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A concept for autonomous and continuous observation of melt pond morphology: Instrument design and test trail during the 4th CHINARE-Arctic in 2010

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Abstract Accelerated decline of summer and winter Arctic sea ice has been demonstrated progressively. Melt ponds play a key role in enhancing the feedback of solar radiation in the ice/ocean-atmosphere system, and have thus been a focus of researchers and modelers. A new melt pond investigation system was designed to determine morphologic and hydrologic features, and their evolution. This system consists of three major parts: Temperature-salinity measuring, surface morphology monitoring, and water depth monitoring units. The setup was deployed during the ice camp period of the fourth Chinese National Arctic Research Expedition in summer 2010. The evolution of a typical Arctic melt pond was documented in terms of pond depth, shape and surface condition. These datasets are presented to scientifically reveal how involved parameters change, contributing to better understanding of the evolution mechanism of the melt pond. The main advantage of this system is its suitability for autonomous and long-term observation, over and within a melt pond. Further, the setup is portable and robust. It can be easily and quickly installed, which is most valuable for deployment under harsh conditions.

Keywords **Observing system, melt pond, morphology, Arctic**

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0 Introduction

When temperatures rise in summer, sea ice and the snow above start melting. The meltwater gathers in depressions to produce melt ponds[1]. On first year sea ice, these ponds start as shallow melt pools situated randomly on the ice surface. With further melting of snow and ice and greater melt pond formation, channels open between individual ponds, creating a network of pools and channels[2]. As the melt season progresses, because of the smaller albedo of water compared to snow and bare ice, the melt ponds absorb more solar radiation than surrounding icy and snowy surfaces. The ponds thereby deepen, but do not increase in diameter[3]. If the ice survives the first melt season, melt ponds that have not drained into the sea will refreeze in autumn. Every new melt season on multiyear ice deepens old pond sites, since the ponds of the previous summer are preferential locations into which new melt water collects[1].

Because of their smaller albedo, melt ponds are important in strengthening ice-albedo feedback. This increases the absorbing heat flux of sea ice cover, and accelerates underlying sea ice and snow cover thaw[4].

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Albedo of sea ice cover is a significant input to current ocean–sea ice–atmosphere (OSA) models and Arctic climate change modeling and forecasting[5]. This albedo is strongly influenced by the melt pond fraction[3,6]. Pond fractions have been determined by analyzing aerial photographs[2,7]. Most *in situ* investigations and theoretical research on melt ponds were done by directly measuring and simulating their albedo or reflectivity, as well as some other optical factors[5,8–10].

The Surface Heat Budget of the Arctic Ocean (SHEBA) experiment is regarded as one of the most comprehensive and successful research expeditions[11]. In this experiment, the evolution of multiyear Arctic sea ice, snow cover and melt ponds were investigated for over a year, with respect to albedo and various surface features. Previous works have revealed that the albedo or reflectivity of melt ponds is influenced or controlled by many topographic and hydrologic parameters, such as ice type, pond depth, pond bottom configuration and pond age[6,12–13]. However, hydrologic processes on sea ice are still inadequately understood. Although theoretical analyses and assumptions are supplemental, they do not substitute for indispensable ground-measured data. Those data are required for initialization, formulation and validation of OSA models and satellite retrieval algorithms. Unfortunately, melt pond topography, morphology and hydrology are still determined manually, awkwardly, randomly and discontinuously[12–13]. All these defects of ongoing survey skills and systems seriously retard the acquisition of knowledge about melt ponds, and understanding of their evolution and functioning in polar regions.

Based on summer Arctic sea ice and melt pond conditions and variations, the present paper formulates a modern concept for field surveying of melt pond morphology and hydrology. This can obtain autonomous and continuous data for many melt pond parameters, including vertical profiles of pond water temperature and salinity, pond surface conditions and bottom shape, surface ice growth and decay processes, and temporal variations of these features. Current devices were evaluated *in situ*, during an ice camp of the fourth Chinese National Arctic Research Expedition (4th CHINARE-Arctic) in summer 2010. Much valuable data were recorded to further our knowledge of melt pond development.

1 Modern concept for melt pond morphology

Melt ponds in the Arctic are very important in changing the spatial features of sea ice floes. In summer, solar radiation can penetrate melt ponds and warm the upper ocean mixing layer, which accelerates ice bottom melt. The melt pond can also significantly alter surface albedo, leading to massive surface melt. Therefore, evaluation of these ponds is critical to understanding the entire Arctic sea ice mass balance. We formulate here a modern concept for investigation of the bottom and surface melt in the ponds, toward a better understanding of the mechanisms of pond dynamics and thermodynamics.

Our melt pond measuring concept consists of three major parts: Temperature-salinity measuring (TSM), surface morphology monitoring (SMM), and water depth monitoring (WDM) units. Figure 1 shows a skeleton chart of the concept.

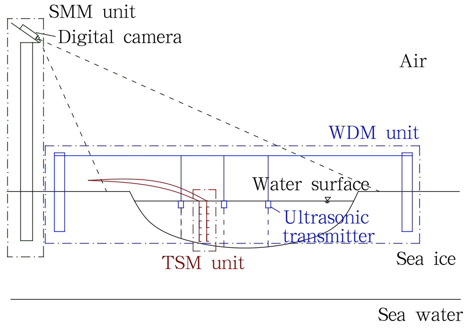


Figure 1 Design of the modern concept for monitoring melt ponds.

The TSM unit is composed of a thermistor cable (TC) and salinometer chain (SC), to continuously determine temperature and salinity profiles of water in the pond over a long period. For the TC, A-class PT100 thermo-sensors (Dalian Branch of JUMO Germany and China), with accuracy 0.1℃, are deployed to obtain temperature variations, and an Environmental Meteorology Monitor (Jinzhou Sunlight Technology Ltd, China) is used for data procedures and storage. For the SC, a string of salino-sensors are arranged in the vertical direction to determine vertical salinity profiles of pond water. The number of thermo-sensors and salino-sensors is flexible, according to the pond water depth and sensor interval.

The SMM unit consists of a vertical lifting tower and a digital camera in a protective box. A Nikon P6000 digital camera (13 megapixels, Japan) is placed in a sealed, rigid plastic box with a glass window, which protects the camera from rain and snowfall. This box is affixed to the top of the lifting tower with the aid of a hinge support. Hence, the angle between the optical axis of the camera and sea level can be adjusted according to melt pond size, camera height, and distance between the pond and lifting tower. This adjustment permits the viewing field of the camera to cover the entire pond.

The WDM unit is constituted by a WUUL-I polar ultrasonic range finder (PURF, Wuhan University, China) and a crown block-steel rope support (BRS) unit. The PURF is designed exclusively for surveillance of ice-water interface movement in polar regions. Its ultrasonic transmitters have an accuracy of 2 mm and measuring range 100–2 000 mm, and are downward looking (Figure 1). In practice, two timber piles can be placed in the sea ice cover on both sides of the melt pond, and two crown blocks fixed atop the piles. A steel rope is wound over all the crown blocks to make an annular track support. The ultrasonic transmitters can thereby be hung on the rope, enabling them to be moved in place for measuring the bottom change. All transmitters should be suspended beneath the water surface, because the PURF algorithm accounts for ultrasound propagation velocity only within water.

2 Field test in the 4th CHINARE-Arctic in summer 2010

2.1 Introduction to the ice camp

The 4th CHINARE-Arctic in summer 2010 was the last and important cruise of the China Program for International Polar Year 2007–2008. It lasted from 1 July to 20 September 2010 (Beijing Time), a total of 82 d. The R/V *XUE LONG* icebreaker sailed into the Arctic sea ice zone at 71.9°N, 168.8°W on 24 July, and exited at 75.5°N, 172.2°W on 28 August, during which it discovered that the edge of marginal ice zone was moving rapidly northward. This cruise reached its northernmost point at 88.4°N on 20 August. The primary research area was in the Pacific Arctic sector (including Bering Sea, Bering Strait, Chukchi Sea, Beaufort Sea, Canada Basin and high Arctic sea), where sea ice retreats faster than in other Arctic sectors[14–15].

Our aim is to better understand melt pond mechanisms and evolution in summer, and pond interaction with neighboring ice and snow. Consequently, during a 12-day ice camp launched on a multiyear ice floe from 8 to 20 August (Figure 2), our proposed concept for morphologic monitoring of melt ponds was adopted and put into practice (Figure 3). The ice floe was lightly ridged and snow-covered, with a diameter of approximately 10 km. Over the entire ice camp research area, numerous melt ponds of highly variable areas appeared. An elongated pond of about 60 m^2 was deemed representative and was selected for study. The evolution of morphology, the surface freezing-thaw process, pond depth, and temperature and salinity of pond water were investigated autonomously and continuously, during the ice camp period from 9–19 August 2010.

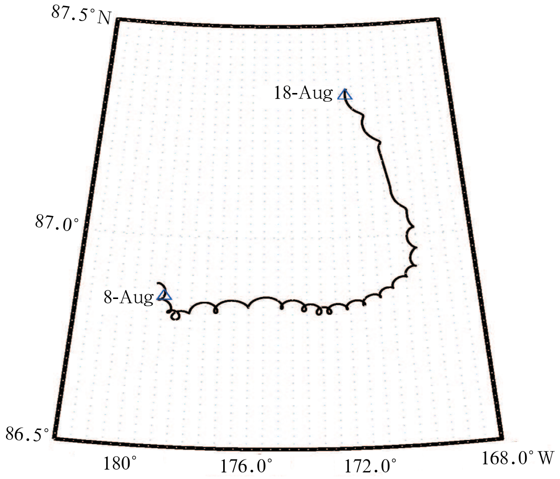


Figure 2 Position of ice camp (blue triangle) and its drift track (black solid line). Track is largely controlled by the transpolar current and prevailing wind.

2.2 *In situ* monitoring devices and methods

The monitoring system for melt pond morphology, designed on the new concept, was deployed and tested. As shown in Figure 3, two timber piles were placed on opposite banks of the study pond, with a span of 13 m. The distances between timber piles and pond boundaries were 1.5 m, which took into consideration potential ice melt between the two.

As a core part of the WDM, the PURF was encoded to control the ultrasonic transmitter (a kind of portable

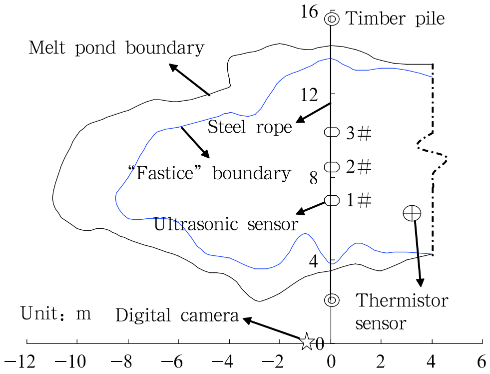


Figure 3 Planar graph of in situ monitoring system (2010-08-16). "Fast ice" is a thin ice cover of ~1–3 cm thickness, which underlies melt pond water and is connected to the ice bank at the pond boundary.

micro sonar). The transmitter emits ultrasonic pulses and receives the signals reflected by the ice. The distance between the transmitter and ice can be calculated based on the propagation velocity of ultrasonic waves in water, and the time between emission and reception of the pulse. Three ultrasonic sensors were attached to parallel steel ropes and were set downward looking, below the water surface by tens of centimeters. This was done because they only function underwater (Figures 4a, 4d). Eventually, all sensors were fixed on floaters, which glided horizontally to determine water depth at different positions along the steel ropes. These floaters always sit on the water surface and do not tilt, owing to their wide, thin bases (Figure 4b). This ensures that the transmitters always operate in the vertical direction. Sensors 1♯, 2♯ and 3♯ were placed 310, 460 and 610 cm from the pond bank, respectively, along the vertical axis of Figure 3. All ultrasonic sensors were adjusted to measure and record depth data automatically once every minute, throughout the ice camp campaign.

A thermistor chain of three thermo-sensors was installed in the pond water, about 2 m away from the bank. These thermo-sensors were placed 10, 25 and 40 cm below the water surface, to obtain a water temperature profile. The water depth at this site was approximately 50 cm. The temperature profile was recorded once every minute. However, a salinometer chain was not prepared, because homogeneous pond salinity was assumed because of its small depth. Instead, we sampled the pond water once every three days to determine salinity. Unfortunately, a portable salinometer probe with only 0.1 PSU accuracy was used, because an in-lab salinity analyzer with 0.001 PSU accuracy (National Center of Marine Technology, China) was broken during early transportation.

A digital camera was placed at 622 cm height, within a sealed box (Figures 4a, 4c). The box was mounted on a lifting tower, whose base pile was embedded in the ice cover by 80 cm and could be dilated divergently[16]. The base pile was so constructed to avoid tilting of the lift

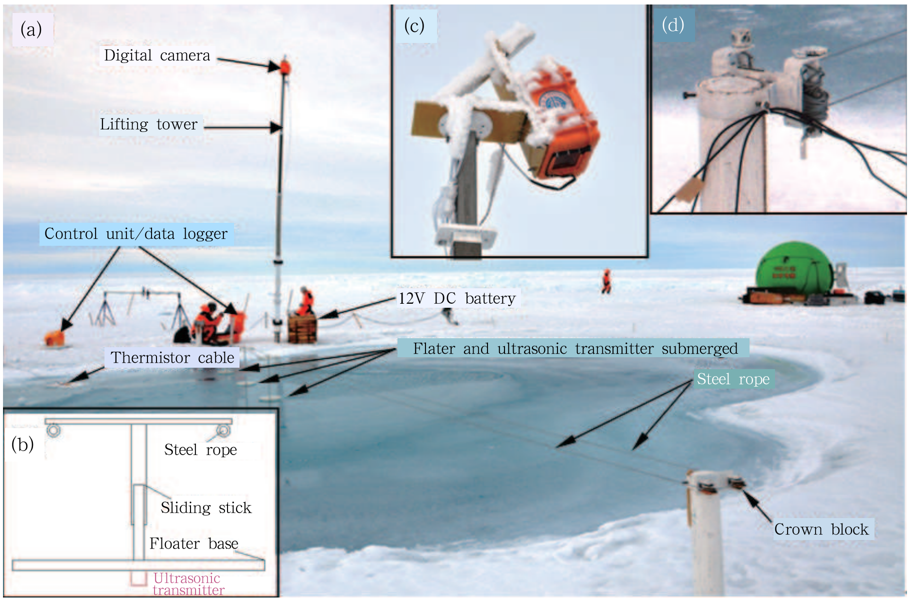


Figure 4 Field monitoring of melt pond during ice camp period. (a) *In situ* instrumentation; (b) floater for ultrasonic transmitter; (c) adjustable support and sealed box for digital camera; (d) *BRS* unit.

tower after (potentially) significant melt. The inclination angle between sea level and camera optical axis was 50.5°. Unfortunately, the viewing field of the digital camera was unable to cover the entire pond boundary, since its area was too large. Therefore, the part of the boundary that could be observed most clearly was selected for monitoring, with shots taken every half hour. All the aforementioned equipment was supported by several 12V DC storage batteries, which could be replaced and recharged every two or three days. Figure 4 shows photographs of field observation equipment at the ice camp melt pond.

2.3 Results and discussion

2.3.1 Rapid mounting foundation

For the equipment installed stably and to save the install time, a patent technology of rapid mounting foundation for inserting ice depth in the range of 60–90 cm was developed by Dalian University of Technology[16]. This kind of foundation was a special setup which can expand divergently to adhere tightly to the wall of the ice hole. Several foundations were used for the mast of wind profile measurements and for other equipment bases in Antarctic and Arctic Expeditions. During the polar summer, the ice temperature is higher and its strength is lower, the ice around the foundation can be melt and the foundation would tilt and creating measurement accurate problems. Actually, we have taken into consideration the potential tilt as a result of further melting, a vertical adjust screws are arranged. In this field test, the anchoring pole of camera was inserted into ice cover by 80 cm, the foundation is stable.

2.3.2 Weather and melt pond conditions

An overcast sky was prevalent during the entire camp period. The solar disk was completely visible for only a few hours, on 8, 14, 16 and 18 August. There were a couple minor snowfall events, on 10, 11 and 16 August, and the new snow melted in one or two days. There was light drizzle during a period of slightly warmer air temperature (AT), from the afternoon of 16 August through the morning of 17 August (Figure 5). This slight rainfall and the AT rise almost cleared the sea ice cover of snow.

Most of the melt pond surface was covered by a thin ice cover of thickness 1–2 cm, before 17 August. Based on analysis using a salinometer probe with accuracy 0.1 PSU, pond water samples from 13 and 17 August showed water salinity ∼0.5 PSU. Figure 5 shows that AT was between –3.0℃ and 5.0℃, with a mean ∼0℃. Since AT fluctuated before 17 August, all temperature series at 10 cm, 25 cm and 40 cm depths went up or down accordingly and without any lag, probably because of the small water depth. Nevertheless, after 17 August, as AT rose and remained above 0℃ for one day, water temperature did not simultaneously increase but remained constant for 6–8 h. This was largely because melting of the thin ice cover (∼20–30 mm thick around the TC) overlying the water took away heat energy, reducing and delaying downward heat flux[3,8]. Although the melt pond water temperature profiles have a similar trend with the AT variation, the values of the water temperature are in a range of –0.1℃— –0.9℃, which is much lower than the calculated freezing point (about –0.03℃) based on a 0.5 PSU salinity. Furthermore, in a shallow melt pond, the pond water is supposed to be vertically homogeneous and isothermal. So we speculate that there is a systematic deviation amongst these three thermistors, causing a large temperature difference. Therefore, a thermistor cable with higher accuracy and consistency is more applicable to gauge the melt pond water temperature variation.

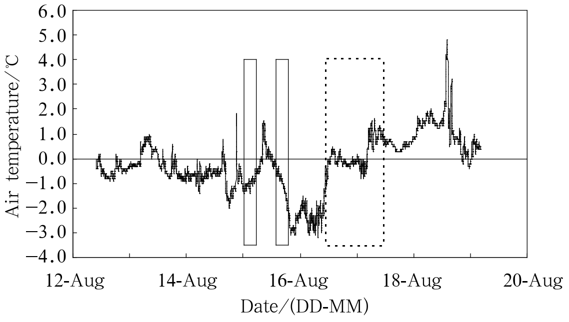
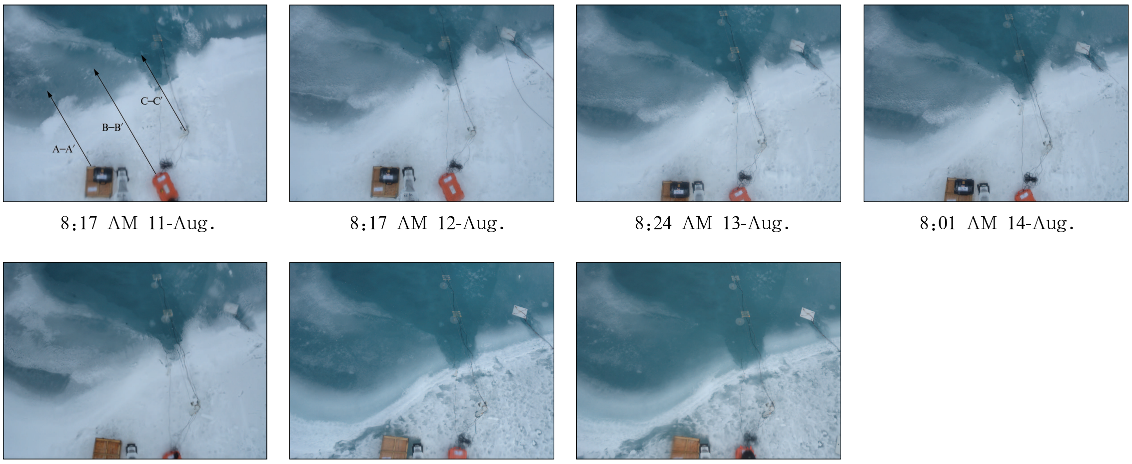


Figure 5 Air temperature during ice camp period. The solid blocks denote the periods of minor snowfalls, while the dotted block denotes a slight drizzle event.

2.3.3 Widening and deepening of melt pond

SMM provided a series of tilt high-resolution pictures to trace surface evolution of the melt pond, including the behavior of the pond boundary and changes in pond surface conditions. Figure 6 indicates that nearly the entire water surface was covered by a gray, thin ice cover. The thin ice and pond boundary changed little before 18 August. However, after 18 August (possibly the 17th), the thin ice almost melted completely and the pond



8:17 AM 11-Aug. 8:17 AM 12-Aug. 8:24 AM 13-Aug. 8:01 AM 14-Aug.

8:26 AM 17-Aug. 8:26 AM 18-Aug. 4:26 AM 19-Aug.

Figure 6 Oblique pictures of part of the melt pond. Inclination angle of the major axis of camera's view field is 50.5°, and camera height is 622 cm. The side of dark yellow cubic box in each picture is 65 cm long. Pictures on 15 and 16 August were missed, because battery power was exhausted.

boundary advanced progressively by ~550 mm (Figure 7), owing to the increasing AT (Figure 5). Further, rainfall on 17 August accelerated the melt of ice and snow cover, making the pond boundary and ice bank clearer and cleaner. However, the surface conditions between 19:00 PM on 14 August and 4:00 AM on 17 August could not be photographed, because battery power was exhausted and the battery could not be replaced in time.

Based on WDM data, evolution of the melt pond bottom (i.e., water depth) was documented (Figure 8).

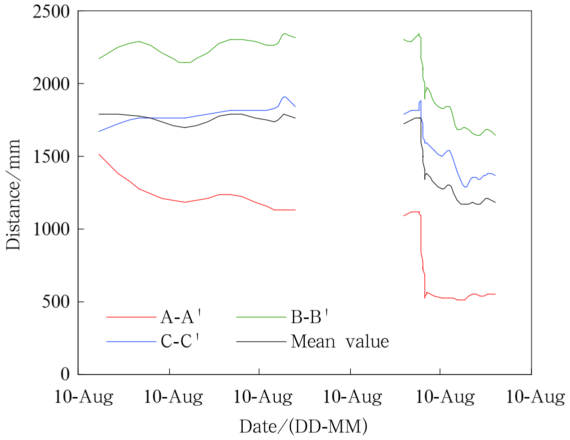


Figure 7 Distances between melt pond boundary (dark blue-white boundary in Figure 6) and different references (dark yellow wooden cabinet, orange box and white timber pile in first picture of Figure 6, respectively). Variations of these distances are presumed to be movement of pond boundary. Legends are consistent with first picture of Figure 6.

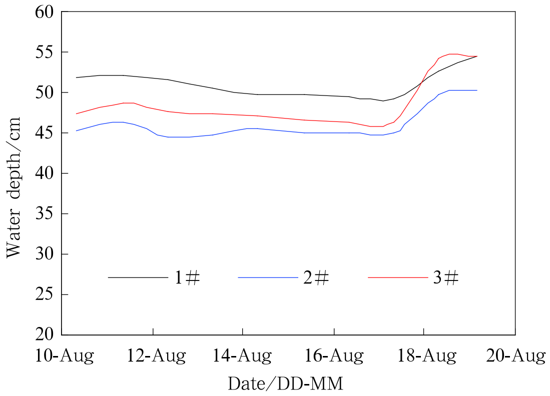


Figure 8 Depth variations of melt pond water. Legend numbers correspond to ultrasonic sensor numbers.

Melt pond water depth is influenced by many factors, such as melting of underlying ice cover, inflows of floe surface meltwater, and rainfall. The water depth of the melt pond changed little, until a rapid rise on 17 August. This was because of rainfall and AT in excess of 0℃ over one day, which caused an intense thaw of snow cover and ice. The bottom melt rate observed in the pond agrees well with SHEBA investigation (~0.7 cm·d^{-1})[17–18] and simulated values from Taylor and Feltham[9]. However, Marassuti and LeDrew's value[12] is much greater (~1.0 cm·d^{-1}), mainly because their investigation covered only the initial melt period, when snow cover melts rapidly.

Melt ponds are important in the summer heat budget of sea ice. They reduce the albedo of ice cover, increase light transmittance to the ocean, and serve as a storage reservoir for surface meltwater[19]. These ponds usually begin to form on the first year sea-ice surface during mid-June, in response to snowmelt. As melt progresses, these ponds grow in area and depth, as in Figures 7 and 8. Based on SHEBA observations, there are generic types of ponds: sea level ponds and "alpine" ponds[17]. The melt pond studied here was a sea level pond. Its water level was a few centimeters below the "bank" ice. When massive inflows of new meltwater collect in sea level ponds, their water surfaces potentially grow larger than alpine ponds. The overall increase in pond fraction observed in aerial images likely results from the preponderance of sea level ponds[20].

3 Conclusions and future improvements

The evolution of melt ponds in the Arctic summer plays an important role in current changes of Arctic ice cover and climate, and is an increasing focus for research. Reliable and stably functioning equipment and systems are critical for field investigation in Arctic research. A new concept has been formulated for autonomous and continuous monitoring of melt pond morphology, which includes surface evolution and variations of water depth, temperature and salinity. A field campaign based on this concept was conducted during a long-period ice camp of the 4th CHINARE-Arctic. Continuous, 10-day datasets of melt pond surface conditions, water depth and temperature were acquired from 10–19 August.

Although the concept is scientific and feasible for withstanding the hard Arctic conditions, some concerns about its field implementation arose. Many improvements and extensions of the present concept remain, before better understanding of melt pond mechanisms can be achieved. Variation of the pond water temperature is very small, so only a thermistor with accuracy better than 0.01°C can be used to detect such slight change. Up- and down-welling radiometers should be deployed to interpret water temperature and heat budget in the pond. The salinity analyzer should be more accurate than 0.1 PSU for determination of pond water salinity. To avoid loss of data, a battery with greater capacity should be used and replaced/recharged on a timely basis. Furthermore, the 12-day ice camp was too short to span an entire cycle of melt ponding, limiting the testing of this setup and knowledge of melt pond evolution.

Nevertheless, the main advantage of this system is its suitability for autonomous and long-term observation over and within a melt pond, even in the face of low temperatures, snow/rainfall, strong wind and humidity. Furthermore, the setup is portable and robust. It can be easily and quickly installed, which is most valuable for deployment under harsh conditions.

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