would use traditional sediment traps to capture sinking particulate matter exported to the deep ocean beneath areas of concentrated iceberg activity (e.g. “Iceberg Alley”; Smith, this issue) in the NW Weddell Sea. These observatories would have an upward-looking sonar component, similar in function to that on the LSTs, to detect the presence of an iceberg or the seasonal pack ice. The combination of these assets would allow us to more effectively assess the impact of free-drifting icebergs on the export and sequestration of carbon in the Southern Ocean.

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Figure Legends

Figure 1. The LST design was based on adding sediment traps and an upward-looking sonar to the existing SOLO float. (1) A solid model of the Lagrangian sediment trap (LST) illustrates the placement of the sediment traps (A) on the SOLO frame (B). The collection cups (C) are shown in the collection position. The ARGO satellite antenna (D) and the CTD sensors (E) are mounted on top of the float. (2) A cut-away view of the LST displays the internal mounting of the SOLO controller (F), the serial datalogger (G), and the lithium battery packs (H). In the center of the internal chassis is the piston (I) that pushes oil into the external bladder (J). External to the vehicle are the modem transducer (K) and the descent weight (L).

Figure 2. The LST on deck before a deployment under a drifting iceberg in the NW Weddell Sea.

Figure 3. Four deployments of the LST beneath and in the area surrounding iceberg C-18a. The position of iceberg C-18a was determined from satellite images on both the day of LST deployment (solid line) and the day of recovery (dotted line).. Plotted on the same reference frame is the latitude and longitude of the LST drop sites ("D") and the LST recovery site ("R"). The goal of deployment Stas. 43 (a), 95 (b) and 96 (c) was to deploy the LST beneath and in the immediate vicinity of C-18a. Deployment Sta.142 (d) was a designated "control" site, 74 km away from C-18a. Because the satellite images are very coarse, it was not possible to determine the exact orientation of the ellipse shaped iceberg.

Figure 4. The salinity (a) and temperature (b) measurements taken with the LST (line) and those taken from ship-based CTD casts (dots) at the same depth over the same time period. Vertical profiles of salinity (c) and temperature (d) taken from three CTD casts. The distances between the LST drop site and the three ship-based CTD casts were 22.2km (March 28), 18.8 km (March 29), and 21.7 km (March 31).

Figure 5. The upward-looking sonar returns on the LSTs detecting the presence of an iceberg overhead and the air-sea interface. Each sonar return from Sta. 95 (a) and Sta. 96 (c) is plotted as a circle, whose area is proportional to the signal strength and whose y-coordinate is the calculated vertical distance between the LST and target iceberg or sea surface. A blue-shaded panel highlights the drift phase, during which LST deployment Sta. 95 passes underneath an iceberg (a). A vertical expansion of these acoustic data, plotted as a line to illustrate the surface profile determined acoustically by the LST (Sta. 95). For comparison, acoustic returns from deployment Sta. 96, show no indication of overlying ice (c, d). The acoustic returns all are generated from the air-sea interface which is consistently at 600 m above the LST until the vehicle begins ascending.

Figure 6. Photomicrographs of particulate matter collected in the sample cups of the Lagrangian sediment trap on deployment Sta. 43 beneath and around iceberg C-18a. a) Diatom frustules of *Corethron pennatum*. b) Phytodetritus. c) Fragment of euphausiid (Euphausia sp.). d) String fecal material from euphausiids (brown) and fish fecal pellet (red).

Table Legends

Table 1. Summary of the five LST deployments during the March/April 2009 cruise to the NW Weddell Sea.

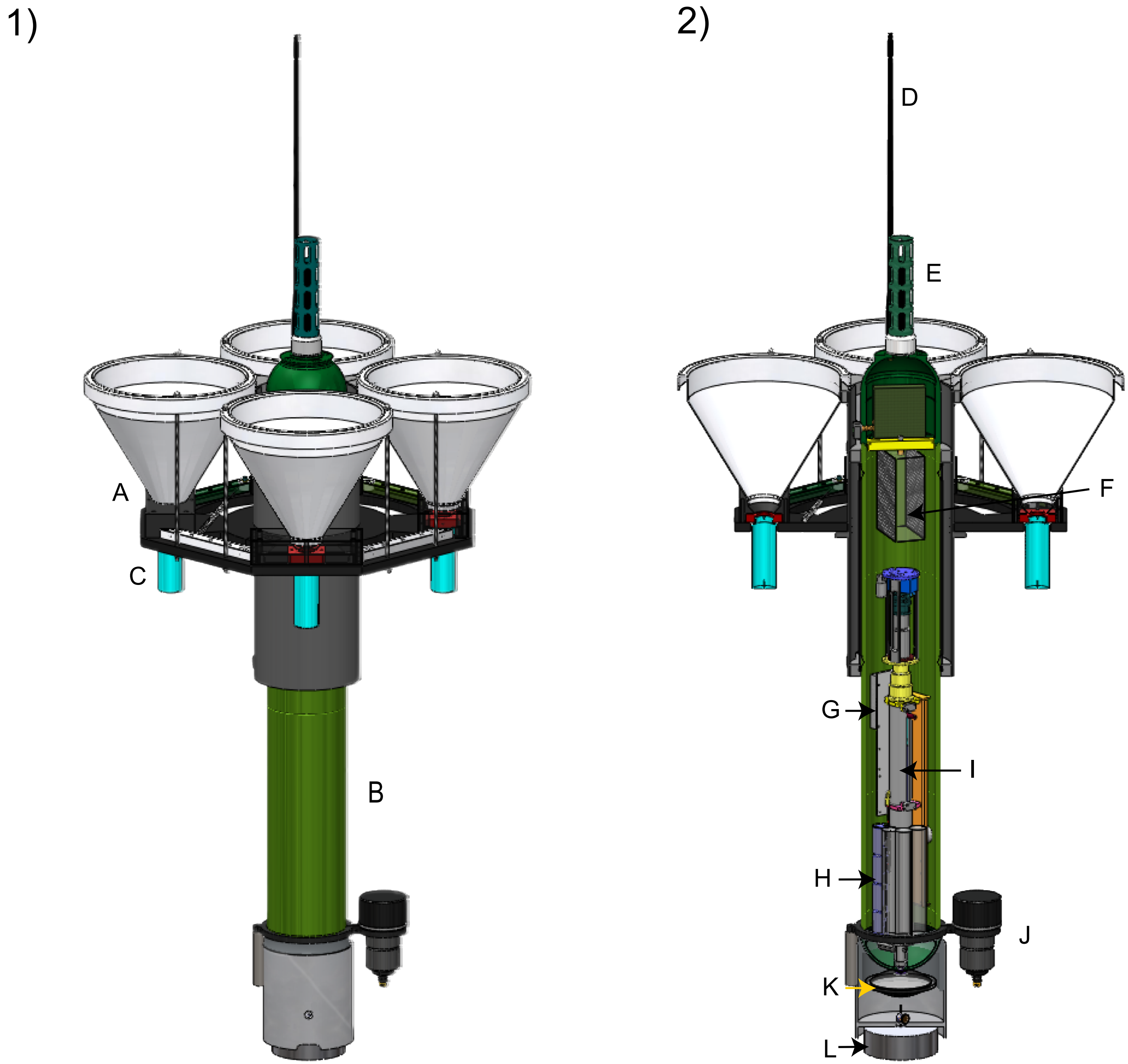
Table 2. Comparison of free-drifting neutrally buoyant sediment traps including the NBST, PELAGRA and LST.

Table 1.

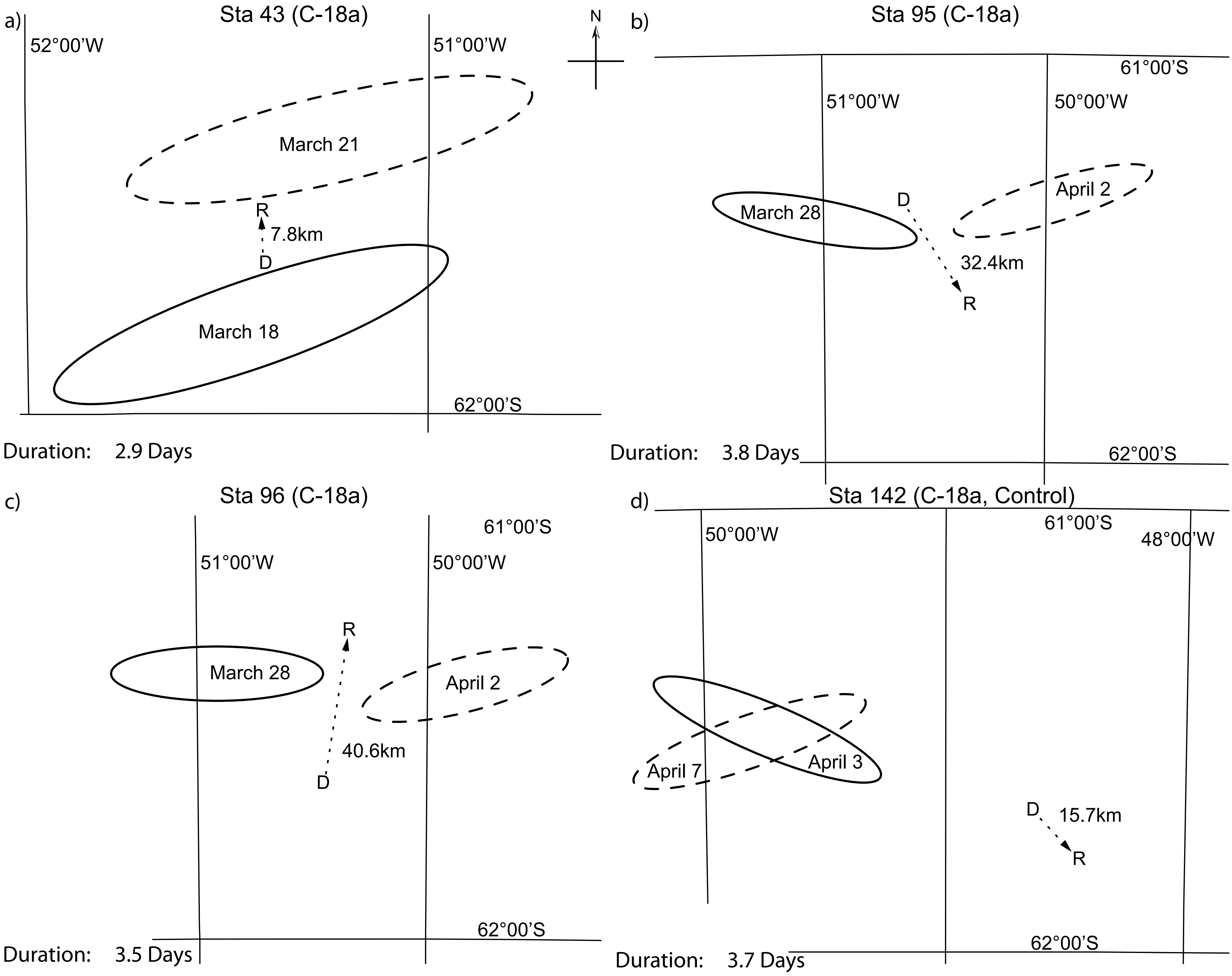
Deployment Number	LST float #	Duration	Drift Distance	Under Iceberg	Notes
27	2745	0.2 days	2.7 km	Probably not	Test
43	2745	2.9 days	7.8 km	Yes	Under C-18a
95	2745	3.8 days	32.4 km	Yes	Under C-18a
96	2833	3.5 days	40.6 km	No	Near proximity
142	2844	3.7 days	15.7 km	No	“Control”

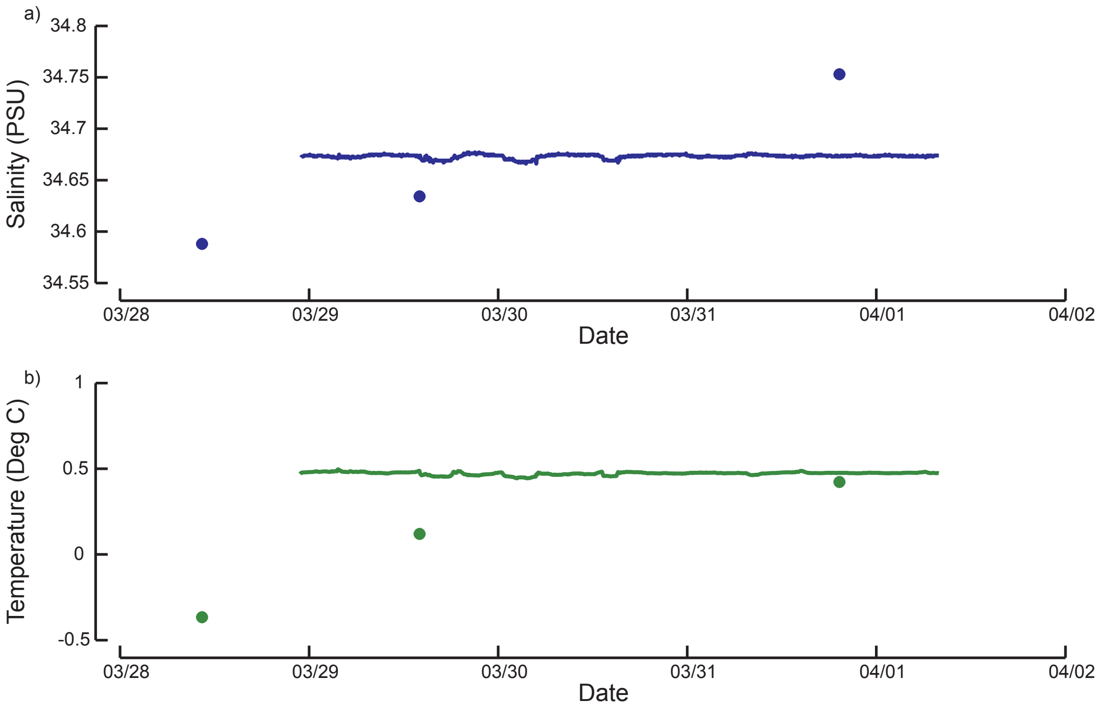
Table 2.

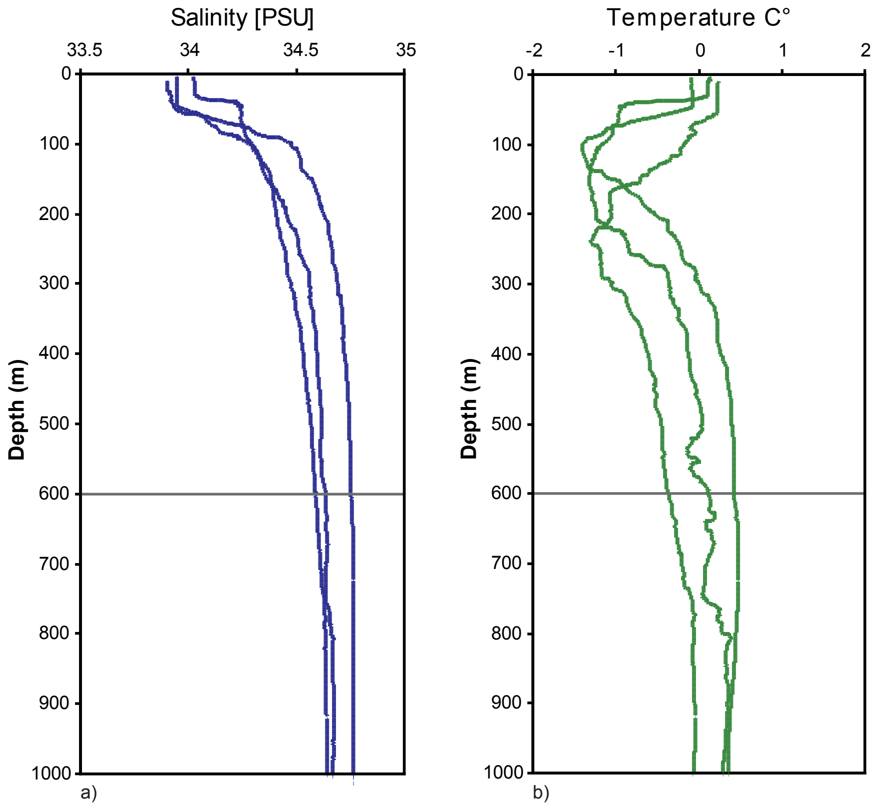
Name	Collection Configuration	# of Samples	Total Collection Area (m^2)	Opening/ Closing	Buoyancy	CTD	Max Operational Depth (m)	Reference
Neutrally - Buoyant Sediment Trap (NBST)	cylinder	4	0.0171	closing (recovery)	volume changer (VOCHA)	No	500m	Valdes and Price, 2000
PELAGRA (Particle Export Lagrangian Trap)	asymmetrical funnel	4	0.46	closing (recovery)	APEX float	Yes	600 m	Lampitt et al. 2008
Lagrangian Sediment Trap (LST)	symmetrical funnel	4	0.32	opening closing	SOLO float	Yes	1500m	This Study

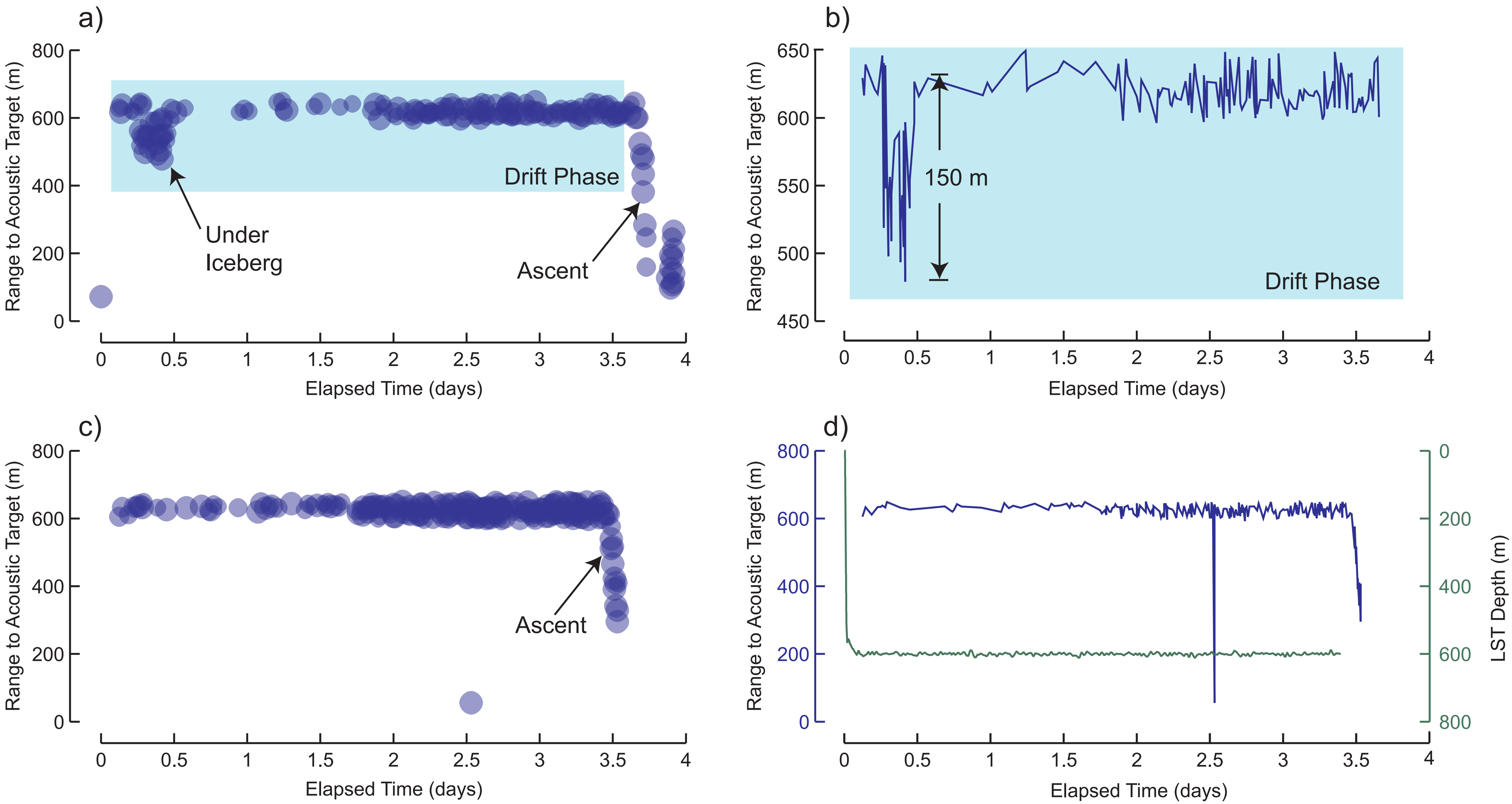


1)
2)
A
B
C
D
E
F
G
H
I
J
K
L

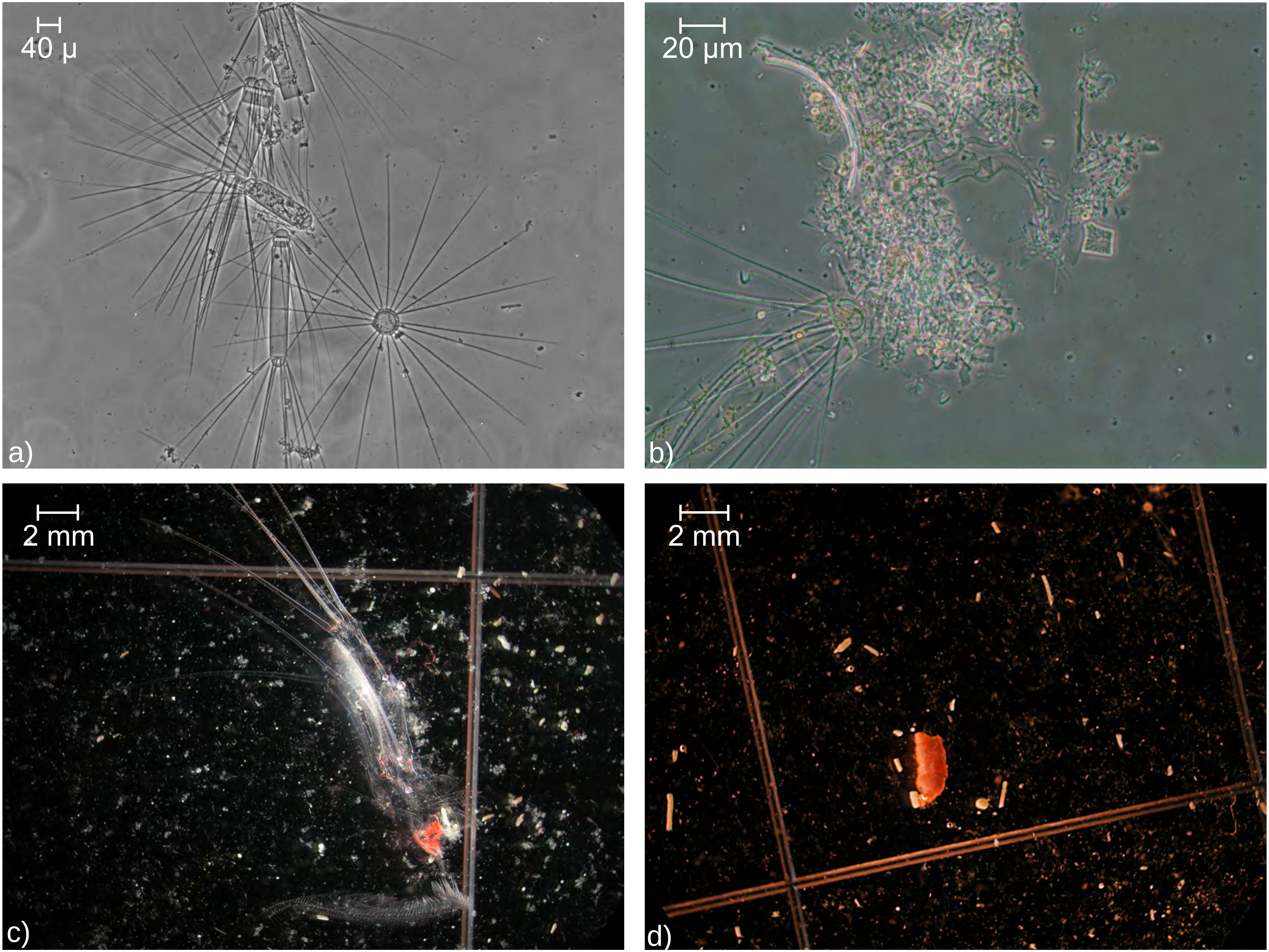

a)
Sta 43 (C-18a)
N
52°00'W
51°00'W
March 21
R
7.8km
D
March 18
62°00'S
Duration: 2.9 Days
b)
Sta 95 (C-18a)
61°00'S
51°00'W
50°00'W
April 2
D
March 28
32.4km
R
Duration: 3.8 Days
62°00'S
c)
Sta 96 (C-18a)
61°00'S
51°00'W
50°00'W
R
March 28
April 2
40.6km
D
62°00'S
Duration: 3.5 Days
d)
Sta 142 (C-18a, Control)
61°00'S
50°00'W
48°00'W
April 7
April 3
D
15.7km
R
62°00'S
Duration: 3.7 Days


a)
Salinity (PSU)
34.8
34.75
34.7
34.65
34.6
34.55
03/28
03/29
03/30
03/31
04/01
04/02
Date
b)
Temperature (Deg C)
1
0.5
0
-0.5
03/28
03/29
03/30
03/31
04/01
04/02
Date


Salinity [PSU]
33.5
34
34.5
35
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
a)
Temperature C°
-2
-1
0
1
2
Depth (m)
0
100
200
300
400
500
600
700
800
900
1000
b)



a)
800
600
400
200
0
Range to Acoustic Target (m)
Drift Phase
Under
Iceberg
Ascent
0
0.5
1
1.5
2
2.5
3
3.5
4
Elapsed Time (days)
b)
650
600
550
500
450
Range to Acoustic Target (m)
150 m
Drift Phase
Elapsed Time (days)
c)
Range to Acoustic Target (m)
Ascent
Elapsed Time (days)
d)
Range to Acoustic Target (m)
LST Depth (m)
0
200
400
600
800
Elapsed Time (days)


40 μ
a)
20 μm
b)
2 mm
c)
2 mm
d)