



## Abstract

The first measurements of bubble size spectra within the near-surface waters of open leads in the central Arctic pack ice were obtained during the Arctic Summer Cloud-Ocean Study (ASCOS) in August 2008 at 87–87.6° N, 1–11° W. A significant number of small bubbles (30–100 µm diameter) were present, with concentration decreasing rapidly with size from 100–560 µm; no bubbles larger than 560 µm were observed. The bubbles were present both during periods of low wind speed ( $U < 6$  m/s) and when ice covered the surface of the lead. The low wind and short open-water fetch precludes production of bubbles by wave breaking suggesting that the bubbles are generated by processes below the surface. When the surface water was open to the atmosphere bubble concentrations increased with increasing heat loss to the atmosphere. The presence of substantial numbers of bubbles is significant because the bursting of bubbles at the surface provides a mechanism for the generation of aerosol and the ejection of biological material from the ocean into the atmosphere. Such a transfer has previously been proposed as a potential climate feedback linking marine biology and Arctic cloud properties.

## 1 Introduction

Bubbles provide an important link between ocean waters and boundary layer clouds. Bursting bubbles at the air-sea interface eject droplets which evaporate to leave aerosol particles consisting of the salts dissolved in sea water, along with any other material contained within the ejected droplet (O'Dowd et al., 2008). Such sea-spray aerosol are typically highly hygroscopic, and act as very effective cloud condensation nuclei (CCN). The radiative properties of clouds and their albedo depend strongly on their droplet size spectra, for which CCN concentration is a controlling factor. The properties of the bubble population within surface waters can thus have a direct influence on cloud properties.

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Stratus clouds are near-ubiquitous over the Arctic pack ice (north of 80°) during the summer months, and are the dominant control on the surface radiation budget (Intrieri et al., 2002). Arctic stratus is very poorly represented within numerical models (Curry et al., 2000; Tjernström et al., 2005, 2008; Birch et al., 2009). Their properties are rather different from those of their mid-latitude counterparts; very low CCN concentrations (Lannerfors et al., 1983; Covert et al., 1996; Bigg et al., 1996; Bigg and Leck, 2001) result in clouds with fewer, but larger droplets, and hence different radiative properties (Tjernström et al., 2008). A series of studies (Leck et al., 1996, 2001, 2004) of atmospheric aerosol over pack ice in the central Arctic Ocean has raised questions as to the source of the aerosol particles that act as CCN. Measurements of CCN composition (Leck and Persson, 1996a, b) are consistent with aerosol grown from the oxidation products of dimethyl sulphide (DMS) released in the uppermost ocean when zooplankton graze on phytoplankton around the biologically productive edges of the pack ice area. In the presence of near-ubiquitous low-level arctic stratus and fog during summer; however, the aerosol would be expected to be scavenged by droplets and not survive long enough to grow from nucleation size ( $\sim 3$  nm diameter) to CCN size ( $\sim 100$  nm). Leck and Bigg (1999) found no sulphuric acid ( $\text{H}_2\text{SO}_4$ ) in aerosol smaller than about 50 nm, implying either recent formation or growth from something other than DMS oxidation products. Leck and Bigg (2005a, b) described observations of particles collected within the atmospheric surface layer, and compared them with those collected from the ocean surface microlayer in open leads (Bigg et al., 2004). The similarity of the morphologies, chemical and physical properties of these particles strongly suggested that the airborne particles originated in the water. Many particles appeared to be microcolloids and their gels (amorphous gel-like material), called copolymer secretions (EPS) or microgels (Decho, 1990). Other particles appeared to consist of bacteria, viruses and fragments of marine microorganisms such as diatoms.

The implication of these findings for the CCN-cloud-radiation interaction over the pack ice area is twofold: (1) fresh EPS aggregates with gel on them could act as CCN directly because of the gel's strong surface-active properties; (2) those that have

lost their gel could still act as sites for condensation of the oxidation products of DMS advected in confined plumes (Lundén et al., 2007) over the pack ice subsequent to its release by plankton at the ice edge (Leck et al., 1996a, b). The detection of insoluble marine microcolloids in most (50–90% of total number counted) of the predominantly sulphate particles (Leck and Bigg, 2005b) is evidence of this. Their acquisition of sulphuric acid provides a much more direct and faster path to CCN status than growth from newly nucleated particles (Leck and Bigg, 1999).

Although these previous studies suggest that biogenically derived material from the open leads is transferred to the atmosphere, many aspects of the process remain uncertain. Bubble bursting within open leads is the most likely transfer mechanism. In the open ocean the dominant source of bubbles is the breaking of wind-generated waves (Kolovayev, 1976). Within the central Arctic, however, wind speeds are typically low, and the extent of open water within leads in the pack ice is usually modest (10–30%) so that fetches are short and the generation of waves is limited. Leck et al. (2002) measured aerosol size spectra for cases both with and without breaking waves within open leads and concluded that film drop (centred on 100 nm diameter) generation depended less, and jet drop (centred on 1 µm diameter) production more on wind speed than over the open ocean. The enhanced presence of film drop particles at winds speeds  $<5 \text{ m s}^{-1}$  suggested a source of bubbles other than from wind generated waves. Non-wave related sources of bubbles include the release of bubbles trapped in melting sea ice, expelled by freezing water (Wettlaufer, 1998), produced by the respiration of phytoplankton (Medwin, 1970; Johnson and Wangersky, 1987), or released from the sea bed (e.g., Leighton and Robb, 2008).

We present the first direct measurements of bubbles within open leads in sea ice in the central Arctic Ocean: including details of the typical size spectra, the observed variability in bubble concentrations, and to some extent their dependence on environmental conditions. Our purpose is to evaluate the bubble measurements only; we do not attempt here to assess any of the – very extensive – aerosol measurements made during ASCOS. Detailed studies of the physical and chemical properties of particles

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sampled from the air (below, within, and above cloud), the ocean surface microlayer, and from collected fog/cloud droplets are underway and will be presented in future papers.

## 2 Measurements

### 2.1 The field campaign

The measurements presented here were made as part of The Arctic Summer Cloud-Ocean Study (ASCOS, [www.ascos.se](http://www.ascos.se)) field campaign in the central Arctic Ocean. Based on the icebreaker Oden, between 1 August and 8 September 2008 ASCOS was designed to be a highly interdisciplinary study of Arctic summer stratus and the many processes that control its properties and coupling it to the surface, including: synoptic meteorology, boundary layer mean and turbulent structure, cloud macro- and microphysical properties, marine biochemistry, aerosol physical and chemical properties, and gas-phase chemistry.

During the main observation period of 13 August–1 September the Oden was moored to an ice floe, and drifted with it within the region 87.0–87.6° N, 1–11° W (Fig. 1). The ice-drift spanned the end of the summer melt season and the onset of the autumn freeze-up. The ice floe was approximately 6 km by 3 km – one of the largest in a region of closely packed ice floes of widely varying sizes (Fig. 2a).

### 2.2 Bubble measurements

The bubble measurements were made at a field site established at the edge of an open lead (Fig. 2) approximately 3 km from the Oden – chosen so as to avoid contamination of marine bio-chemistry samples by the ship. The width of the open lead varied from day to day with the movement of the ice from approximately 20 m to 100 m. Bubble size spectra were measured with a video-based bubble imaging system

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with an effective measurement range of 30–1000  $\mu\text{m}$  (diameter). The sample volume ( $20 \times 2.9 \times 1.9 \text{ mm}^3$ ) is imaged by a video camera, and illuminated on-axis from directly opposite the camera. Bubbles appear as a dark ring with a brighter surrounding ring and central bright spot. An automated algorithm identifies candidate bubbles, while rejecting other particles such as algae. Full technical details of system and image processing algorithms are given by Leifer et al. (2002). This system has previously been used to determine bubble size spectra both in the open ocean (de Leeuw and Cohen, 2001; de Leeuw et al., 2003; Brooks et al., 2009) where close agreement has been found with spectra measured via acoustic techniques (Brooks et al. 2009), and in the laboratory (Mårtensson et al., 2003; Sellegri et al., 2006; Fuentes et al., 2010a, b).

The bubble camera was suspended from a buoy positioned approximately 2 m from the ice edge, with its field of view located approximately 0.7 m below the surface (Fig. 3). Images were obtained in bursts of 100 frames sampled at 20 Hz; image acquisition pauses briefly while these are written to disk and is then resumed. Data collection continued in this manner over 2-min periods at 15 min intervals throughout the days on which the remote field site was manned. 126 2-min samples were obtained over a total of 32 h during 10 days between 17 August and 1 September; a total of approximately 194 000 images. The individual bubbles identified by the image processing algorithm are sized and aggregated to produce spectra over each 2-min sampling period.

The water within the Arctic leads had much lower levels of turbulence than the open ocean or laboratory flows in which the system has previously been used. This occasionally resulted in single bubbles becoming stuck to one of the windows through which they are illuminated and imaged, resulting in one bubble being repeatedly sampled throughout a large fraction of an averaging period, biasing the sample and producing a pronounced spike in the size spectra. Where such spikes were observed, all the contributing images have been individually checked, stuck bubbles identified and sized, and the spectra corrected.

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## 2.3 Measurements of mean environmental conditions

Supporting measurements of oceanographic and meteorological conditions were obtained at sites located within about 500 m of the ship. A 10-m wind speed was derived from a logarithmic profile fit to sonic anemometer measurements on a micrometeorological mast; the near-surface air temperature was measured by an aspirated thermocouple at 1.02 m on the mast. Ocean current velocity relative to the ice and the turbulent stress were measured by a Sontek/YSI Acoustic Doppler Velocimeter mounted on a sub-surface mast located in a bore hole through the ice. Water temperature was measured by a Seabird Electronics SBE-3 sensor at a depth of 2 m below the underside of the ice; approximately 3.8 m below the ocean surface. The ice drift velocity and floe orientation are derived from continuous measurements of GPS position at the oceanography and meteorological tower sites.

## 3 Results

### 3.1 Bubble size spectra

Figure 4 shows time series of mean conditions during the ice drift with the periods during which bubble measurements were obtained highlighted. During the first 4 days of bubble measurements (17–20 August) the lead was completely ice free; following a sharp drop in temperature on the 21st – primarily the result of cold air advected into the region – the surface of the lead started to freeze and by the 22nd was covered with a layer of frazil ice about 5 cm deep. On the 27th the surface of the lead opened up exposing open water again; it remained largely ice free for the remainder of the campaign although fragments of ice collected along the lead edge and around the buoy.

The maximum wind speed during the bubble measurements was  $6 \text{ m s}^{-1}$ . The water temperature spanned a very narrow range from  $-1.66$  to  $-1.72$  °C, with an average of

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–1.7°C, while the air temperature varied between 0 and –6°C during the majority of the ice drift, falling to –12°C early on 1 September, rising again to –7.5°C during the last period of bubble measurements. The salinity of the ocean mixed layer was approximately 32.3 psu, varying very little during the campaign. The velocity of subsurface water relative to the ice floe ( $V_{rel}$ ), and the drift speed of the ice ( $V_d$ ) vary between 0 and 0.1 m s<sup>-1</sup> during the measurement period and are correlated both with each other (correlation coefficient=0.46) and the local wind speed (correlation coefficients=0.5, 0.36, respectively). The drift velocity also displays a distinct semi-diurnal periodicity associated with both tidal motions and inertial currents.

The mean bubble spectra for each day are shown in Fig. 5 along with a number of open ocean and surf zone spectra for comparison; the means and the standard errors about the means of concentrations for each spectra are listed in Table 1. The concentrations of bubbles with diameters less than 100 µm are comparable to those reported in the open ocean under moderate wind speeds, of order 10 m s<sup>-1</sup>. For bubbles larger than 100 µm the Arctic number concentrations decrease more rapidly with size than for the open ocean cases; the mean logarithmic gradient of  $dN/dD$  with  $D$  for the arctic spectra ( $D > 100$  µm) is  $-5.1 \pm 0.35$ , about double the mean gradient of  $-2.6 \pm 0.46$  for the open ocean spectra. For mean diameters of 200–560 µm the number concentrations are roughly comparable with open ocean measurements under winds of about 5 m s<sup>-1</sup>, which is approximately the minimum wind speed for which whitecapping occurs. The maximum size of bubbles observed varied from day to day between approximately 200 and 560 µm; very few samples contained bubbles larger than about 270 µm and no bubbles were observed larger than 560 µm. The typical variability between the individual 2-min estimates of the spectra is illustrated in Fig. 6, where the individual estimates and mean spectra are shown for 17 and 31 August – the cases with lowest and highest mean concentrations, respectively.

Figure 7 shows all the individual 2-min estimates of total number concentration along with the daily means. The mean values span about one order of magnitude and are roughly clustered into low concentrations ( $< 2.4$  cm<sup>-3</sup>; on 17, 18, 21, and 26 August)

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and higher concentrations ( $>5.8 \text{ cm}^{-3}$ ; on 19, 20, 27, 29, 30, 31 August, and 1 September). The lower concentration cases correspond with cases where the lead is either mostly frozen over (21, 26 August) or the flow is out from under the large ice floe on which the surface measurements were based (17, 18 August). The higher concentration cases, with the exception of 1 September, all have a local current from the lead towards the ice edge and a substantial area of open water within the lead. On 30 August the lead began to freeze over as the temperature dropped rapidly and by 1 September was completely frozen over.

### 3.2 Variability with environmental conditions

An examination of the bubble number concentration as a function of the various mean atmosphere and ocean conditions reveals little in the way of convincing relationships, with the exception of the air-sea temperature difference (not shown). Along with wind speed the air-sea temperature difference drives the surface heat flux; Fig. 8 shows the total bubble number concentrations plotted against the surface heat flux estimated from the SHEBA bulk flux algorithm (Andreas et al., 2010a, b); a water surface is specified for cases when the lead open, and an ice surface when it is frozen over. It should be noted that owing to the short fetch across the lead near-surface turbulence is unlikely to have reached a state of equilibrium and the flux can be considered an indicative approximation only. Although direct flux measurements were made at the open lead site we use a bulk flux estimate because the flux system at the ice edge was either not operating, or the data failed quality control test for most of the periods for which bubble measurements were made. Where good quality flux measurements were available the SHEBA bulk algorithm is in good qualitative agreement, but tended to slightly overestimate the magnitude of the sensible heat flux. Here we are concerned primarily with relative changes in the surface flux and a slight bias in absolute magnitude does not affect our conclusions. On the days on which the lead is largely ice-free there is a distinct trend of increasing bubble concentrations with increasing positive heat fluxes

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(heat transfer from surface to atmosphere); the range of negative heat fluxes is too narrow to reveal any systematic behaviour, but on these two days (19, 20 August) the total number concentration differs little from that for the cases with positive fluxes less than  $10 \text{ W m}^{-2}$ . Where the lead is frozen or the flow is from under the large ice floe, the bubble concentrations show little variability and no systematic dependence on the surface heat flux. 1 September is an isolated case – the lead is frozen but the bubble concentration remains relatively high.

## 4 Discussion

### 4.1 Implications for aerosol production

The presence of significant numbers of bubbles within the near-surface waters of leads in Arctic sea ice provides support for a bubble-mediated mechanism for transporting highly surface-active gels with embedded aggregated microcolloids into the atmosphere as suggested by Leck and Bigg (1999, 2005a); and Bigg and Leck (2008). Such materials are scavenged from the bulk water by the rising bubble and further enriched with respect to bulk sea water composition as the bubble protrudes the surface microlayer; this material is ejected into the atmosphere as film droplets, and jet droplets the composition of which likely has a greater sea-water content.

The bubbles observed here were all smaller than  $560 \mu\text{m}$  mean diameter and the majority (by approximately 2 orders of magnitude) were smaller than  $100 \mu\text{m}$ . The size and number of droplets produced by a single bubble depends on the bubble size (Blanchard, 1983). The smallest bubbles produce only jet droplets, the largest only film droplets; the limits are not well defined, however, and depend on the properties of both water and surface microlayer. Day (1964) found a bubble diameter of  $\sim 100 \mu\text{m}$  to be the minimum size producing film droplets while Spiel (1998) found the limit to be  $2.4 \text{ mm}$ ; and the upper limit for the production of jet droplets to be about  $3.4 \text{ mm}$  (Spiel, 1997). During high wind episodes ( $> 12 \text{ m s}^{-1}$ ) Leck et al. (2002) found both the film

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and jet drops to have a strong exponential wind-speed dependence. For low winds (around  $5 \text{ m s}^{-1}$  or lower) similar to this study, however, Leck et al. (2002) observed an enhanced presence of film drops. Given the bubble sizes observed here, this implies that the bubble size limits for production of jet and film droplets might differ substantially from those found in the laboratory studies cited above. The extent to which aerosol generated from bubble bursting within the leads contributes to the overall aerosol load within the boundary layer relative to nucleation of new aerosol particles or entrainment of aerosol from above the boundary layer remains an open question. Eddy covariance measurements of the total aerosol number flux during ASCOS confirm that the leads do act as a source of aerosol, but that this flux cannot explain the magnitude of observed changes in aerosol concentration over time (Held et al., 2010).

## 4.2 Production mechanisms

The measurements made during this study do not provide any information on the mechanisms by which the observed bubbles were generated, although we can be confident that they do not arise from wind generated wave breaking processes. Here we speculate briefly about potential production mechanisms. The dependence of the observed number concentration on open surface water and the surface heat flux suggests exchange processes with the atmosphere are important. A plausible mechanism is that, in the low turbulence environment of the open lead, a thin layer of surface water approaches gas saturation in equilibrium with the local atmospheric conditions. Loss of heat to the atmosphere will result in this layer of surface water being cooled below the bulk water temperature; this in turn will result in an increase in density, initiating buoyancy-driven mixing. As the surface layer sinks and mixes with warmer water below, gas solubility will decrease resulting in local supersaturation and the nucleation of bubbles. The magnitude of the surface heat flux will affect both the depression of surface temperature below the bulk water temperature and hence the attainable supersaturation, and the strength of buoyancy driven mixing. When the lead is frozen over, gas exchange with the atmosphere is prevented; continued heat loss through the thin

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surface ice may maintain convective mixing driving local fluctuations in gas saturation and continued nucleation of bubbles at a lower rate. In this case bubble production may depend on the length of time since the last contact with the open air. This picture is consistent with the total number concentrations and their variability with the surface conditions and heat flux.

Regardless of the surface conditions or whether the lead was frozen over, a minimum total number concentration of order  $1\text{ cm}^{-3}$  was observed. This baseline bubble population may be maintained by one or more of a number of processes. Nucleation resulting from fluctuations in gas saturation due to mixing processes as discussed above; respiration by the substantial population of algae and phytoplankton (Medwin, 1970; Johnson and Wangersky, 1987); the release of trapped bubbles from within melting ice and the rejection of gas from freezing water (Wettlaufer, 1998). All of these are plausible mechanisms, and might all take place to varying degrees; however the limitations of the available data do not allow us to distinguish the extent to which any of them actually take place.

## 5 Conclusions

We have presented the first measurements of bubble size spectra made within the surface waters of open leads in the pack ice of the central Arctic Ocean. Substantial numbers of bubbles were found with mean diameters between  $30\text{ }\mu\text{m}$  (the lower detection limit of the instrument) and  $560\text{ }\mu\text{m}$ ; the shape of the spectra implies that significant numbers of bubbles smaller than  $30\text{ }\mu\text{m}$  are to be expected. The concentrations observed for  $D < 100\text{ }\mu\text{m}$  are comparable with those found in the open ocean under moderate wind speeds of order  $10\text{ m s}^{-1}$ , but at larger sizes the concentration decreases more rapidly with increasing size than do open ocean spectra; no bubbles larger than  $560\text{ }\mu\text{m}$  were observed. The total bubble number concentration shows two distinct dependencies on the local environmental conditions: concentrations were highest when the sampled flow has a significant fraction of surface water open to the

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atmosphere, and about an order of magnitude lower when the surface was completely frozen or the flow was from under the large ice floe, and thus isolated from open air for a period of order 10 h or more. When the surface was open to the atmosphere, the total number concentration increased with increasing heat flux from the surface to the atmosphere.

The presence of a significant population of bubbles provides a potential pathway for the transfer of biological material from the bulk water and surface microlayer into the atmosphere via bubble-mediated droplet production as suggested by Leck and Bigg (1999, 2005a) and Leck et al. (2002). This mechanism could provide an important but poorly understood link between cloud microphysical properties – and hence their radiative properties and the surface energy budget – and marine biochemistry in the summer central Arctic through the production of CCN.

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**Table 1.** The mean and standard errors in  $dN/dD$  ( $m^{-3} \mu m^{-1}$ ) for the daily mean bubble size distributions. Standard error values are omitted where only a single estimate for a given channel is available.

	Mean Diameter ( $\mu m$ )	30	36	45	57	69	84	102	123	150	183	222	267	321	387	465	558
17 Aug	Mean	$1.63 \times 10^4$	$2.40 \times 10^4$	$1.51 \times 10^4$	$9.80 \times 10^3$	$5.90 \times 10^3$	$2.19 \times 10^3$	$6.74 \times 10^2$	$3.13 \times 10^2$	$1.43 \times 10^2$	$4.84 \times 10^1$	$1.07 \times 10^1$	0.00	0.00	$1.38 \times 10^1$	0.00	0.00
	std err	$2.59 \times 10^3$	$5.63 \times 10^3$	$5.36 \times 10^3$	$1.98 \times 10^3$	$1.00 \times 10^3$	$7.06 \times 10^2$	$3.30 \times 10^2$	$1.52 \times 10^2$	$5.61 \times 10^1$	–	–	0.00	0.00	–	–	–
18 Aug	Mean	$2.32 \times 10^4$	$3.78 \times 10^4$	$2.42 \times 10^4$	$1.80 \times 10^4$	$1.26 \times 10^4$	$3.61 \times 10^3$	$1.57 \times 10^3$	$3.15 \times 10^2$	$1.27 \times 10^2$	0.00	7.29	$2.20 \times 10^1$	$1.23 \times 10^1$	0.00	0.00	0.00
	std err	$3.25 \times 10^3$	$6.41 \times 10^3$	$3.95 \times 10^3$	$1.97 \times 10^3$	$2.17 \times 10^3$	$9.06 \times 10^2$	$9.21 \times 10^2$	$2.23 \times 10^2$	$6.10 \times 10^1$	–	–	–	–	–	–	–
19 Aug	Mean	$4.54 \times 10^5$	$3.90 \times 10^5$	$3.93 \times 10^4$	$1.97 \times 10^4$	$1.18 \times 10^4$	$4.18 \times 10^3$	$1.00 \times 10^3$	$9.31 \times 10^2$	$1.77 \times 10^2$	$5.72 \times 10^1$	$1.65 \times 10^1$	0.00	0.00	0.00	0.00	0.00
	std err	$1.12 \times 10^5$	$3.72 \times 10^4$	$4.93 \times 10^3$	$2.39 \times 10^3$	$3.22 \times 10^3$	$1.22 \times 10^3$	$2.11 \times 10^2$	$3.75 \times 10^2$	$1.50 \times 10^2$	$3.88 \times 10^1$	–	–	–	–	–	–
20 Aug	Mean	$5.04 \times 10^5$	$5.29 \times 10^5$	$2.95 \times 10^4$	$2.07 \times 10^4$	$1.45 \times 10^4$	$9.61 \times 10^3$	$2.95 \times 10^3$	$9.48 \times 10^2$	$1.70 \times 10^2$	$3.29 \times 10^1$	$2.26 \times 10^1$	$2.98 \times 10^1$	0.00	0.00	0.00	0.00
	std err	$1.77 \times 10^5$	$5.27 \times 10^4$	$2.25 \times 10^3$	$1.89 \times 10^3$	$1.58 \times 10^3$	$2.13 \times 10^3$	$6.50 \times 10^2$	$2.14 \times 10^2$	$4.67 \times 10^1$	$2.26 \times 10^1$	–	$2.10 \times 10^1$	–	–	–	–
21 Aug	Mean	$3.61 \times 10^4$	$4.66 \times 10^4$	$3.07 \times 10^4$	$2.41 \times 10^4$	$1.88 \times 10^4$	$7.80 \times 10^3$	$4.49 \times 10^3$	$2.78 \times 10^3$	$7.11 \times 10^2$	$1.41 \times 10^2$	$8.82 \times 10^1$	$1.01 \times 10^2$	$1.38 \times 10^1$	3.05	0.00	0.00
	std err	$5.32 \times 10^3$	$5.87 \times 10^3$	$3.25 \times 10^3$	$3.38 \times 10^3$	$2.92 \times 10^3$	$1.40 \times 10^3$	$1.32 \times 10^3$	$1.26 \times 10^3$	$3.05 \times 10^2$	$3.76 \times 10^1$	$3.19 \times 10^1$	$6.02 \times 10^1$	–	–	–	–
26 Aug	Mean	$5.75 \times 10^4$	$6.58 \times 10^4$	$4.45 \times 10^4$	$3.92 \times 10^4$	$2.58 \times 10^4$	$1.05 \times 10^4$	$4.10 \times 10^3$	$2.06 \times 10^3$	$3.30 \times 10^2$	$3.79 \times 10^2$	$1.69 \times 10^2$	$1.93 \times 10^1$	8.40	0.00	0.00	0.00
	std err	$1.68 \times 10^4$	$2.10 \times 10^4$	$4.49 \times 10^3$	$5.13 \times 10^3$	$4.72 \times 10^3$	$1.92 \times 10^3$	$1.97 \times 10^3$	$1.35 \times 10^3$	$1.31 \times 10^2$	$1.24 \times 10^2$	$6.64 \times 10^1$	$1.32 \times 10^1$	–	–	–	–
27 Aug	Mean	$2.27 \times 10^5$	$1.53 \times 10^5$	$4.63 \times 10^4$	$3.15 \times 10^4$	$1.90 \times 10^4$	$4.23 \times 10^4$	$5.06 \times 10^4$	$1.15 \times 10^4$	$8.16 \times 10^3$	$1.12 \times 10^2$	$3.30 \times 10^1$	$3.00 \times 10^1$	$2.52 \times 10^1$	0.00	0.00	0.00
	std err	$5.95 \times 10^4$	$9.04 \times 10^3$	$8.11 \times 10^3$	$5.70 \times 10^3$	$1.05 \times 10^3$	$7.22 \times 10^3$	$1.46 \times 10^3$	$9.46 \times 10^3$	$2.44 \times 10^3$	$4.56 \times 10^1$	–	–	–	–	–	–
29 Aug	Mean	$1.50 \times 10^5$	$1.66 \times 10^5$	$1.94 \times 10^5$	$4.09 \times 10^4$	$4.87 \times 10^4$	$2.73 \times 10^4$	$2.99 \times 10^4$	$1.88 \times 10^3$	$1.29 \times 10^3$	$2.69 \times 10^2$	$3.97 \times 10^1$	0.00	0.00	0.00	$2.48 \times 10^1$	$2.24 \times 10^1$
	std err	$2.48 \times 10^4$	$1.55 \times 10^4$	$1.30 \times 10^4$	$7.53 \times 10^3$	$1.13 \times 10^4$	$4.62 \times 10^3$	$8.00 \times 10^3$	$1.86 \times 10^3$	$2.50 \times 10^2$	$9.81 \times 10^1$	–	–	–	–	–	–
30 Aug	Mean	$1.47 \times 10^5$	$1.25 \times 10^5$	$7.96 \times 10^4$	$4.67 \times 10^4$	$8.37 \times 10^4$	$8.01 \times 10^4$	$9.84 \times 10^4$	$2.31 \times 10^4$	$1.34 \times 10^3$	$4.70 \times 10^2$	$1.07 \times 10^2$	$1.93 \times 10^1$	$3.36 \times 10^1$	6.91	$1.32 \times 10^1$	$1.24 \times 10^1$
	std err	$1.21 \times 10^5$	$5.93 \times 10^3$	$3.89 \times 10^3$	$2.37 \times 10^3$	$6.84 \times 10^3$	$7.22 \times 10^3$	$5.21 \times 10^3$	$4.42 \times 10^3$	$8.90 \times 10^2$	$9.41 \times 10^1$	$3.04 \times 10^1$	$1.32 \times 10^1$	$1.93 \times 10^1$	–	–	–
31 Aug	Mean	$3.07 \times 10^5$	$2.21 \times 10^5$	$1.16 \times 10^5$	$8.54 \times 10^4$	$1.43 \times 10^5$	$1.11 \times 10^5$	$2.92 \times 10^4$	$2.44 \times 10^4$	$2.63 \times 10^3$	$7.39 \times 10^2$	$2.65 \times 10^2$	$7.50 \times 10^1$	$7.87 \times 10^1$	0.00	0.00	0.00
	std err	$3.84 \times 10^4$	$2.05 \times 10^4$	$1.11 \times 10^4$	$1.68 \times 10^4$	$6.49 \times 10^4$	$3.10 \times 10^4$	$6.49 \times 10^3$	$4.83 \times 10^3$	$9.26 \times 10^2$	$2.12 \times 10^2$	$1.25 \times 10^2$	$4.01 \times 10^1$	–	–	–	–
1 Sep	Mean	$1.26 \times 10^5$	$1.37 \times 10^5$	$1.41 \times 10^5$	$7.13 \times 10^4$	$4.77 \times 10^4$	$2.90 \times 10^4$	$2.95 \times 10^4$	0.00	0.00	$3.29 \times 10^3$	0.00	0.00	0.00	0.00	0.00	0.00
	std err	$1.40 \times 10^4$	$1.33 \times 10^4$	$7.56 \times 10^3$	$5.24 \times 10^3$	$6.29 \times 10^3$	$1.81 \times 10^3$	$1.83 \times 10^3$	–	–	–	–	–	–	–	–	–

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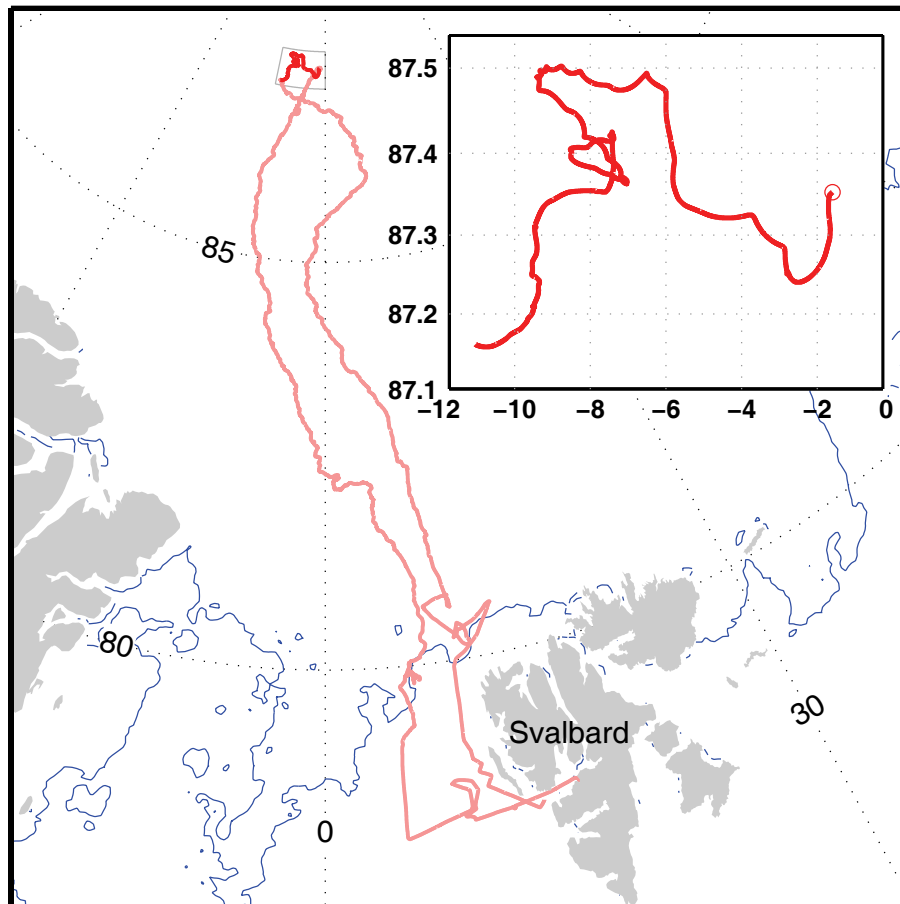
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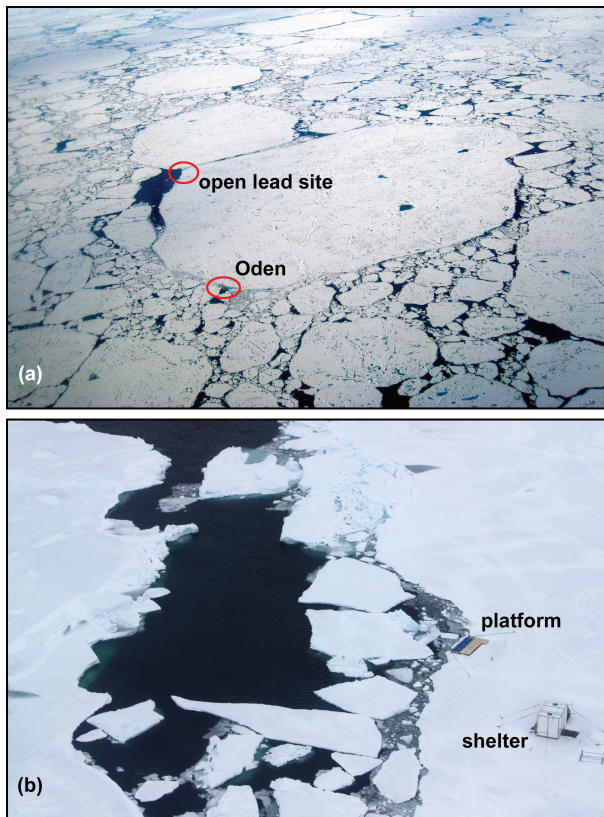
**Fig. 1.** Map of the ASCOS cruise track (pink) with ice-drift period highlighted (red) and (inset) shown in detail with the start of the drift marked by the circle. The ice edge is shown for the start of the drift period on 12 August 2008.

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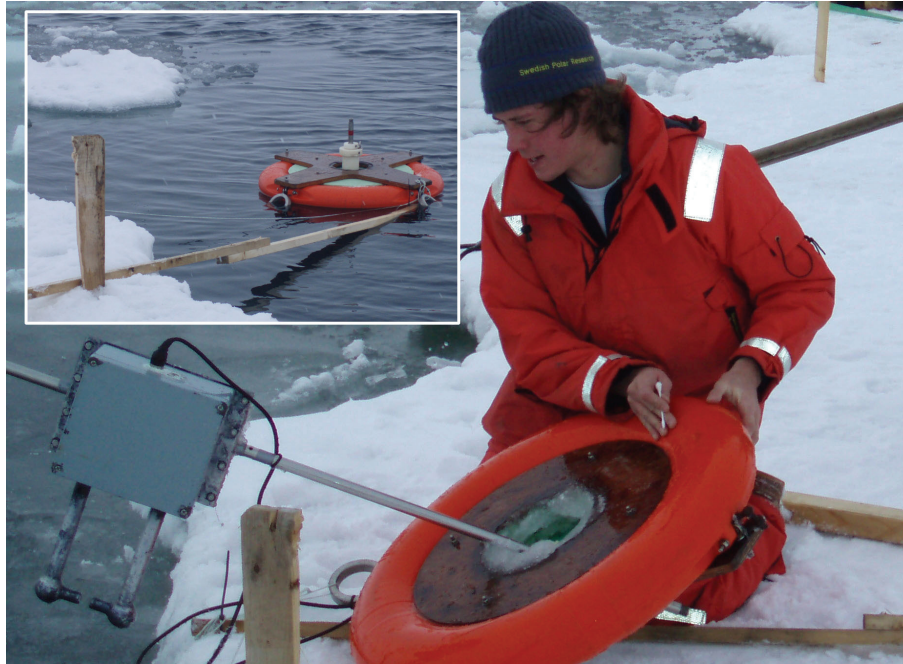
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**Fig. 2. (a)** The ice floe on which the ASCOS measurements took place with the Oden and open lead sampling site ringed. **(b)** The open lead sampling site seen from the air on 14 August 2008 during a period when the wind had narrowed the lead and driven small sections of ice against the near side. The small shelter at bottom right housed the bubble camera data acquisition system and acted as an equipment store. The platform provided a secure location to take water samples from. The bubble camera was deployed close to the near side of the platform.



**Fig. 3.** The bubble camera being readied for deployment, and (inset) in position off the side of the ice floe.

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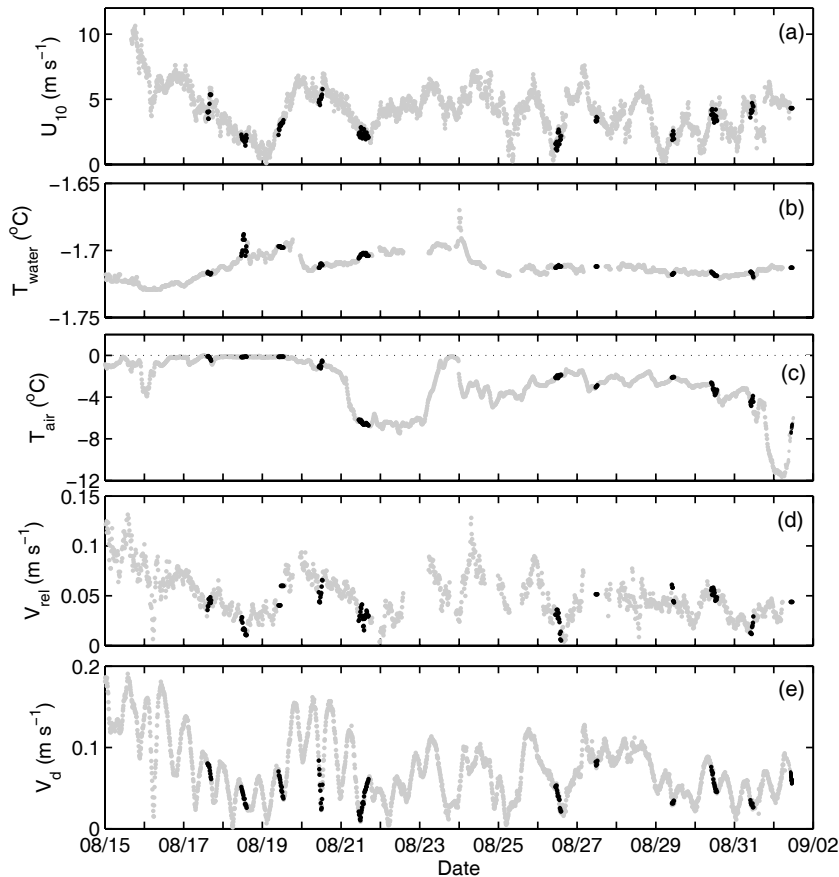
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**Fig. 4.** Time series of mean conditions during ASCOS: **(a)** wind speed ( $U_{10}$ ), **(b)** water temperature ( $T_{\text{water}}$ ), **(c)** air temperature ( $T_{\text{air}}$ ), **(d)** current speed relative to ice at 2 m below underside of ice **(e)** the drift speed of the ice floe. The black points indicate the periods during which the bubble spectra were obtained.

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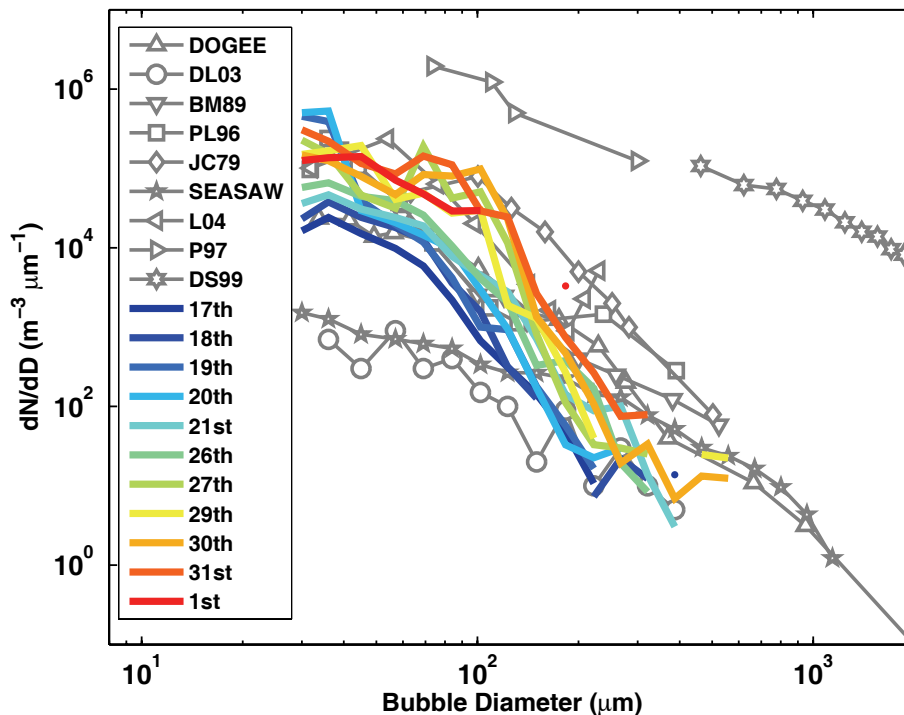
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**Fig. 5.** Mean bubble spectra for each day. A number of open ocean and surf zone spectra are shown for comparison. The SEASAW ( $U=8\text{ m s}^{-1}$ ), de Leeuw et al. (2003) (DL03,  $U=5\text{ m s}^{-1}$ ), and the ASCOS data were all measured at a depth of approximately 0.4 m using the same optical instrument. Acoustic measurement systems were utilized in the open ocean by DOGEE (averaged over a depth of 0–3 m,  $U=13\text{ m s}^{-1}$ ), Breitz and Medwin (1989) (BM89, depth 0.25 m,  $U=12\text{--}15\text{ m s}^{-1}$ ), Phelps and Leighton (1998) (PL96, depth 0.5 m,  $U=12\text{--}14\text{ m s}^{-1}$ ) and Johnson and Cooke (1979) (JC79, depth 0.7 m,  $U=11\text{--}13\text{ m s}^{-1}$ ), and in the surf zone by Leighton et al. (2004) (L04), Phelps et al. (1997) (P97), and Deane and Stokes (1999) (DS99). SEASAW and DOGEE measurements are summarized in Brooks et al. (2009).

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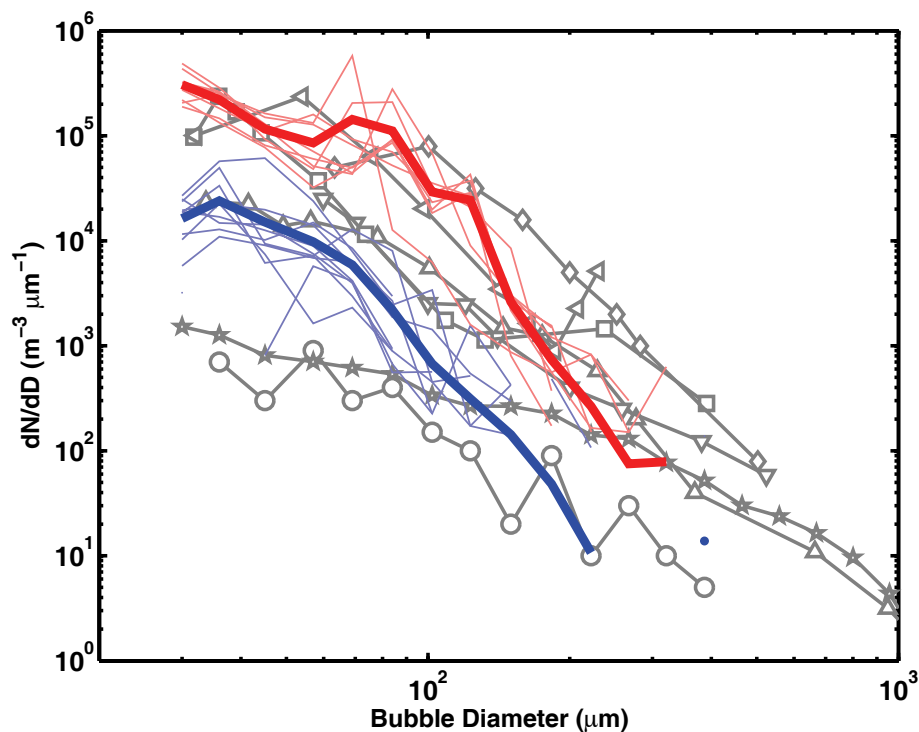
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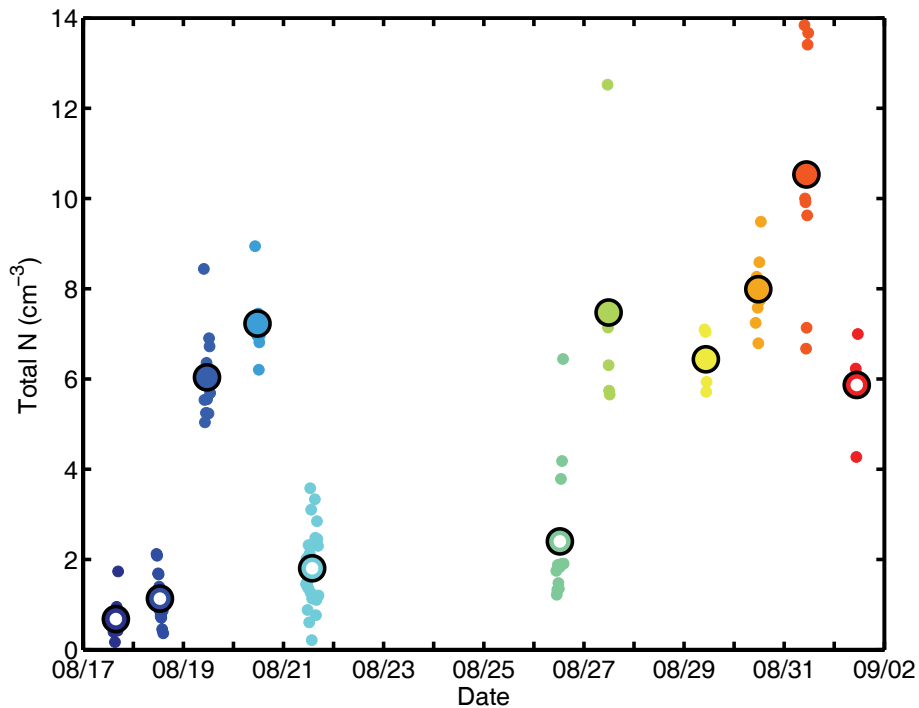
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**Fig. 6.** The individual 2-min estimates of bubble size spectra for 17 August (blue) and 31 August (red) along with their means. Open ocean spectra in grey are as Fig. 5.

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**Fig. 7.** Time series of individual 2-min estimates of total bubble concentrations (small dots) and their daily means (large circles), coloured by date. In cases where the flow was from below an ice covered surface the mean value is shown with a central white dot.

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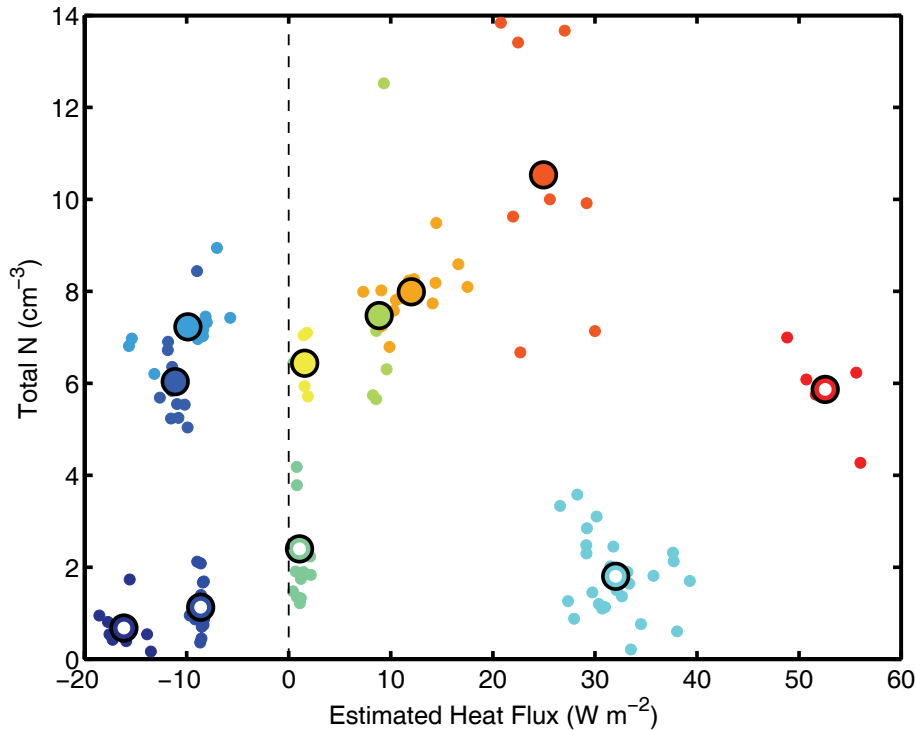
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**Fig. 8.** Individual 2-min estimates of total bubble concentrations (small colour dots) and their daily means (large circles) plotted against the estimated surface heat flux over the lead. In cases where the flow was from below an ice covered surface the mean value is shown with a central white dot. Colours indicate date as in Fig. 7.

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