Comparison of stationary acoustic monitoring and visual observation of finless porpoises

Satoko Kimura[a)]
Graduate School of Informatics, Kyoto University, 606-8501 Kyoto, Japan

Tomonari Akamatsu
National Research Institute of Fisheries Engineering, Hasaki, Kashima, Ibaraki 314-0421, Japan

Kexiong Wang,[b)] Ding Wang, Songhai Li, and Shouyue Dong
Institute of Hydrobiology, Chinese Academy of Sciences, Wuhan 430072, People's Republic of China

Nobuaki Arai
Graduate School of Informatics, Kyoto University, 606-8501 Kyoto, Japan

(Received 8 May 2008; revised 6 October 2008; accepted 13 October 2008)

The detection performance regarding stationary acoustic monitoring of Yangtze finless porpoises *Neophocaena phocaenoides asiaeorientalis* was compared to visual observations. Three stereo acoustic data loggers (A-tag) were placed at different locations near the confluence of Poyang Lake and the Yangtze River, China. The presence and number of porpoises were determined acoustically and visually during each 1-min time bin. On average, porpoises were acoustically detected $81.7 \pm 9.7\%$ of the entire effective observation time, while the presence of animals was confirmed visually $12.7 \pm 11.0\%$ of the entire time. Acoustic monitoring indicated areas of high and low porpoise densities that were consistent with visual observations. The direction of porpoise movement was monitored using stereo beams, which agreed with visual observations at all monitoring locations. Acoustic and visual methods could determine group sizes up to five and ten individuals, respectively. While the acoustic monitoring method had the advantage of high detection probability, it tended to underestimate group size due to the limited resolution of sound source bearing angles. The stationary acoustic monitoring method proved to be a practical and useful alternative to visual observations, especially in areas of low porpoise density for long-term monitoring. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3021302]

PACS number(s): 43.80.Ka, 43.80.Jz, 43.66.Hg [WWA] Pages: 547–553

I. INTRODUCTION

Visual observation of surfaced cetaceans is well established and has been applied widely to species ranging from small odontocetes to large baleen whales. However, data gathered using visual surveys are limited to daytime since this is the only time visual observation is possible. Weather conditions such as fog and glare also have considerable effects on the visibility of animals. Patient long-term visual observation can be very costly, particularly under the very low-density conditions of endangered species.

The Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*), a freshwater porpoise subspecies unique to the Yangtze River in China, is a typical example. In the early 1990s, the population size was estimated at approximately 2700 individuals (Zhang *et al.*, 1993). By 2006, estimates had decreased to as low as 1800 over the porpoise's entire distribution range (Zhao *et al.*, 2008). Recent genetic studies have confirmed that populations of the Yangtze finless porpoise are scattered throughout the habitat area (Zheng *et al.*, 2005), so monitoring them requires a great deal of effort. In addition, the Yangtze finless porpoise is one of the most difficult species to observe visually due to the turbid river's low visibility (less than 1 m) and the porpoise's lack of dorsal fin and rostrum.

Use of acoustic monitoring can avoid some major difficulties related to visual observation. Researchers have recently applied stationary acoustic monitoring methods to observe many species of aquatic mammals in various water systems. These methods are considered to be suitable for long-term automatic monitoring. The underwater sounds produced by aquatic animals can be used to monitor various characteristics of a species, including presence, behavior, and distribution (Nishimura and Conlon, 1994; Janik, 2000; Janik *et al.*, 2000; van Parijs *et al.*, 2002; Au and Benoit-Bird, 2003; Ichikawa *et al.*, 2006; Tsutsumi *et al.*, 2006). For example, researchers have used the T-POD (a passive acoustic porpoise or dolphin detector system) to monitor harbor porpoises and bottlenose dolphins (Thomsen *et al.*, 2005; Philpott *et al.*, 2007). The T-POD system can detect the presence and sensing effort of echolocating animals, indicated by the detection rate of clicks per hour or day (Thomsen *et al.*, 2005; Verfuß *et al.*, 2007), the number of minutes containing clicks (Carstensen *et al.*, 2006), the click characteristics of animals (Philpott *et al.*, 2007), and the length of interclick intervals (Leeney *et al.*, 2007). However, unlike visual observation, the T-POD system is not suitable for counting the

---

[a)] Electronic mail: sk0130@bre.soc.i.kyoto-u.ac.jp
[b)] Electronic mail: wangk@ihb.ac.cn

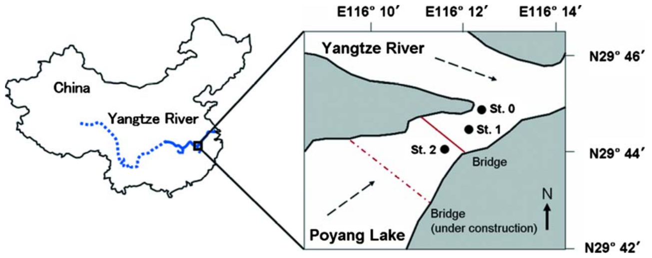

FIG. 1. (Color online) Study area around the junction of the Yangtze River and Poyang Lake, China. The solid line in the left panel indicates the historical habitat of Yangtze finless porpoises (Wei *et al.*, 2002). The dashed arrows in the right panel indicate the direction of the current.

specific number of animals because it is a monaural system. Wang *et al.* (2005) used the stereo acoustic data logger, A-tag (Little Leonardo, Tokyo, Japan), in an oxbow of the Yangtze River that contained an *ex situ* conservation area for finless porpoises. The researches found a weak positive linear correlation between the number of recorded signals and the group size of sighted porpoises. The number of signals may be an indicator of the number of individuals in a group, but because the sound production ratio varies between animals, Wang *et al.* (2005) were not successful in using stationary acoustic data to determine the exact number of porpoises.

Counting the number of finless porpoises from a moving boat is possible using the sound source bearing angle, monitored by a stereo acoustic system (Akamatsu *et al.*, 2008). Acoustic transect observation from a moving platform effectively prevents double-counting of animals, whereas stationary acoustic observations require additional evaluation by comparing with ground truth data such as visually observed number of animals to determine the number of animals. In this study, we used a stereo acoustic monitoring system to conduct a stationary counting of finless porpoises in the channel where Poyang Lake flows into the Yangtze River. We compared the detection performance of a stationary acoustic monitoring system to that of visual observations.

II. MATERIALS AND METHODS

A. Study area

We conducted simultaneous acoustic and visual observations from boats at the confluence of the Yangtze River and Poyang Lake located in the middle reaches of the Yangtze River in South-Central China (Fig. 1). Three stations were used in the study area in April 27–29, 2006 and May 9 and 10, 2007. Data were collected over a summed period of 5 days. Station 0 (29°45′06″ N, 116°12′41″ E) was located at the point where the lake joined the main channel of the Yangtze River. Station 1 (29°44′34″ N, 116°12′10″ E) was located at the mouth of the lake approximately 1300 m upstream from Station 0. Station 2 (29°44′02″ N, 116°11′47″ E) was situated between two bridges and was located approximately 1100 m upstream from Station 1. During observation, boats at each station were fixed using double anchors to minimize drifting. Each boat engine was completely stopped. Water depth was approximately 3 m at all stations.

B. Acoustic data logger

We used stereo acoustic data loggers, A-tag (Little Leonardo Ltd., Tokyo, Japan, in 2006; Marine Micro Technology, Saitama, Japan, in 2007), for the acoustic observations. An A-tag is an event data logger that records sound pressure and the difference in time arrival between two hydrophones. It does not record the waveforms of received sound.

An A-tag consists of a stereo hydrophone, preamplifier with bandpass filter, CPU (PIC18F6620), flash memory (128 Mbytes), and lithium battery cell (CR2). The hydrophones had a sensitivity of MHP-140 (Marine Micro Technology) −201 dB (1 V/μPa) and a resonant frequency of 130 kHz, similar to the dominant frequency of finless porpoise sonar signals. This setting reduced noise outside the sensitive band of the hydrophone at sound reception. Hydrophone sensitivity was calibrated using an acoustical measurement tank (10 m in width, 15 m in length, and 10 m in depth) at the Fisheries Research Agency in Ibaraki, Japan. The ultrasonic sound transmission system used in calibration consisted of a function generator (NF1930A, NF Corp., Tokyo, Japan) and a transducer (B&K8103, Brüel & Kjaer, Naerum, Denmark); the system generated a 10-cycle tone burst for any frequency. A-tags were also confirmed to be able to record sounds made by free-ranging porpoises in an *ex situ* oxbow of the Yangtze River (Akamatsu *et al.*, 2005a).

Each A-tag had two hydrophones, approximately 170 mm apart, which were used to identify the sound source direction. Electronic bandpass filters at the preamplification stage were adjusted to 70–300 kHz (in 2006) or 55–235 kHz (in 2007) to match the frequency band of Yangtze finless porpoise sonar signals, which ranges from 87 to 145 kHz and averages at 125±6.92 kHz (Li *et al.*, 2005a). The acoustic data logger recorded sound pressure at the primary and secondary hydrophones, as well as the difference in sound arrival times between the two hydrophones, every 0.5 ms (2 kHz event sampling frequency). The three data sets and the absolute time were recorded automatically only when the received sound pressure was greater than the trigger level of the primary hydrophone. Otherwise, no data were stored to conserve memory capacity. An A-tag can record information up to 30–40 h, depending on the number of pulses stored.

Peak-to-peak source levels for this species were 163.7–185.6 dB, referred to 1 μPa (Li *et al.*, 2006), and the sound pressure level off the beam axis at 90° reached a maximum of 162 dB (Akamatsu *et al.*, 2005b). Transmitted sound pressure levels can be highly variable, but off-axis signals still reached significant levels during this study, and it was possible to observe them using the data logger. We set the detection threshold level of the data logger at 135.3 dB. Our calibration experiment revealed that each A-tag had a slightly different threshold level, but the threshold level of 135.3 dB was higher than any one A-tag threshold. Our offline analysis used recorded pulses greater than 135.3 dB (5.85 Pa). We allowed a maximum of 50.3 dB propagation loss for detecting signals. Assuming a simple spherical propagation model based on the freshwater values set out by Fisher and Simmons (1977) (absorption coefficient of

0.004 dB/m at 125 kHz), the maximum detection distance of the stereo acoustic data logger was approximately 290 m.

The bearing angle of a sound was calculated using the difference in time arrival between the two hydrophones. The triggering time of both hydrophones was monitored every 271 ns, which was sufficiently fast to determine the onset of a pulse wave. Sounds traveled 0.4 mm in 271 ns, while the baseline (the separation between the two hydrophones) was 170 mm. Therefore, even this short baseline system allowed a fair bearing angle resolution. Signal processing and structure are described in more detail in Akamatsu *et al.* (2005a).

C. Acoustic observations

We used a bamboo rod to fix the acoustic data logger at a 1-m depth from the side of each anchored boat. In 2006, we fixed two A-tags underwater from boats at Stations 1 and 2, and we fixed an additional A-tag at Station 0 in 2007. The stations were spaced more than 1000 m apart, well outside the A-tag detection range of 290 m. This design ensured that the observations at each station were independent. We assumed no simultaneous detection of individual animals. The two hydrophones of each A-tag were set parallel to the current direction to monitor the direction of porpoise movement between the river and the lake. The primary hydrophone of the A-tag was directed upstream of the site (Poyang Lake side), and the secondary hydrophone was directed downstream (the Yangtze River side).

D. Visual observations

During acoustic observations, we conducted simultaneous visual observations from the same anchored boat; four observers each covered a 90° arc from the boats. Observers watched for 1 h and rested for 30 min; eye height was approximately 2 m above the water surface. When porpoises were sighted, the observer recorded the minimum group size, the direction of movement (upstream or downstream), and the distance and bearing angle from the bow of the survey boat. These parameters were the same as those measured by the stereo acoustic data logger, with the exception of distance. To ensure that these results could be compared with those obtained by acoustic detection, we only recorded visual observation data detected within 300 m, similar to the acoustical detection range. The minimum group size was defined as the number of the animals that respired successively within a few seconds because this species has an average shallow dive time of 4.86 ± 4.72 s (Akamatsu *et al.*, 2002). For the purposes of analysis, groups separated by more than 1 min were considered to be different sightings because this species has an average deep dive time of 70.9 ± 22.9 s (Akamatsu *et al.*, 2002). Currents and winds affected the direction of the observation boat; this parameter was identical with the direction of the data logger. The direction of the boat's bow was used as a reference to synchronize data collected through acoustic and visual observations.

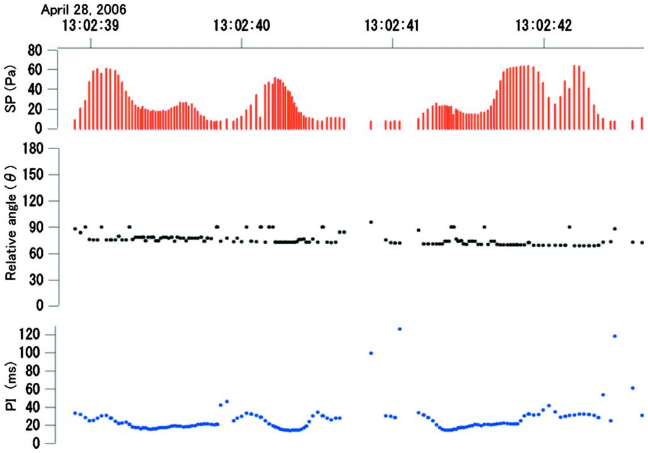

FIG. 2. (Color online) Example of time series data of porpoise sounds recorded by the stereo acoustic data logger. The vertical axes show the received sound pressure (SP), relative bearing angle to the porpoise, and interclick interval (ICI). In the center graph, 180° indicates upstream from the survey boat and 0° means downstream. The porpoise ICIs and sound pressure levels changed smoothly (Akamatsu *et al.*, 2005c).

E. Acoustic signal processing

We eliminated contamination from noise and reflection and calculated the interclick intervals and relative angles of sound sources using a custom-made program developed using IGOR PRO 5.03 (WaveMetrics, Lake Oswego, OR). Relative angles to the sound source were calculated using the difference in time arrival between the two hydrophones.

Sample data shown in Fig. 2 illustrate sound pressure, relative bearing angle, and the interclick interval of porpoise clicks. We were able to track porpoises easily because they phonated frequently. As shown in the figure, interclick intervals and sound pressure levels changed smoothly (Akamatsu *et al.*, 2005c), while background or boat noise caused randomly changing patterns in the interclick interval and sound pressure. We were unable to use frequency information to exclude noise because A-tags do not record waveform. Instead, we used interclick intervals to discriminate signals from noise. We excluded any successive clicks greater than twice or less than half the previous interclick intervals (Akamatsu *et al.*, 1998, 2001).

The multipath propagation in the Yangtze River can cause echolocation signals to have a multipulse structure (Li *et al.*, 2005b). In this shallow freshwater system, reflected signals came just after the direct path signal. Because the animals had a very shallow depth, the surface reflection had an angle similar to the direct path signal; this resulted in the echo's very short delay time. Pulses within 2 ms after a direct path pulse were eliminated during offline signal processing. Since the mean minimum lag time to process returning echoes inside an animal brain is 2.5 ms (Au, 1993), porpoises' sound is considered to be not excluded in this processing.

F. Number and movement direction of animals

The number and movement direction of animals were determined manually from click trains. This species usually produces an interclick interval shorter than 130 ms (Li *et al.*, 2005a; Akamatsu *et al.*, 2007), as shown in Fig. 2. We defined a click train as a series of clicks in which intervals were 130 ms or shorter. We considered some click trains 10 s or less apart and within a similar bearing angle to have been produced by the same individual; these were defined as a single track. The number of independent traces of sound source bearing angle in a 1-min time bin was defined as the observed number of animals in a unit time (or group size). When click trains were separated by intervals longer than 10 s, determining the number of porpoises within a detection area was not possible; one or more porpoises may have phonated. In these cases, we underestimated the number of porpoises. This was used as a conservative criterion to avoid double-counting of animals.

Simultaneous phonation of two individuals swimming close together could be identified through the double different cyclic characteristics of the sound pressure and/or interclick intervals within a single trace, so we counted these as originating from two porpoises. This phenomenon was relatively easy to discriminate from reflections because reflection sound always involves a separation time after the direct path click.

In contrast, when single periodicity in interclick intervals and/or a smoothly changing sound pressure accompanied close parallel traces, we counted only one porpoise. These parallel traces were caused by an error in the trigger point among multiple wavelengths in a click. The trigger point of primary and secondary hydrophones could differ when the sound pressure at the onset of a click is comparable to the detection threshold level. Among finless porpoises, click amplitude rises gradually. Therefore, the second wave highlight next to the first onset wave tends to be triggered by the secondary hydrophone, even if the first onset was triggered by the primary hydrophone. One wavelength ambiguity of the trigger point occurred, resulting in close parallel traces of a single phonating animal.

Animals were counted visually through observation around the survey boat during the same time bin as they were counted using the acoustic method. If porpoises passed near the observation station, they were likely to be observed once within a 1-min time bin, which is close to the average respiration interval of an adult finless porpoise engaged in deep diving activity.

We also compared the visually and acoustically measured movement directions of animals. In the acoustic method, direction was determined by changes in the bearing angles of received sounds. A change in bearing angle from positive to negative indicated that the porpoise moved from the lake side to the river side, and vice versa. The difference in time arrival between the two hydrophones, correlated with the bearing angles, had a minimum resolution 13.6 μs. When the difference in time arrival was considerably greater than 13.6 μs, the swimming direction was determined to be either upstream toward Poyang Lake or downstream toward the Yangtze River. Otherwise, we did not record a swimming direction. When the trace consisted of only one click train, determining the swimming direction was impossible. When the primary hydrophone of the data logger was triggered but the secondary hydrophone received an insufficient sound level, the difference in time arrival was 0 and indicated as a line at 90°, as shown in Fig. 3. We did not use these measurements to count individuals but used them instead to identify simultaneous phonation of multiple individuals.

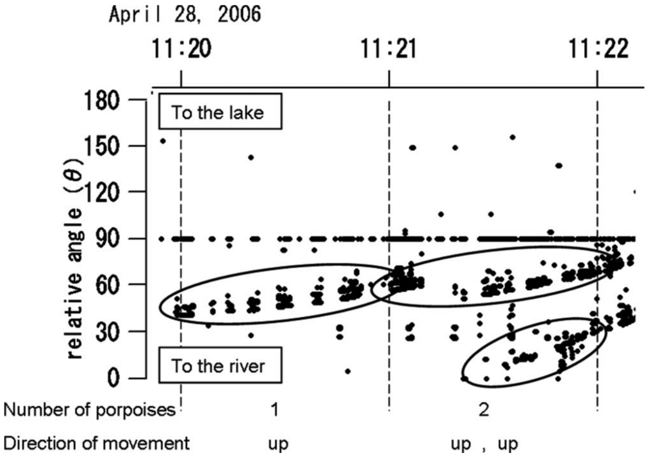

FIG. 3. Number of porpoises counted acoustically in each time bin. This example shows two porpoises. One porpoise continued phonating and swam upstream from the river to the lake. The second porpoise appeared in the observable area at 11:21. The number of animals and movement direction were counted as one upstream at 11:20 and two upstream at 11:21. Within the one track, click trains were not separated by more than 10 s.

III. RESULTS

We obtained 1216 min of effective visually and acoustically measured data at Station 1 and 504 min at Station 2 in 2006, and 464 min at Station 0 in 2007, for an overall total of 2184 min of observations.

In total, 2987 and 591 animals were detected acoustically and visually. At Stations 0, 1, and 2, respectively, animals were detected acoustically in 92.9%, 76.2%, and 76.0% of all time bins, whereas animals were detected visually in 23.5%, 13.1%, and 1.6% of all time bins. On average, porpoises were detected acoustically in 81.7% ± 9.7% and visually in 12.7% ± 11.0% of all observation times; the acoustic detection rate during the total observation time was significantly higher than the visual detection rate (Scheffe's test, $P<0.01$). As shown in Fig. 4, both methods detected the most porpoises at Station 0 and the least at Station 2 (Scheffe's test, $P<0.01$). Detection rates differed among observation sites.

We monitored the swimming direction of porpoises using bearing angles and compared the results of acoustic observations of swimming direction with visual observations. At each station, the number of positive swimming direction identifications divided by the total observation time was similar for both observation methods (Fig. 5).

Figure 6 shows the number and size of detected groups by time bin. Note that the ordinate is logarithmic. Over the total observation time (2184 min), both methods determined the same group size for only 458 min. The most detected numbers of animals were zero by the visual method (1881 min) and one by the acoustic one (866 min). The

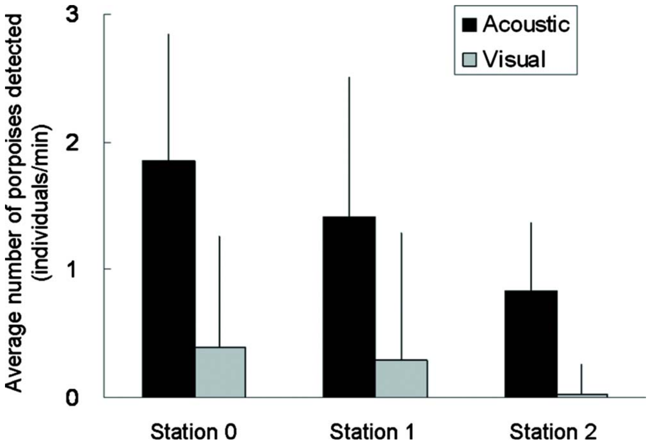

FIG. 4. (Color online) Number of porpoises detected in 1 min at the three stations. The greatest number of porpoises was detected at Station 0 and the fewest at Station 2 (Scheffé's test, $P < 0.01$).

acoustic data logger could count group sizes to a maximum of five individuals, whereas visual observation could count group sizes to a maximum of ten individuals.

IV. DISCUSSION

Stationary acoustic monitoring was effective for counting Yangtze finless porpoises that were echolocating; this method yielded a detection rate seven times higher than visual observation (Fig. 4). The results clearly show that the acoustic method was more effective at detecting the presence of animals than the visual method.

We were able to detect porpoises frequently using the acoustic method, while only occasionally using visual observation. This was a result of different visual and acoustic cues from porpoises. Porpoises can be recorded acoustically when they produce sonar phonates within a detection range. Yangtze finless porpoises produce sonar click trains every 5–6 s on average (Akamatsu *et al.*, 2005c, 2007), so their frequent phonation resulted in a high detection rate using the acoustic method. In contrast, we were only able to observe the porpoises visually when they surfaced in the turbid water of the Yangtze River. Among adult Yangtze finless porpoises, long dive duration averages 70.9 s (Akamatsu *et al.*, 2002). The acoustic and visual detection methods used cues of differing intervals. In addition, because finless porpoises are small cetaceans, do not have dorsal fins, and exhibit little aerial behavior, they are easily overlooked even when they are near the surface.

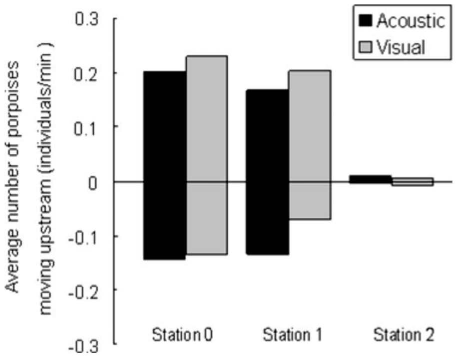

FIG. 5. Average number of moving porpoises per time bin at each station. Positive numbers indicate movement upstream toward Poyang Lake. Negative bars indicate movement downstream toward the Yangtze River. Both methods showed similar trends at all stations.

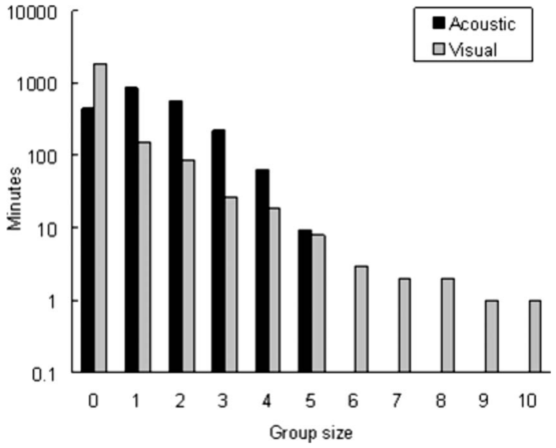

FIG. 6. Comparison of group sizes as determined acoustically and visually. The total of all observations comprised 2184 min. The acoustic data logger could count groups up to five, whereas visual observation could count up to ten individuals at a time. Acoustic detection was greater than visual detection for groups sized 1–5.

The stereo acoustic data logger systems revealed high and low porpoise density areas, which agreed with visual observations (Fig. 4). The average number of detected porpoises was highest at Station 0, which was near the confluence of the lake and the river. This finding is consistent with previous research indicating that Yangtze finless porpoises tend to aggregate in that area (Wei *et al.*, 2003).

Acoustic observations were used successfully to detect the movement direction of porpoises underwater (Fig. 5). The stereo system was more powerful than a monaural system because it could separate sound sources to count the number of animals and also identify their swimming direction. This feature is most suitable for long-term monitoring of porpoise migration by using several A-tags.

The number of time bins in which no porpoises were detected acoustically (447 min) was about one-quarter the number in which none were detected visually (1881 min). Therefore, the acoustic method missed fewer porpoises than the visual method. A towed acoustic survey also resulted in a large ratio of individual animals that were missed (Akamatsu *et al.*, 2008). The acoustic method could detect group sizes to a maximum of five individuals but tended to underestimate the size of larger groups (Fig. 6). When the group size was fewer than four individuals, the acoustic method detected porpoises in 1728 1-min bins, approximately four times the number of bins in which porpoises were detected visually (286 min).

The inability of the acoustic method to detect more than five individuals in a 1-min bin was probably due to the limited resolution of the stereo acoustic data logger's bearing angle. The short distance between the two hydrophones (170 mm) was a possible cause for this limitation. A longer baseline should improve the bearing angle resolution. Other possible causes may have been the small source level of porpoises (including off-axis sounds), alternate phonations of multiple individuals near each other, or eavesdropping to maintain silence. In addition, previous research has suggested that large groups may not vocalize as much as small groups (Götz *et al.*, 2006). Several porpoises swimming together within the detection range phonate alternately, but our passive acoustic system was unable to differentiate them. Yangtze finless porpoises, however, often swim alone or in very small groups and in areas in which visual observations may not be practical, as indicated in Fig. 6. The results indicate that our acoustic monitoring system would have a limited application to species that form larger groups. We used a conservative criterion when counting the number of porpoises to avoid double-counting.

In conclusion, the stationary acoustic monitoring system using stereo acoustic data loggers performed more efficiently than the visual method, especially in areas of low-density echolocating animals. Stationary acoustic observation is suitable for use in areas in which porpoises appear infrequently and form small groups, where visual observation may not be practical. The acoustic system appears to be powerful at monitoring porpoises in a narrow channel such as a river system. In future research, we will monitor porpoise migration using multiple acoustic monitoring systems.

ACKNOWLEDGMENTS

We thank all members of the Laboratory of Conservation Biology of Aquatic Animals at the Institute of Hydrobiology, Chinese Academy of Sciences, the National Research Institute of Fisheries Engineering, the Japan Fisheries Resource Conservation Association, Biosphere Informatics, Graduate School of Informatics, Kyoto University, and the Fisheries Administration Bureau of Hukou Jiangxi Province. This study was partly supported by a Grant-in-aid for Scientific Research (B) (19405005) from the Japanese Research and Development Program for New Bio-Industry Initiatives, the National Natural Science Foundation of China (30730018 and 30570233), the Chinese Academy of Sciences (Present Fund), the Ocean Park Conservation Foundation of Hong Kong, and the Sasagawa Scientific Research Grant from The Japan Science Society (19-740M).

Akamatsu, T., Matsuda, A., Suzuki, S., Wang, D., Wang, K., Suzuki, M., Muramoto, H., Sugiyama, N., and Oota, K. (**2005a**). "New stereo acoustic data logger for tagging on free-ranging dolphins and porpoises," Mar. Technol. Soc. J. **39**, 3–9.

Akamatsu, T., Teilmann, J., Miller, L. A., Tougaard, J., Dietz, R., Wang, D., Wang, K., Siebert, U., and Naito, Y. (**2007**). "Comparison of echolocation behaviour between coastal and riverine porpoises," Deep-Sea Res., Part II **54**, 290–297.

Akamatsu, T., Wang, D., Nakamura, K., and Wang, K. (**1998**). "Echolocation range of captive and free-ranging baiji (*Lipotes vexillifer*), finless porpoise (*Neophocaena phocaenoides*), and bottlenose dolphin (*Tursiops truncates*)," J. Acoust. Soc. Am. **104**, 2511–2516.

Akamatsu, T., Wang, D., and Wang, K. (**2005b**). "Off-axis sonar beam pattern of free-ranging finless porpoises measured by a stereo pulse event data logger," J. Acoust. Soc. Am. **117**, 3325–3330.

Akamatsu, T., Wang, D., Wang, K., Li, S., Zhao, X., Barlow, J., Stewart, B. S., and Richlen, M. (**2008**). "Estimation of the detection probability for Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*) with a passive acoustic method," J. Acoust. Soc. Am. **123**, 4403–4411.

Akamatsu, T., Wang, D., Wang, K., and Naito, Y. (**2005c**). "Biosonar behavior of free-ranging porpoises," Proc. R. Soc. London, Ser. B **272**, 797–801.

Akamatsu, T., Wang, D., Wang, K., and Wei, Z. (**2001**). "Comparison between visual and passive acoustic detection of finless porpoises in the Yangtze River, China," J. Acoust. Soc. Am. **109**, 1723–1727.

Akamatsu, T., Wang, D., Wang, K., Wei, Z., Zhao, Q., and Naito, Y. (**2002**). "Diving behavior of freshwater finless porpoises (*Neophocaena phocaenoides*) in an oxbow of the Yangtze River, China," ICES J. Mar. Sci. **59**, 438–443.

Au, W. W. L. (**1993**). *The Sonar of Dolphins* (Springer, New York).

Au, W. W. L., and Benoit-Bird, K. J. (**2003**). "Automatic gain control in the echolocation system of dolphins," Nature (London) **423**, 861–863.

Carstensen, J., Henriksen, O. D., and Teilmann, J. (**2006**). "Impacts of offshore wind farm construction on harbour porpoises: Acoustic monitoring of echolocation activity using porpoise detectors (T-PODs)," Mar. Ecol.: Prog. Ser. **321**, 295–308.

Fisher, F. H., and Simmons, V. P. (**1977**). "Sound absorption in sea water," J. Acoust. Soc. Am. **62**, 558–564.

Götz, T., Verfuß, U. K., and Schnitzler, H. U. (**2006**). "'Eavesdropping' in wild rough-toothed dolphins (*Steno bredanensis*)?," Biol. Lett. **2**, 5–7.

Ichikawa, K., Tsutsumi, C., Arai, N., Akamatsu, T., Shinke, T., Hara, T., and Adulyanukosol, K. (**2006**). "Dugong (*Dugong dugon*) vocalization patterns recorded by automatic underwater sound monitoring systems," J. Acoust. Soc. Am. **119**, 3726–3733.

Janik, V. M. (**2000**). "Whistle matching in wild bottlenose dolphins (*Tursiops truncatus*)," Science **289**, 1355–1357.

Janik, V. M., van Parijs, S. M., and Thompson, P. M. (**2000**). "A two-dimensional acoustic localization system for marine mammals," Marine Mammal Sci. **16**, 437–447.

Leeney, H. R., Berrow, S., MacGrath, D., O'Brien, J., Cosgrove, R., and Godley, J. B. (**2007**). "Effects of pingers on the behavior of bottlenose dolphins," J. Mar. Biol. Assoc. U.K. **87**, 129–133.

Li, S., Wang, K., Wang, D., and Akamatsu, T. (**2005a**). "Echolocation signals of the free-ranging Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*)," J. Acoust. Soc. Am. **117**, 3288–3296.

Li, S., Wang, K., Wang, D., and Akamatsu, T. (**2005b**). "Origin of the double- and multi-pulse structure of echolocation signals in Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*)," J. Acoust. Soc. Am. **118**, 3934–3940.

Li, S., Wang, D., Wang, K., and Akamatsu, T. (**2006**). "Sonar gain control in echolocating finless porpoises (*Neophocaena phocaenoides*) in an open water (L)," J. Acoust. Soc. Am. **120**, 1803–1806.

Nishimura, C. E., and Conlon, D. M. (**1994**). "IUSS dual use: Monitoring whales and earthquakes using SOSUS," Mar. Technol. Soc. J. **27**, 13–21.

Philpott, E., Englund, A., Ingram, S., and Rogan, E. (**2007**). "Using T-PODs to investigate the echolocation of coastal bottlenose dolphins," J. Mar. Biol. Assoc. U.K. **87**, 11–17.

Thomsen, F., van Elk, N., Brock, V., and Piper, W. (**2005**). "On the performance of automated porpoise-click-detectors in experiments with captive harbor porpoises (*Phocoena phocoena*) (L)," J. Acoust. Soc. Am. **118**, 37–40.

Tsutsumi, C., Ichikawa, K., Arai, N., Akamatsu, T., Shinke, T., Hara, T., and Adulyanukosal, K. (**2006**). "Feeding behavior of wild dugongs monitored by a passive acoustical method," J. Acoust. Soc. Am. **120**, 1356–1360.

van Parijs, S. M., Smith, J., and Corkeron, P. J. (**2002**). "Using calls to estimate the abundance of inshore dolphins: A case study with Pacific humpback dolphins *Sousa chinensis*," J. Appl. Ecol. **39**, 853–864.

Verfuß, U. K., Honnef, C. G., Meding, A., Dähne, M., Mundry, R., and Benke, H. (**2007**). "Geographical and seasonal variation of harbour porpoise (*Phocoena phocoena*) presence in the German Baltic Sea revealed by passive acoustic monitoring," J. Mar. Biol. Assoc. U.K. **87**, 165–176.

Wang, K., Wang, D., Akamatsu, T., Li, S., and Xiao, J. (**2005**). "A passive acoustic monitoring method applied to observation and group size estimation of finless porpoises," J. Acoust. Soc. Am. **118**, 1180–1185.

Wei, Z., Wang, D., Zhang, X., Zhao, Q., Wang, K., and Kuang, X. (**2002**). "Population size, behavior, movement pattern and protection of Yangtze finless porpoise at Balijiang section of the Yangtze River," Resources and Environment in the Yangtze Basin **11**, 427–432.

Wei, Z., Zhang, X., Wang, K., Zhao, Q., Kuang, X., Wang, X., and Wang, D. (**2003**). "Habitat use and preliminary evaluation of the habitat status of the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*) in the Balijiang section of the Yangtze River, China," Acta Zoologica Sinica

49, 163–170.

Zhang, X., Liu, R., Zhao, Q., Zhang, G., Wei, Z., Wang, X., and Yang, J. (**1993**). "The population of finless porpoise in the middle and lower reaches of Yangtze River," Acta Theriologica Sinica **16**, 490–496.

Zhao, X., Barlow, J., Taylor, B. L., Pitman, L. R., Wang, K., Wei, Z., Brent, S., Stewart, S. B., Turvey, T. S., Akamatsu, T., Reeves, R. R., and Wang, D. (**2008**). "Abundance and conservation status of the Yangtze finless porpoise in the Yangtze River, China," Biol. Conserv. **141**, 3006–3018.

Zheng, J., Xia, J., He, S., and Wang, D. (**2005**). "Population genetic structure of the Yangtze finless porpoise (*Neophocaena phocaenoides asiaeorientalis*): Implications for management and conservation," Biochem. Genet. **43**, 307–320.