Long-Term Measurement of Solar Irradiance above, within, and under Sea Ice in Polar Environments by Using Fiber Optic Spectrometry

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ABSTRACT

An irradiance profiling system was developed to obtain long-term autonomous measurements of solar irradiance above, within, and under sea ice in the Arctic. Two miniature spectrometers were adopted to sequentially sense light signals collected and transmitted by eight fiber probes deposited at different levels of the sea ice environment. Each spectrometer was aligned to each fiber probe by rotating the spectrometer to the desired angle by using a rotary spectrometer switching device. A small optical probe was developed that could be placed in an auger hole with a diameter of 5 cm and enable a high transmission rate for the light signal. The temperature dependence of the signal output was examined and evaluated over the entire operating temperature range from -50° to $+30^{\circ}\text{C}$. A signal output correction model was proposed to correct temperature-induced biases in the system output; this was combined with the system spectral sensitivity correction to determine the absolute irradiance entering the system. The performance of the system was examined for two days during the ninth Chinese National Arctic Research Expedition by deploying it in a 185-cm-thick ice pack in the Arctic and measuring the solar irradiance distribution at different levels. The spectral shape of the measured solar irradiance above the sea ice agreed well with that measured using other commercial oceanographic spectroradiometers. The measured optical properties of the sea ice were generally comparable to those of similar ice measured using other instruments.

1. Introduction

Sea ice is a substrate that, after the initial freezing of seawater, is considerably modified by the interaction of physical, biological, and chemical processes (Thomas and Dieckmann 2009). In recent years, the total area occupied by both polar regions has ranged between 15×10^6 and $22 \times 10^6 \text{ km}^2$, accounting for approximately 4% of the

total surface of Earth (Arrigo 2014). Owing to this large area, sea ice, which mediates the material and energy exchanges between the ocean and the atmosphere, significantly influences the global biogeochemical cycles and global climatology (Vancoppenolle et al. 2013).

Solar radiation is one of the most fundamental concerns in the sea ice environment. Light exerts considerable influence on the heat and mass balance of the sea ice and upper ocean by being the primary driving force for the evolution of the summer melt season in the Arctic (Light et al. 2008; Perovich et al. 2002). Furthermore, the availability of solar radiation, especially that pertaining to the visible wavelengths, is vital in structuring habitats

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developed within the sea ice and in the underlying ocean (Arrigo et al. 1991; Boetius et al. 2013; Leu et al. 2015; Perovich 1996). Therefore, detailed information concerning the distribution of solar radiation in the sea ice environment cannot only help understand the heat and mass balance in the atmosphere–ice–ocean system, but also help clarify the evolution of the Arctic marine ecosystem (Comiso 2006; Comiso 2002; Perovich et al. 1993). In particular, the sea ice in the Arctic has undergone considerable changes throughout the years, in terms of its extent, thickness, age, and concentration (Arrigo et al. 2008; Maslanik et al. 2007; Serreze et al. 2007). The significant variation in the composition and structure of the sea ice, which occurs in its surface and interior regions, can in turn reshape the inner light field at both the spatial and temporal scales (Nicolaus et al. 2012). Considering this background, it is particularly necessary and urgent to obtain long-term time-serial measurements of the solar radiation distribution. However, most previous measurements of ice albedo and/or transmittance have been obtained in air and/or under ice (Frey et al. 2011; Grenfell and Perovich 1984; Perovich et al. 2002; Zhao and Li 2009). Research pertaining to the measurement of the solar radiation distribution within sea ice are rather limited.

Grenfell and Maykut (1977) used a specially designed portable spectrophotometer to measure the light signal transmitted from a fiber optic light guide, which was sequentially introduced into multiple horizontal holes drilled at various levels in the wall of a narrow trench evacuated in multiyear ice near Fletcher's Ice Island located in the Beaufort Sea. Following a similar approach, Arrigo et al. (1991) obtained the photosynthetically active radiation profile within a congelation ice sheet in the Antarctic. Light et al. (2008) and Ehn et al. (2008b) gradually lowered a fiber probe down boreholes with stepwise increments along the depth to measure radiation using a spectrophotometer located in the air, to obtain vertical profiles of solar irradiance within these boreholes. With help from a diver, Ehn et al. (2008a) drilled an auger hole with a diameter of 0.05 m from the ice bottom to the surface in an upward manner and inserted a cosine collector at the top of the hole to collect and transmit the irradiance signal. The irradiance profile was obtained using a spectroradiometer, which was used to measure the signal when the hole was drilled gradually in intervals of 0.05 m vertically. All of the above mentioned studies provided valuable solar radiation profile data concerning the sea ice. However, most of these measurements were conducted in boreholes or auger holes instead of a solid sea ice medium. Moreover, the holes could distort or re-freeze rather rapidly, and the movement of the optical

probe or optical sensor onward could cease. Therefore, the use of the above mentioned methods or technologies to obtain long-term solar irradiance profile measurement is infeasible, particularly over seasonal scales.

A novel approach to obtain long-term autonomous measurements of the solar irradiance profile above, within, and under the sea ice has been proposed previously; this approach involves embedding multiple fiber probes at different levels of sea ice to collect and transmit solar radiation signals, using one miniature spectrometer to sense these signals in sequence (Wang et al. 2014). A prototype system following this approach has been developed and successfully examined in the laboratory. In this study, a refined system was developed based on the previous works, with the objective of measuring the solar irradiance profile in the Arctic sea ice environment, potentially over the entire melting season. The temperature dependence of the system output was investigated. A signal output correction model was developed to correct temperature-induced biases in the system output, which was then combined with the approach of correcting the spectral sensitivity of the system to determine the absolute incident irradiance entering the profiling system. Finally, a field examination of the system was carried out in the Arctic sea ice environment to validate the overall performance and practicability of the system.

2. Methods

a. Measurement principle

To obtain long-term measurements of solar irradiance in multiple levels of the polar sea ice environment (i.e., above, within, and under the sea ice), specific measures are required in terms of the collection and measurement of irradiance signals. However, to the best of the authors' knowledge, no previous study has addressed these two aspects concurrently and practically in the polar sea ice environment. The measurement of the irradiance profile in the sea ice environment is considerably more difficult than and different from the corresponding measurement in water; this is because sea ice is solid, which renders most irradiance profiling methods applied to water, such as taking measurements while profiling up and down water, inapplicable (Kikuchi et al. 2007; Krishfield et al. 2008). In addition, the noninvasive irradiance measurement technology is still under development, and novel methods that exploit the advantages of modern technologies to simultaneously address the two abovementioned aspects must be developed.

It is known that fiber probes (i.e., optical fibers equipped with optical probes) are small in size, and they have

FIG. 1. Measurement principle of solar irradiance in multilevels of the sea ice environment based on fiber optic spectrometry.

the advantage of small self-shading, which can facilitate their convenient embedding in sea ice to collect and transmit irradiance signals without considerably disturbing the surrounding medium. Furthermore, commercially available monochromators have various spectral ranges from ultraviolet to far infrared, which can satisfy the different scientific measurement requirements. Hence, long-term measurement of the irradiance profile in the sea ice environment could be performed by placing multiple fiber probes above, within, and under different layers of sea ice to collect and guide corresponding light signals, and some monochromators could be placed on the surface to sense these signals (Fig. 1). Such a configuration has the advantage of not considerably disturbing the ambient medium, which is attributable to the small size of fiber probes; moreover, the cost of developing such a system is lower than that for installing multiple optical sensors at desired positions.

b. System description

1) HARDWARE CONSIDERATIONS

To validate the abovementioned concept, a prototype system has been constructed and examined in the laboratory (Wang et al. 2014). The prototype used one miniature spectrometer (Hamamatsu Photonics K.K. C11009MA) to sense the signal transmitted from each of 12 fiber probes in a predesigned order, and the switch of each fiber probe was controlled using a rotary fiber multiplexer. The number of optical probes connected to the system and the position of the fiber probe in sea ice could be readily adjusted as required. Laboratory tests indicated that temperature-induced biases in key parts of the system (e.g., spectrometer, optical fibers, and fiber

multiplexer) could be identified well and corrected accordingly. An assessment performed using simulated ice columns (i.e., by freezing four fiber probes at four different levels of an ice column with a height and diameter of 1.2 m and 12 in. (1 in. = 2.54 cm), respectively, and obtaining measurements while illuminating the ice column from above) demonstrated that the overall performance of the system was promising to warrant further refinement for application in real sea ice environments. However, the spectral range of the system, determined using the miniature spectrometer (i.e., C11009MA), was only 340–780 nm. This range might satisfy the requirements for investigating biological processes that occur within and below the ice; however, it is too narrow to evaluate the heat and energy balance in the atmosphere–ice–ocean system, in which wavelengths of at least up to 1000 nm are involved (Grenfell and Maykut 1977). This aspect limits the application scope of the system and the usefulness of the measurements. Furthermore, the alignment of each fiber probe to the spectrometer was accomplished by rotating the fiber multiplexer with 12 fibers connected at 12 predesigned angles, where the selected fiber points to the optical entrance of the spectrometer. During this process, the 12 fibers may twist as the multiplexer rotates, and the degree of twisting increases with increases in the rotating angle. This phenomenon is dangerous for the fibers as they might break when the twisting exceeds certain limits; alternatively, the fibers may undergo fatigue when the system operates repeatedly. Furthermore, the sea ice environment is cold, and the fibers are much more fragile at low temperatures, which increases the risk of fracture.

To overcome these shortcomings, a refined system was developed based on the described prototype to record solar irradiance profiles in the Arctic sea ice environment, potentially over seasonal scales. In this improved profiling system, a near-infrared miniature spectrometer (Hamamatsu Photonics K.K. C11010MA) covering a spectral range of 640–1050 nm was included in addition to the C11009MA-visible spectrometer module (Fig. 2). The operation mechanism and general physical components of these two spectrometers are very similar except for the spectral range, and their collaborative operation can cover a range of 350–1000 nm, which pertains to the region of interest (Table 1). This type of spectrometer configuration is suitable for the considered application because, except for the external optical and electrical interfaces, all other relevant optical components and electronics are sealed inside a waterproof metal shell, which protects the spectrometer from potential condensation of airborne water vapor when the ambient temperature drops below the dewpoint. A fiber collimating lens (SPL-tech SPL-COL-5) was attached at the

FIG. 2. Physical arrangement of the refined irradiance profiling system, indicating the mechanical arrangement and electrical connection of the parts involved in this system.

optical entrance (i.e., an optical fiber with a core diameter of 0.6 mm) of the spectrometer via a SMA-905 interface to improve the signal coupling between the spectrometer and the aligned fiber. Considering the spectral bands of the solar radiation of interest (i.e., 350–1000 nm), a high-transmission silica fiber with a spectral range of 350–2200 nm (CeramOptec Optran Ultra HWF) was adopted to transmit the light collected using an optical probe, which is described in the following section. The typical transmission of this fiber is higher than 99% m^{-1} for wavelengths of approximately 450–1000 nm, and it is higher than 90% m^{-1} for shorter wavelengths. For the longest fiber (i.e., 6 m) used in this system, at least 94% energy of the light signal could be transmitted to the spectrometer for most wavelengths, which is believed to be acceptable for the considered application. A new optical probe was developed using a thin film of polytetrafluoroethylene (PTFE) to function as the diffuser. The PTFE replaced opaline glass, which is adopted by most commercially available optical probes such as the Ocean Optics, Inc., CC-3

cosine-corrected irradiance probe, to decrease its attenuation coefficient as much as possible. The film was placed inside a stainless steel case and covered by a silica glass window to prevent it from coming in contact with the external medium (Fig. 3). The seal between the glass window and the stainless steel case was realized using fast cure epoxy (Henkel AG and Co. Loctite EA9017). The probe had a standard SMA-905 interface; therefore, any optical fiber with this interface could be connected to it, which considerably improves the flexibility of the application. The transmission of the optical probe with a 0.2-mm-thin PTFE film was approximately 30 times as strong as that of the CC-3 probe.

Instead of rotating the fibers, a rotary spectrometer switching device was developed to rotate the two spectrometers aligned to the selected fibers. The device was composed of a direct current (DC) motor, an optical encoder, a gear pair, a slip ring, and a spectrometer holder (Fig. 2). The DC motor (Maxon Motor AG A-max26) configured with a planetary gearhead (Maxon Motor AG GP26A) could provide a nominal torque of 1.9 N m. This torque could be doubled after the amplification of the gear pair with a speed reduction ratio of 2, which was sufficiently high to drive the rotation of the two spectrometers. The angle at which the spectrometers rotated was controlled using an optical encoder (Avago Technologies HEDS-5540#A12). This encoder produces 500 counts per revolution, and it can generate 4-times-greater angular resolution of $\pm 0.18^\circ$ after quadrature encoding. Because the two spectrometers were mounted symmetrically around the main rotating axle with a rotating radius of 30 mm, the switching device had a maximum position precision of approximately 0.1 mm, which is far smaller than the radius of the lens (i.e., 2.5 mm) used to couple the fiber to the optical entrance of the spectrometer. The symmetrical arrangement of the spectrometers also reduced the number of times that the device rotates, because each of the two spectrometers aligned to one of the fibers during measurement. This is because the number of fibers was even, and the fibers were symmetrically fixed around the same

TABLE 1. Performance and characteristics of the C11009MA and C11010MA spectrometer module used in the system.

Parameter	C11009MA	C11010MA	Units
Spectral range	340–780	640–1050	nm
Pixels	256	256	—
Spectral resolution	9	8	nm
Wavelength reproducibility	From -0.5 to 0.5	From -0.5 to 0.5	nm
Wavelength temperature dependence	From -0.5 to 0.5	From -0.5 to 0.5	$\text{nm } ^\circ\text{C}^{-1}$
Numerical aperture	0.22	0.22	—
Fiber core diameter	600	600	μm
Operating temperature (no condensation)	5–40	5–40	$^\circ\text{C}$

FIG. 3. (a) Schematic of the components of the optical probe, and (b) the optical probe with an optical fiber connected via the SMA-905 interface.

rotating axle as the spectrometers (i.e., the main rotating axle in Fig. 2). This configuration is highly effective for reducing the power consumption of a battery-powered system. In this system, the spectrometer-driver electronics used to control the operation of the spectrometer were required to derive power from the system driver electronics used to handle the operation of the entire system, and the spectrometer driver electronics were required to transmit the measured irradiance data back to the system driver electronics for subsequent processing. Therefore, a slip ring was interposed between the spectrometer driver electronics and system driver electronics to avoid the potential physical tangling of electrical wires after several runs, while maintaining the electrical connections between them.

The proposed profiling system included eight fiber probes in total, with two probes deployed under the sea ice (i.e., in the underlying ocean) to collect and transmit the solar radiation signals in the underlying ocean. To prevent the optical probe from potential contamination or biofouling during long-term application, a probe antifouling device was developed (Fig. 4). A copper cover was rotated using a DC motor; owing to this rotation, the copper cover could conceal the glass window of the optical probe during nonoperation, and uncovering the window could allow the light signal to enter the optical probe during operation. Before each measurement, the device moved the copper cover along its rotating axle several times such that the optical window could be cleaned using a brush fixed on the edge of the cover. This device was powered by a small DC motor (Maxon Motor AG A-max16 with GP16A planetary gearhead). The motor provides a nominal torque of 0.8 N m, which is sufficiently high for rotating the cover by overcoming the friction between the seal components. The two limiting positions of the cover during the cleaning movement were monitored by two normally open detector switches

(Panasonic Corp. ESE-18R11B and ESE-18L11B) with one switch placed at each limit position. The motor and the relevant position monitoring electronics were installed inside a stainless steel case for waterproofing, and the electrical connection to the system driver electronics was made via a miniature underwater electrical connector (SEACON HUMK-BCR and HUMK-CCP). The probe antifouling device, without the electrical connector and cable, had a height and length of 71 and 123 mm, respectively, and it could be readily deployed in the underlying water through an auger hole with a diameter of 10 cm.

2) CONSIDERATIONS FOR CONTROL AND DRIVER ELECTRONICS

The system driver electronics developed to handle the operation of the entire system were based on an 8-bit low-power microprocessor (Atmel Corp. ATX-mega128A1; Fig. 5). This microprocessor was selected because the featured abundant onboard peripherals could significantly simplify the design of the external control and driver electronics. An onboard 32-MHz resistor-capacitor (RC) oscillator was selected as the

FIG. 4. The probe antifouling device with an underwater electrical connector.

FIG. 5. Schematic of controller, sensors, and data flow for the irradiance profiling system. Solid arrows represent bidirectional digital communication, thick solid arrows represent power, and dashed arrows represent logic-level connections.

system clock source, and the frequency was reduced to 8 MHz via an onboard clock prescaler to meet the requirements of fast operation and energy conservation. To maintain stability of the 32-MHz RC oscillator in the entire operation temperature range from -50°C to 30°C , it was calibrated via an external 32.768-kHz crystal oscillator (Citizen Finedevice Co., Ltd., CM200C), which is considerably more temperature stable and accurate.

The onboard peripherals of the microprocessor were assigned as shown in Fig. 5. The operation of the two spectrometer driver electronics used to control the two spectrometers (i.e., C11009MA and C11010MA) was realized via two of the microprocessor's universal synchronous and asynchronous serial receiver and transmitter (USART) ports (i.e., USART 0 and 1) (Nan et al. 2017). The rotation of the A-max26 DC motor and cooperation with the optical encoder in the spectrometer switching device were realized through a commercial servo motor controller (All Motion, Inc., EZSV10) via the control of one of the serial ports (i.e., USART 2). One serial port (i.e., USART 3) was reserved to control a GPS receiver (Garmin International, Inc., GPS-19X HVS), and two other serial ports were reserved for system debugging (i.e., USART 4) and communication with the buoy for remote data transmission via an iridium satellite modem included in the buoy (i.e., USART 5).

In addition, the operation of the A-max16 DC motor and sensing of the closing status of the detector switches involved in the probe antifouling device were realized by using several general-purpose input/output (GPIO) ports. Solar irradiance measurements from the two spectrometers were stored in a 32-Mbit flash memory (Adesto Technologies AT25DF321A) over a serial

peripheral interface (SPI), and some of the data were selected and transmitted to the buoy for satellite transmission via a serial port, as stated previously. The working schedule of the system was governed by a real-time clock module (Abracon AB-RTCMK-32.768kHz) through a two-wire interface (TWI). The entire instrument was driven by a 12-V battery pack located inside the buoy. Therefore, except for at time of operation, the system remained in a low-power sleep mode to save power. Maximum power consumption (approximately 3.6 W) occurred when the DC motor was rotating the spectrometers to find the desired position, whereas the minimum power consumption, that is, in the sleep mode, was less than 12 mW.

3) DEPLOYMENT CONSIDERATIONS

As stated previously, the objective of the profiling system developed in this study is to obtain long-term measurements of the solar irradiance above, within, and under the sea ice autonomously. Although the fiber probes collecting the light signals must be placed at the desired positions, other parts of the system can be placed as required to facilitate the field deployment activity. Considering the importance of minimum disturbance to the sea ice, a preferred deployment scenario is shown in Fig. 6. The four fiber probes used to sense the downwelling irradiance within the sea ice can be embedded in a standard 5-cm auger hole. The auger hole should be tilted, and a tilt angle of 60° can be considered as effective to reduce the potential shading that arises when the probes are placed in proximity to each other. The two probes under the sea ice, along with the corresponding antifouling device, can be deposited via a much larger 10-cm auger hole. Two additional probes can be

FIG. 6. Deployment scenario of the irradiance profiling system where the main body contains the system driver electronics, the core spectrometers and associated electronics, and mechanics as shown in Fig. 2.

located approximately 1.5 m above the ice via a plastic pole to measure the incident and reflected irradiance separately. Other parts of the system can be deposited in the buoy for protecting the system from the harsh ambient environment. It should be noted that a certain distance (e.g., at least 2 m) should be maintained between the auger holes and the buoy to minimize potential shading.

3. Laboratory examination, evaluation, and correction

Temperature is a major concern when using the developed profiling system in polar environments. In the Arctic winter, the temperature can fall to -40°C , which is considerably lower than the lowest operating temperature of the two spectrometers (i.e., 5°C ; Table 1), as specified by the vendor. Temperature-driven mechanical distortion or stretching of the optical components in the spectrometer and changes in the performance of the module's internal electronics might alter the optical characteristics of the spectrometer and input–output relationship of the system (Wang et al. 2014). However, temperature stabilization is not feasible for this system because it is powered by a limited 12-V battery pack. As an alternative, the temperature dependence of the spectrometers can be examined to quantify the variation of the spectrometer modules with temperature. On the basis of the examination, a signal output correction model can be developed to convert the measurement made at any temperature and integration time to that at a given

reference temperature T_{ref} and integration time t_{ref} . When the spectral sensitivity of the system is corrected at T_{ref} and t_{ref} , the measurement obtained at any temperature and integration time can be corrected to determine the absolute incident irradiance that enters and is measured by the profiling system.

a. Temperature effects on signal output of the spectrometers

To determine the temperature dependence of signal output of the two miniature spectrometers (i.e., C11009MA and C11010MA), they were placed along with the relevant driver electronics inside a temperature-controlled environmental chamber (Beijing Yashilin Testing Equipment Co., Ltd., GDS-500); measurements were taken over a range from -50° to $+30^{\circ}\text{C}$ while providing the instruments with a constant light source (Fig. 7). This test temperature range (80°C) covered the entire operating temperature of the system (i.e., from -50° to 30°C). A 20-W quartz tungsten halogen light bulb (Newport Corp. 6319) was enclosed inside a lamp housing assembly (Newport model 6000) at room temperature ($\sim 25^{\circ}\text{C}$) and powered by a stabilized DC power supply (Topward 6306D) to ensure the stability of the emitted light. The emitted light was guided to the two spectrometers via two silica fibers (CeramOptec Optran Ultra HWF), and the potential intensity fluctuation of the light was monitored using a photodiode (Thorlabs, Inc., DET100A/M) for subsequent correction. The temperature of the system was gradually decreased from 30° to -50°C , and measurements were obtained every 5°C .

FIG. 7. Schematic diagram of the test configuration of the spectrometers used to assess the spectrometer output and dark output.

At each examination temperature, the authors first waited approximately 25 min to ensure that the temperature of the spectrometer module was stabilized, as indicated by an onboard 12-bit digital temperature sensor (Maxim Integrated Products DS1775R) present in the module. Subsequently, the spectrometer output was measured while gradually increasing the integration time of the spectrometer from 0.001 to 7 s. This integration time range was selected to ensure that the spectrometer remains within its linear operating range for all measurements. At each integration time, measurements were obtained 25 times to minimize the statistical uncertainty. It should be highlighted that the output of the spectrometer is composed of two parts, namely, the signal output and dark output (Wang et al. 2014). To obtain the signal output, the dark output of the spectrometer was measured in the absence of any light (i.e., by closing the shutter, as shown in Fig. 7) at each test temperature and integration time combination.

In the process of analyzing the data, to obtain the signal output, first, the influence of the dark output on the spectrometer output was eliminated by subtraction. Then the signal output was averaged over the 25 replicate measurements to minimize the statistical uncertainty. The averaged signal output was normalized for any fluctuations in the light source, as determined by the photodiode, by referencing the corresponding photodiode voltage to that in the first measurement (i.e., at a test temperature of 30°C and integration time of 0.001 s). The results indicated that the general shapes of the corrected and normalized signal outputs were remarkably similar for all integration times over the entire operating temperature from −50°C to 30°C for each spectrometer (Figs. 8a,b). However, the temperature dependence of the signal output was slightly different for the two spectrometers (Figs. 8a–d). For C11009MA, the signal output was relatively stable with temperature for wavelengths shorter than approximately 600 nm, and the output

decreased slightly for longer wavelengths when the temperature was below 0°C (Figs. 8a,c). However, the signal output decreased significantly with lower temperatures for wavelengths longer than approximately 700 nm for C11010MA (Figs. 8b,d). As expected, the signal output increased in a strongly linear manner with the integration time for each wavelength over the entire operating temperature range for both spectrometers (Figs. 8e,f). This finding verified that such types of miniature spectrometer modules can work reliably even at temperatures far below that specified by the vendor and are thus appropriate for the considered application.

For further analysis, a polynomial was adopted to represent the signal output C_s as a function of temperature T and integration time t as follows:

$$C_s(\lambda, t, T) = a_0(\lambda) + a_1(\lambda)t + a_2(\lambda)T + a_3(\lambda)tT + a_4(\lambda)T^2 + a_5(\lambda)tT^2 + a_6(\lambda)T^3 + a_7(\lambda)tT^3 + a_8(\lambda)T^4, \quad (1)$$

where a_0 – a_8 are the least squares fitted coefficients. The goodness of this polynomial fitting as indicated by the R^2 value was higher than 0.99 for all wavelengths (Figs. 8g,h).

Note that the fitted coefficients in Eq. (1) (i.e., a_0 – a_8) are applicable only to the quartz tungsten halogen light source used in this examination because the signal output C_s in Eq. (1) is generated by this light source. Provided that the temperature dependence of the spectrometer is stable and independent of the incident light source, a signal output correction model, which can be used to correct the temperature-induced biases in the signal output under incident light sources, apart from the light bulb adopted in this study, can be developed based on the above examination. The relative signal output was obtained by referencing the corrected signal output to that measured at the reference temperature T_{ref} and integration time t_{ref} . The T_{ref} was

FIG. 8. (a),(b) Signal output as a function of wavelength for five test temperatures at 1 s, (c),(d) signal output as a function of temperature for five wavelengths at 1 s, (e),(f) signal output as a function of integration time for five wavelengths at -50°C , and (g),(h) the goodness of fit shown for all wavelengths for (left) C11009MA and (right) C11010MA.

taken as the room temperature (i.e., 25°C) in this study because the spectral sensitivity of the system was corrected at room temperature, as discussed in the following section. The value of t_{ref} was taken as 1 s for convenience. The temperature dependence and time dependence of the relative signal output were similar to the corresponding values of the signal output. Therefore, the relative signal output f as a function of temperature T and integration time t could be approximated using

$$f(\lambda, t, T) = \frac{C_s(\lambda, t, T)}{C_s(\lambda, t_{\text{ref}}, T_{\text{ref}})} = b_0(\lambda) + b_1(\lambda)t + b_2(\lambda)T + b_3(\lambda)tT + b_4(\lambda)T^2 + b_5(\lambda)tT^2 + b_6(\lambda)T^3 + b_7(\lambda)tT^3 + b_8(\lambda)T^4, \quad (2)$$

where $C_s(\lambda, t, T)$ is the signal output at any integration time t and temperature T , $C_s(\lambda, t_{\text{ref}}, T_{\text{ref}})$ is the signal output at t_{ref} and T_{ref} , and b_0 – b_8 are the least squares

fitted coefficients. The goodness of fit was the same as that of Eq. (1) (Figs. 8g,h). Measurements taken at any temperature and integration time within the linear operating range of the spectrometer could be converted to those taken at T_{ref} and t_{ref} by dividing it by Eq. (2). Therefore, Eq. (2) can be considered as the signal output correction model.

To evaluate the uncertainty of the signal output correction model, the same experimental setup as that shown in Fig. 7 was adopted; however, a neutral density filter with a nominal transmission coefficient of 79% (Thorlabs, Inc., ND 01B) was added between the lens and the beam splitter to change the intensity of the light incident on the spectrometers. Measurements were obtained under a constant integration time of 5 s when the temperature of the system gradually decreased from 30° to -50°C in intervals of 20°C . This temperature range was selected to validate the performance of the signal output correction model over the entire 80°C range of operating temperatures of the profiling system. At each

temperature, the spectrometer output was measured 25 times to minimize the statistical uncertainty, and the dark output was also measured for the subsequent subtraction. These measurements (i.e., spectrometer output and dark output) were also obtained at T_{ref} (i.e., 25°C), but the integration time of t_{ref} (i.e., 1 s) was used instead of 5 s to obtain the reference signal output for this light source configuration.

To analyze these measurements, first, the dark output was subtracted from the corresponding spectrometer output to obtain the signal output. Next, the signal output was averaged for all the collections, and the influence of the light source fluctuation in the averaged signal output was corrected. Next, the signal output at temperatures other than T_{ref} was converted to that at T_{ref} and t_{ref} by dividing the corrected signal output by Eq. (2) and the fitted coefficients. When compared with the signal outputs measured directly at T_{ref} and t_{ref} , all of the converted signal outputs fluctuated within $\pm 5\%$ for the entire range of wavelength of 350–780 nm (which pertain to the region of interest) and within $\pm 2\%$ for wavelengths larger than 410 nm over the entire verification temperature range (80°C) for C11009MA (Fig. 9a). The uncertainty was relatively larger for wavelengths shorter than 410 nm, possibly because of the weak light intensity emitted by the light source and detected by the spectrometer. For C11010MA, the discrepancy was less than $\pm 2\%$ for almost the entire spectral range of 640 to 1000 nm (Fig. 9b). This uncertainty was believed to be acceptable for the considered application and laid a solid foundation for subsequent correction of temperature dependence in the signal output.

b. Temperature dependence and spectral sensitivity correction

The previous section focused on the examination and evaluation of the temperature dependence of the signal output of the two spectrometers, and the development of a signal output correction model. The results were applied to correct the temperature-induced biases in the signal output. Assuming that the temperature dependence of the spectrometer is stable and independent of the light source, for any incident light measured by the system at any temperature T (i.e., $-50^\circ \leq T \leq 30^\circ\text{C}$) and integration time t (i.e., with the spectrometer output kept within the linear operating range), the corresponding system output $C_s(\lambda, t, T)$ can be converted to $C_s(\lambda, t_{\text{ref}}, T_{\text{ref}})$ at t_{ref} and T_{ref} using the signal output correction model:

$$C_s(\lambda, t_{\text{ref}}, T_{\text{ref}}) = C_s(\lambda, t, T)f(\lambda, t, T)^{-1}. \quad (3)$$

Using Eq. (3), the temperature-induced biases in the system output of the profiling system can be

FIG. 9. Discrepancy of the signal output correction model as a function of wavelength at five measurement temperatures for the (a) C11009MA and (b) C11010MA miniature spectrometers.

minimized, and the measurements taken at different temperatures and integration times can be compared because they are converted to the values pertaining to the same reference temperature T_{ref} and reference integration time t_{ref} .

In addition, the spectral sensitivity of the system (i.e., each combination of the spectrometer, lens, and fiber probe) can be corrected by a simultaneous comparison study carried out using a radiometrically calibrated hyperspectral irradiance sensor (TriOS Mess- und Datentechnik GmbH RAMSES-ACC-VIS) as a standard, at room temperature (i.e., 25°C). The relationship between the system output (i.e., spectrometer signal output) C_{cali} and intensity of the light source (i.e., the quartz tungsten halogen light bulb used in the above examination) E_{cali} as measured by the RAMSES-ACC-VIS can be defined as

$$C_{\text{cali}}(\lambda, t_{\text{ref}}, T_{\text{ref}}) = S_{\text{ref}}(\lambda)E_{\text{cali}}(\lambda), \quad (4)$$

where S_{ref} is the spectral sensitivity of each combination of the spectrometer, lens, and fiber probe at T_{ref} and t_{ref} , and it is obtained by dividing C_{cali} by E_{cali} . For any incident light E_I measured by the profiling system at T_{ref} and t_{ref} , the system output C_s is

$$C_s(\lambda, t_{\text{ref}}, T_{\text{ref}}) = S_{\text{ref}}(\lambda)E_I(\lambda). \quad (5)$$

Conversely, the intensity of the incident light E_I can be calculated using

$$E_I(\lambda) = C_s(\lambda, t_{\text{ref}}, T_{\text{ref}}) S_{\text{ref}}(\lambda)^{-1}. \quad (6)$$

By replacing $C_s(\lambda, t_{\text{ref}}, T_{\text{ref}})$ with Eq. (3), Eq. (6) can be rewritten as

$$E_I(\lambda) = C_s(\lambda, t, T) f(\lambda, t, T)^{-1} S_{\text{ref}}(\lambda)^{-1}. \quad (7)$$

Using Eq. (7), the absolute incident irradiance entering the profiling system can be determined via the system output C_s at any temperature T and integration time t , the signal output correction model, and the spectral sensitivity of the system.

c. Temperature effect on the pixel-to-wavelength relationship

According to the manufacturer, the pixel-to-wavelength relationship of each spectrometer module is a fifth-order polynomial function to convert the pixel number of the module to the corresponding wavelength. This relationship is only calibrated at one temperature (22.7°C). However, the range of operating temperature of the modules is much wider for our application, including temperatures far below the freezing point. We examined temperature dependence of the two modules by gradually their lowering temperature from 30° to −50°C in the temperature-controlled environmental chamber while illuminating with a standard mercury–argon calibration source (Ocean Optics, Inc., HG-1) held at room temperature (approximately 25°C). The emitted light was coupled to each of the spectrometers via the previously mentioned silica fiber (CeramOptec Optran Ultra HWF). Measurements were taken every 10°C. At each test temperature, we first waited approximately 25 min to stabilize the temperature of the modules. Thereafter, measurements were taken at a constant integration time that was set to constrain the spectrometer output within the linear operating range of the spectrometers.

Results indicated that the peaks of the mercury–argon calibration source were observed at the same pixels for both spectrometers across the entire test temperature range, except for peaks at 750.387 nm for C11009MA and 912.297 nm for C11010MA (Table 2). At each of the two peaks, the corresponding pixel of each spectrometer shifted by one pixel in only two instances. This one-pixel shift introduces a shift in the corresponding wavelength of 2 nm at most using the pixel-to-wavelength calibration function provided by the vendor. Therefore, it could be inferred that the spectrometer modules maintained a stable and reasonable pixel-to-wavelength relationship over the entire operating temperature range from −50° to 30°C.

d. Temperature effect on mechanical repeatability

Good repeatability in aligning each spectrometer to each optical fiber is vital for the accurate, stable and

TABLE 2. Correspondence of observed peaks (pixels) from known lines of a mercury–argon calibration source (nm).

C11009MA		C11010MA	
Pixel	Wavelength (nm)	Pixel	Wavelength (nm)
22	365.015	35	696.543
43	404.656	57	738.398
59	435.833	64	750.387
118	546.074	72	763.511
135	576.96	91	794.818
201	696.543	107	826.452
232 (233)	750.387	115	842.465
239	763.511	158 (157)	912.297

reliable operation of the profiling system. In theory, the efficiency of this coupling is primarily determined by numerical apertures of the fibers, diameters of the coupling lenses, and position accuracy of the rotary spectrometer switching device. To evaluate the repeatability of the rotary spectrometer switching device, we measured the intensity of light at five temperatures (i.e., from 30° to −50°C with a temperature interval of 20°C). The light source was the 20-W quartz tungsten halogen light bulb (6319) and the emitted light was transmitted by one fiber of the profiling system when the coupling lens connected to the C11009MA spectrometer was repeatedly rotated in and out of alignment with the aperture of the fiber. Instead of the spectrometer (i.e., C11009MA), a second fiber with the same core diameter as the optical entrance of the spectrometer was connected to the coupling lens, with another end attached to a photodiode (DET100A/M) to measure the light intensity. Potential intensity fluctuation of the light source was monitored using another photodiode (DET100A/M) for subsequent correction. At each test temperature, 35 measurements were taken.

During data analysis, we first corrected the influence of intensity fluctuation of the light source following the same process as in the above signal output examination. Subsequently, we calculated the mean value, standard deviation (std dev), and the coefficient of variation (CV) using the 35 corrected measurements at each test temperature. We observed little variability in the light intensity (Table 3), suggesting that the rotary spectrometer switching device retained good mechanical repeatability and manifested limited temperature dependence over the entire 80°C of operating temperatures.

4. Field examination

The profiling system was successfully examined for two days (i.e., 21 and 22 August 2018) in the Arctic (84°43'N, 167°36'W) during the ninth Chinese National Arctic Research Expedition (CHINARE), on an ice

TABLE 3. Measurements of mechanical repeatability at five test temperatures, including the coefficient of variation, mean, and standard deviation.

T ($^{\circ}\text{C}$)	CV (%)	Mean (V)	Std dev (V)
30	0.7681	2.2654	0.017 40
10	0.6492	2.3013	0.014 94
-10	0.8022	2.2039	0.017 68
-30	0.4093	2.2954	0.009 394
-50	0.4363	2.2455	0.009 797

pack with an ice thickness of 175 cm and snow thickness of 10 cm. The general deployment details were similar to those stated in section 2 and shown in Fig. 6. The main body of the system, involving the two spectrometers, spectrometer switching device, driver electronics, etc., was installed inside a watertight aluminum case (Fig. 2) that was placed inside an aluminum buoy case for further protection (Fig. 10). The eight fiber probes were placed in different media for collecting and transmitting solar irradiance signals from the desired positions. Two probes were located at approximately 1.2 m above the snow surface with one pointing upward and another pointing downward to sense downwelling and upwelling irradiance, respectively. Four probes were attached along a 6-mm-diameter fiberglass pole at intervals of 50 cm. The fiberglass pole with four probes was inserted into an auger hole of diameter 5 cm and tilt angle 60° . The pole was fixed inside the auger hole with the probe attached at the uppermost point on the pole, which was located at a distance of 10 cm below the snow surface. It should be emphasized that the angle between each optical probe and the fiberglass pole was carefully adjusted before the deployment to ensure that the optical probe pointed upward within the ice. The two remaining probes were placed 0.6 m and 1.1 m below the ice bottom through a 10-cm-diameter auger hole, together with the corresponding antifouling device. The system autonomously obtained measurements once per day at solar noon, and the measurements were stored in the flash memory included in the system driver electronics.

To determine the spectral intensity of solar irradiance, the temperature dependence and spectral sensitivity in the system output (i.e., spectrometer signal output) were corrected according to Eq. (7). To obtain the solar spectrum of interest (i.e., 350–1000 nm), we combined measurements from both spectrometers by selecting the corrected signal outputs corresponding to wavelengths shorter than 722 nm from the C11009MA-visible spectrometer and longer than 724 nm from the C11010MA near-infrared spectrometer. The results indicated that the general shape of the solar irradiance incident on the snow surface (line 1 in Fig. 11a) measured by the

FIG. 10. Field deployment of the profiling system in an ice pack in the Arctic.

proposed system agreed well with that measured by other commercial oceanographic spectroradiometers (e.g., RAMSES-ACC hyperspectral irradiance sensors) (Nicolaus et al. 2010). The maximum value of solar irradiance was approximately 460 nm, and it generally decreased on both sides for shorter and longer wavelengths. The general shape of solar irradiance was remarkably similar at all the eight positions of the installed fiber probes; however, the spectral intensity varied significantly for different wavelengths. Spectral intensity was found to decrease at a considerably faster rate in the near-infrared region than in the visible region, as the corresponding position was deeper in the ice (lines 3–6 in Fig. 11a) and in water (lines 7–8 in Fig. 11a). This phenomenon could be explained by the fact that the spectral absorption coefficients of ice and water are significantly larger in the near-infrared band than in the visible band (Perovich 1996).

To analyze the optical property of sea ice in polar environments, two parameters, namely, spectral albedo and spectral transmittance, are widely used to evaluate the fraction of incident irradiance reflected by the ice surface and that entering the water beneath the ice bottom, respectively (Perovich 1996). The spectral albedo of sea ice could be calculated by dividing the downwelling irradiance above the ice (line 1 in Fig. 11a) by the upwelling irradiance above the ice (line 2 in Fig. 11a), wavelength by wavelength. The results indicated that the spectral albedo of sea ice had a maximum value of 0.83 at approximately 590 nm; further, the value of this parameter generally decreased with shorter and longer wavelengths, with a minimum value of 0.46 at 950 nm (Fig. 11b). This characteristic is consistent with that of the spectral albedo of sea ice covered with melting snow (Grenfell and Maykut 1977). The spectral transmittance of sea ice was calculated by dividing the

FIG. 11. (a) Solar irradiance as a function of wavelength at different levels of the sea ice environment; (b) spectral albedo, (c) spectral transmittance, and (d) bulk diffuse spectral attenuation coefficient $K_d(\lambda)$ as a function of wavelength for the sea ice in the system deployed. The line number in (a) also corresponds to the sequence number of the probe. This plot is derived from the system measurements on 21 Aug, which are in good agreement with those on 22 Aug because the sea ice condition is very similar on these two days.

downwelling irradiance above the ice surface (line 1 in Fig. 11a) by the downwelling irradiance below the ice bottom (line 7 in Fig. 11a). Note that the measurements at wavelengths longer than 700 nm were neglected during the calculation of the spectral transmittance primarily because of the very weak light that existed below the ice bottom and the very low value detected by the proposed system at these bands (line 7 in Fig. 11a). The results denoted that the spectral transmittance of sea ice (i.e., ice with a thickness of 175 cm covered with 10 cm of snow) increased with longer wavelengths when the wavelength was shorter than 465 nm, and its maximum value was 0.079 at 465 nm (Fig. 11c). However, the transmittance decreased for the wavelength longer than 465 nm. This may be due to the increasing absorption from ice and brine. In addition, we observed that the measured spectral irradiance decreased in a roughly exponential manner with increased depth of the sea ice, as expected, because sea ice is approximately homogeneous (lines 3–6 in Fig. 11a). Subsequently, the Beer–Lambert

model was adopted to approximate the bulk diffuse spectral attenuation coefficient $K_d(\lambda)$ of the entire column of the sea ice at each wavelength shorter than 700 nm, as follows:

$$E_d(z_i, \lambda) = E_d(z_3, \lambda) e^{[-K_d(\lambda)(z_i - z_3)]}. \quad (8)$$

Four groups of measurements within the ice (lines 3–6 in Fig. 11a) and one group of measurement below the ice bottom (line 7 in Fig. 11a) were employed for this approximation, where $E_d(z_i, \lambda)$ is the downwelling irradiance at depth z_i and wavelength λ , z_i is the vertical distance of the fiber probe i to the upper snow surface in which the system was deployed, and $i = 3-7$. The goodness of the exponential fit indicated by R^2 was higher than 0.85 for all wavelengths from 350 to 700 nm. This finding indicated that K_d fluctuated between 0.54 and 0.78 m^{-1} at wavelengths shorter than 550 nm but increased significantly for longer wavelengths, from 0.78 m^{-1} at 550 nm to 3.80 m^{-1} at 690 nm (Fig. 11d). Both the spectral transmittance and bulk diffuse spectral attenuation coefficient of the sea ice inferred from the obtained measurements were generally comparable to those of similar ice measured using other commercial optical sensors (Ehn et al. 2008b; Light et al. 2008; Nicolaus et al. 2010). Note that the influence of the borehole on the radiation field of the sea ice was not corrected in the measured solar irradiance within the sea ice (lines 3–6 in Fig. 11a) owing to the small size of the borehole (i.e., 5 cm in diameter). This implies that the perturbation to the local radiation field might be limited, especially after refreezing of seawater within the hole. In addition, the borehole was tilted and the front ends of the optical probes were placed against the upper wall of the borehole (Fig. 6), and thus most of the light field that the optical probes faced was undisturbed.

5. Conclusions

An irradiance profiling system was developed to enable long-term autonomous measurement of solar irradiance distribution at different levels of the sea ice environment in the Arctic. Two miniature spectrometers were adopted in the proposed system to detect light signals from eight fiber probes placed at different positions above, within, and under the sea ice. In this manner, the spectral range of the system was increased to 1000 nm as compared with 780 nm in the previous version, and the novel system could thus satisfy the requirements of most scientific studies, such as those pertaining to the heat and mass balance of the Arctic sea ice and the underlying ocean other than the marine ecosystem. The alignment of each spectrometer with

each fiber probe was realized by rotating the two spectrometers controlled by a rotary spectrometer switching device with a position precision of 0.1 mm. In this manner, the rotation of fibers in the previous system could be avoided. The stability and reliability of the system was noted to be considerably improved. Considering the extremely low temperature in the Arctic environment, the temperature dependence of the system output was investigated and evaluated at temperatures far below the lowest operating temperature of the spectrometer specified by the vendor. A signal output correction model was developed to correct temperature-induced biases in the system output, with an uncertainty of $\pm 2\%$ at most wavelengths for both the spectrometers. After incorporating this correction model with the spectral sensitivity of the system corrected directly at room temperature (i.e., 25°C), the absolute irradiance entering the system could be determined based on the system output measured over the entire operating temperature range from -50° to 30°C .

The performance of the system was assessed in an ice pack in the Arctic. The results showed that the proposed profiling system provides satisfactory performance and could ensure autonomous measurement of the distribution of solar radiation in the Arctic sea ice environment, potentially over seasonal scales. The general shape of solar irradiance above the sea ice agreed with that at the sea level, as specified by other researchers. In addition, the calculated optical properties of the sea ice in which the system was deployed were identical to those pertaining to similar sea ice calculated from measurements taken using other commercially available oceanographic optical sensors.

Even though the performance of this system is promising, it has scope for further improvement. First, obtaining more comprehensive knowledge pertaining to the long-term drift of the spectrometer can help enhance the accuracy of irradiance measurements. In this study, the authors examined the temperature dependence of the spectrometer signal output and dark output in the laboratory and the overall performance of the system in the Arctic within a relatively short time. However, long-term variations in the stability or sensitivity were not examined. In particular, long-term drift information regarding the miniature spectrometers was not provided by the vendor, and this aspect should be investigated in detail in the future. Second, the development and incorporation of the protective device for the above-ice optical probes could effectively shield them from the potential influence of the ambient environment (e.g., riming) and maintain the cleanliness of the glass window of the optical probes (Fig. 3). Third, the uncertainty in the measured solar irradiance within the sea ice could be

minimized by modeling and correcting the influence of the borehole on the radiation field of the sea ice, and adopting a light source similar to the sun while correcting the spectral sensitivity of the profiling system.

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