Quantification of the abundance and distribution of the common jellyfish *Aurelia aurita* s.l. with a Dual-frequency IDentification SONar (DIDSON)

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A Dual-frequency IDentification SONar (DIDSON) provided a powerful tool to determine the numerical abundance and spatial distribution of medusae of the common jellyfish *Aurelia aurita* s.l. in shallow coastal waters. The sonar image obtained in high frequency (1.8 MHz) mode enabled us to identify and count individual medusae of 4.1–19.6 cm (mean: 13.1 cm) bell diameter. Deployment of the DIDSON along three ~4-km-long transects in a shallow brackish-water lake (average depth: 5.1 m) revealed that *A. aurita* aggregated (e.g. >8.0 medusae m$^{-3}$) near the lake center. The medusae occurred throughout the water column, but tended to avoid low salinity surface and deoxygenated bottom layers. The overall average density of medusae estimated by the DIDSON was 3.3 times higher than that estimated by net sampling. Use of a DIDSON can facilitate quantitative determination of jellyfish populations that cause problem blooms worldwide in order to better understand their ecological importance.

INTRODUCTION

Determination of the abundance, biomass and spatio-temporal distributions of medusa populations is essential to understand the functional roles of cnidarian jellyfish in the food chain dynamics and material cycling in the ocean (e.g. Gröndahl, 1988; Olesen et al., 1994; Purcell, 2003, 2009; Lynam et al., 2005; Uye and Shimauchi, 2005; Decker et al., 2007). Although patchiness in marine zooplankton populations is of great importance (Omori and Hamner, 1982; Laval et al., 1989; Davis et al., 1992), jellyfish patchiness is especially pronounced (Hamner et al., 1994; Graham et al., 2001). Thus, the traditional method of towing a plankton net may poorly sample jellyfish populations, particularly of large scyphozoan species (Hamner et al., 1975; Sameoto et al., 2000; Graham et al., 2003). To overcome these drawbacks, repeated tows of a net with a large mouth-area at several stations are required. Commercial fishing nets that sample several hundreds cubic meters of water have been used in jellyfish studies (e.g. Brodeur et al., 1999, 2002; Graham et al., 2001; Purcell, 2003; Suchman and Brodeur, 2005). However, these large nets are cumbersome, requiring a large vessel to operate and thus are difficult to use in busy coastal waters.

Due to these net limitations, underwater optical and acoustical instruments have been used in jellyfish studies (e.g. Lenz et al., 1995; Purcell et al., 2000; Alvarez Colombo et al., 2003, 2009; Graham et al., 2003). Underwater video cameras, for example, can identify and quantify jellyfish, and can obtain information on their body size and swimming behavior (Purcell et al. 2000; Graham et al., 2003; Malej et al., 2007). The most serious disadvantage of the optical systems is their limited field of view. Acoustical instruments offer the benefits of obtaining information on both the vertical and horizontal distributions of jellyfish over a wide
geographical range in turbid or dark waters (Purcell et al., 2000; Brierley et al., 2001; Alvarez Colombo et al., 2003). Quantification of jellyfish abundance and biomass from sonar data is problematic. Even determination of target strength is difficult for jellyfish, because of their watery composition and variation in signal strength because of changing shape and orientation (Multu, 1996; Monger et al., 1998; Brierley et al., 2004).

Another approach is the use of aircraft, from which photography or video surveys record the geographical

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**Fig. 1.** A standard DIDSON dual-frequency identification sonar transducer: weight 7 kg, dimensions 17.1 × 30.7 × 20.6 cm (A). Standard DIDSON accessory kit containing data cable, set-top box, Ethernet cables, the transducer (B, from http://www.soundmetrics.com/). A laptop running DIDSON software also is required to operate the unit.

**Fig. 2.** Schematic representation of the pyramid-shaped sonar view field (left), and a sonar image from the DIDSON (right) operated in high frequency mode (1.8 MHz). The upper 0.5 m depth is undetectable view field.
distribution of jellyfish over large areas (Purcell et al., 2000; Uye et al., 2003; Houghton et al., 2006). In this approach, of course, information only on large jellyfish near-surface is obtained.

A Dual-frequency IDentification SONar (DIDSON 300), a high-definition imaging sonar that provides near-video-quality images of underwater objects, was recently developed (Baumgartner et al., 2006; Boswell et al., 2007). The DIDSON has been used to monitor the abundance, size and swimming behavior of fish, particularly anadromous fish (e.g. salmon) in rivers (Tiffan et al., 2004; Baumgartner et al., 2006; Holmes et al., 2006; Handegard and Williams, 2008). The DIDSON has been used in a preliminary study to detect the giant jellyfish, *Nemopilema nomurai* (Honda and Watanabe, 2007).

We used a DIDSON to determine the abundance and spatial distribution of medusae of *Aurelia aurita* in Honjo District, Japan. Han et al. (Han et al., 2009) reported the seasonal population dynamics of *A. aurita* in this brackish-water lake, by estimating medusa abundance and biomass in 5–7 repeated net tows on each sampling date. The sampling variance was extremely large (average: 60%, maximum: 144%, N: 18), indicating that the spatial distribution of medusae was highly heterogeneous. Here
we use the DIDSON for the first time to estimate jellyfish abundance and distribution.

MATERIALS AND METHODS

Survey equipment

The DIDSON system comprises a transducer that operates in either high (1.8 MHz) or low (1.0 MHz) frequency mode, a set-top control box, a data cable, control software and an associated laptop computer (Fig. 1). When operated in high-frequency mode, the DIDSON transducer projects a composite beam consisting of 96 fan-shaped narrow beams, each having two-dimensional angular resolution of 0.3° by 14°. The overall field of view of the composite beam is 29°. When transmitting vertically (i.e. 90° to the water surface), the field of view is defined by the height (or down range: \( D \), m) and the rectangular base area \((0.5D \text{ m} \times 0.25D \text{ m})\) (Fig. 2). Since objects are undetectable within the first 0.5 m from the transducer (i.e. near-field dead zone), the water volume of the sonar field \((V, \text{m}^3)\) is approximately:

\[
V = 0.0417D^3 - 0.0052\text{m}^3
\]

Field survey and deployment

The DIDSON was deployed in a brackish lake, Honjo District (area: 16.2 km², average depth: 5.1 m), Japan, during daytime (0900 – 1600) on 29 August 2007 (Fig. 3). The transducer of the DIDSON was mounted on a wooden frame secured to the boat at 0.5 m depth. The long axis of the transducer was orientated perpendicular to the direction of travel and tilted at an angle of 75° relative to the water surface so that the sonar beams projected to the bottom, slightly forward of the boat. The DIDSON was operated in high-frequency mode with a maximum down range of 12 m. The boat ran at a speed of 0.7 – 0.9 m s⁻¹ along three transects (distance and deployment duration: 3.8 km and 70 min for S1, 4.0 km and 100 min for S2 and 4.2 km and 100 min for S3). The position of the boat was determined by a GPS (GPSMAP 76S) at 10-min intervals. The sonar image (gained sonar strength: 40 dB) was transferred from the unit to the computer via the control software, and saved onto a hard drive at a rate of 10 frames per second for later review.

During daytime (0900 – 13:00) on 30 August 2007, vertical profiles of temperature, salinity and dissolved oxygen concentration were measured with a portable multi-probe sensor (Horiba U-20) at eight stations (see Fig. 3). At that time, A. aurita medusae were sampled by 5-min oblique tows of a net (60-cm mouth diameter, 500-µm mesh) from near-bottom to the surface. Medusae were counted and their bell diameters were measured on board. Mesozooplankton samples were also collected by vertical hauls of a plankton net (25-cm mouth diameter, 80-µm mesh) from the bottom to the surface and immediately fixed in 5% formalin/lake-water solution. At least 300
specimens from split subsamples were identified, counted and their appropriate body lengths measured with the aid of a dissecting microscope. Mesozooplankton carbon biomass was estimated as in Uye and Shimazu (Uye and Shimazu, 1997).

Data analysis

In the high frequency mode, the sonar images provided sufficient resolution to detect individual medusae, but not for the use of the automatic counting function, which has been applicable for fish (Fig. 4). The number of medusae on the PC monitor was therefore manually counted for archived images at 10-s intervals (i.e. 7–9 m distance intervals), and divided by the water volume of the view field to determine the numerical density per m$^3$. For the horizontal distribution of medusae along each transect, densities were averaged over 1 min intervals (distance interval: 40–54 m). In order to express the geographical distribution of medusae with a contour map, the Kriging gridding method (Surfer 7.0) was employed based on the medusa densities at 30 GPS stations (Fig. 3).

Fig. 5. Horizontal distribution of *Aurelia aurita* medusae along three transects (S1, S2 and S3) in Honjo District on 29 August 2007. Each data point represents average medusa abundance determined by DIDSON at 1-min intervals. Vertical lines denote SD. Numbers show time (minutes) after deployment began.
The vertical distribution of medusae was investigated by counting their occurrence in each 1 m depth layer on the PC monitor. The vertical distribution data were obtained along four transects (i.e. S1-20-30, S2-10-20, S2-50-60 and S3-0-10, Fig. 3), where the water depths were 4.5–5.0 m. The difference in abundance of medusae among depth layers (i.e. 1 m depth interval) was tested by one-way ANOVA (SPSS 10.0). Significant ANOVA results were tested through Bonferroni pairwise comparisons.

RESULTS

Horizontal distribution of *Aurelia aurita* medusae

The density of *A. aurita* medusae determined for each 10-s interval varied greatly. Even when averaged over 1 min intervals, the coefficient of variation (CV) often exceeded 100%, particularly when the medusa density was low. The average density for every 1 min interval varied from 0.01 to 20.8 medusae m$^{-3}$ along all transects (Fig. 5). Relatively few medusae occurred (average: 0.22 medusae m$^{-3}$, maximum: 1.36 medusae m$^{-3}$) along the northern transect (S1), where depth varied from 2 to 5 m. Medusae were most abundant (average: 4.27 medusae m$^{-3}$, maximum: 17.8 medusae m$^{-3}$) along the middle transect (S2). Densities were particularly high (e.g. >10.0 medusae m$^{-3}$) in the middle ~0.5 km of S2. Medusa density was high (>10.0 medusae m$^{-3}$) on the western part of transect S3, but was low (<2.0 medusae m$^{-3}$) in the middle part near Daikon Island where depths were <3 m.

The contour map illustrates that the medusa population formed a large aggregation area (approximate size: 0.5 × 0.25 km) of high density (>8.0 medusae m$^{-3}$) in the central part of Honjo District (Fig. 6).

Vertical distribution of *Aurelia aurita* medusae

Vertical profiles of temperature, salinity and dissolved oxygen concentrations were similar at all eight stations, therefore each parameter was averaged (Fig. 7A and B). Temperature was vertically homogenous, ranging from 28.0 to 28.7°C. Salinity was <18.0 near the surface.
Dissolved oxygen concentration was 5.4 mg O₂ L⁻¹ at depths shallower than 3 m, and rapidly declined to 0.25 mg O₂ L⁻¹ at 5 m depth.

The vertical distribution of *A. aurita* medusae was heterogeneous (Fig. 7). Medusae were significantly less abundant in the shallow water layer (i.e. 1–2 m) than the deeper layer (i.e. 2–5 m) along S1-20-30 and S3-0-10 (F: 15.4 and 22.6, respectively, both df: 3, P < 0.01).

Medusa abundance and biomass estimated by the DIDSON and by net sampling

The frequency of bell diameters for 205 medusae caught by net showed a unimodal distribution (Fig. 8). The mean diameter was 13.1 cm (range: 4.1–19.6 cm), corresponding carbon weight of 120 mg C (Han et al., 2009).

Medusa abundance estimated from net sampling varied widely from 0 at S3-20 and S3-70 to 2.55 medusae m⁻³ at S2-50 with average of 0.74 medusae m⁻³ (CV: 125%, Fig. 9). The average abundances determined by the DIDSON for 1 min intervals were averaged for all transects (total data numbers: 270) to estimate the overall average density; this was 2.42 medusae m⁻³ (CV: 170%, Fig. 9). Corresponding average carbon biomass of *A. aurita* was 89.0 mg C m⁻³ by means of net sampling, whereas it was 291 mg C m⁻³ by the DIDSON.

Mesozooplankton biomass

Biomass of mesozooplankton caught at eight stations ranged from 37.9 to 73.2 mg C m⁻³ (mean: 57.9 mg C m⁻³, CV: 37%). The taxonomic composition varied slightly among stations, with the copepods, *Oithona davisae* and *Acartia sinjiensis* and polychaete larvae averaging 44, 21 and 23%, respectively.
DISCUSSION

The most advantageous feature of the DIDSON is the ability to provide near-video-quality images of underwater objects even in water of low visibility. The DIDSON images of gelatinous *A. aurita* medusae were certainly less clear than those of solid-bodied fish (Fig. 4), but defined the body outline, orientation (e.g. viewed from top/bottom or side of the umbrella) and even the four central horseshoe-shaped gonads. At 5 m down range, the sonar image of an object has a 2.6 cm resolution along the azimuthal direction (i.e. 2.5 m) of the composite beam. Hence, we assumed that even the smallest medusa (bell diameter: 4.1 cm) could be detected by the DIDSON. Identification of individual medusae to count by eye on the PC monitor was not difficult except for very dense occurrences. In those cases, the images were repeatedly rewound to confirm the numbers of overlapping medusae.

The medusae showed a contagious patchy distribution in the central part of Honjo District (Fig. 6), where the bottom was relatively level at 5–6 m deep. In our previous surveys in 2005 and 2006, *A. aurita* usually aggregated near the lake center; therefore, our regular sampling station was established there (Han et al., 2009). A number of factors influence the distribution of jellyfish, including physical processes and behavioral responses to the prevailing environment (Graham et al., 2001, 2003; Rakow and Graham, 2006). In the enclosed Honjo District, there is no significant tidal current because of the small tidal range (ca. 30 cm). Wind-driven mixing might occasionally be important (Nakata et al., 2000), but confined only to shallow layer (i.e. <2 m). The medusae were most abundant at mid-depth (i.e. 3–4 m), indicating that the water movement was not responsible for their distribution. The aggregation often became more pronounced during warm months (i.e. June–November), when the medusae sexually matured (Han et al., 2009, our personal observations), suggesting that biological factors are more important than physical factors for their patchy distribution.

The DIDSON deployment and sampling by net were not conducted on the same day because of the availability of the boat. The overall average abundance of medusae estimated by the DIDSON was 3.3 times higher than that estimated by net sampling. The DIDSON surveyed a total water volume of $1.8 \times 10^5 \text{ m}^3$, whereas the net sampled only 363 m$^3$. Although the DIDSON method was time-consuming ($\sim 100$ h for visual counting on the monitor), the results provided much more accurate numerical estimates, as well as spatial distribution, of *A. aurita* medusae. It was surprising that the estimated carbon biomass of the *A. aurita* population (291 mg C m$^{-3}$) overwhelmingly surpassed that of their prey mesozooplankton populations (57.9 mg C m$^{-3}$), which also was higher than biomass usually encountered in estuarine and coastal marine waters (e.g. 20–40 mg C m$^{-3}$, see Uye et al., 2004).

There is great concern about the ecological effects of large jellyfish in marine ecosystems, since their outbreaks have increased in recent decades (Arai, 2001; Mills, 2001; Brodeur et al., 2002; Purcell, 2005; Kawahara et al., 2006; Purcell et al., 2007). Plankton nets, the traditional sampling gear, probably collect only parts of jellyfish populations and underestimate their real population size. The DIDSON is a powerful tool to precisely estimate numerical abundance and spatial distribution of large jellyfish in shallow coastal waters, where eutrophication and marine construction are often prominent and jellyfish populations often cause problem blooms. We recommend the use of the DIDSON, in combination with net sampling to

![Fig. 9. The abundance of *Aurelia aurita* medusae at eight stations estimated by net sampling (A), and average abundances estimated by the DIDSON and net sampling (B). Vertical lines denote SD.](https://academic.oup.com/plankt/article-abstract/31/8/805/1489251)
determine medusa size and biomass distributions, for further study of jellyfish populations and their ecological effects.

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