Cloud Fractions Estimated from Shipboard Whole-Sky Camera and Ceilometer Observations between East Asia and Antarctica

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Abstract

Cloud fractions were observed during research cruises onboard the research vessel (R/V) Shirase between Japan and Antarctica using a whole-sky camera and a ceilometer. The cruises, Japanese Antarctic Research Expeditions (JARE) 55 and 56, took place from November 2013 to April 2014 and from November 2014 to April 2015, respectively. Cloud fractions were estimated from the whole-sky camera based on the sky brightness and spectral characteristics, and the ceilometer recorded the cloud occurrence frequency. According to the comparison of daily-averaged cloud fractions from the whole-sky camera with the ceilometer observations over the open ocean between Japan and Antarctica, the correlation coefficients were 0.87 and 0.93 for JARE 55 and 56, respectively. Overall, the results from both observation methods were consistent over the open ocean. Nevertheless, it was necessary to take surface conditions into consideration, particularly for the estimated cloud fractions from the whole-sky camera, because the contrast in brightness and spectral properties between cloudy and clear skies was lower over the sea ice region, owing to the higher surface albedo. Hence, the classification parameter was expressed as a function of sun elevation over the sea ice region in this study. This parameter was determined from part of the data over the sea ice region during JARE 55 and then applied to JARE 56 as well as to the remaining data from JARE 55. As a result, the daily-averaged cloud fractions over the sea ice region were approximately 84% and 57% from JARE 55 and 56, respectively. The daily-averaged cloud fractions estimated from the whole-sky camera were also consistent with the ceilometer observations, where the correlation coefficients with the sea ice region were 0.93 and 0.96 for JARE 55 and 56, respectively.

Keywords cloud fraction; shipboard observation; whole-sky camera; ceilometer; sea ice region
1. Introduction

Clouds play an important role in the hydrological and energy cycles of the Earth’s climate system, and they have opposite effects on the radiation budget: warming and cooling. Their magnitude depends on many cloud properties such as amount, type, shape, and horizontal and vertical distributions. The large variety of cloud properties is one of the main sources of error for climate predictions (IPCC 2013). It is, therefore, important to determine the cloud behavior over the ocean, which covers approximately 70% of the Earth’s surface. However, observing cloud behavior in detail is not easy because of the cloud spatial and temporal variability. Furthermore, there are not enough observation sites at the surface over the open ocean. Thus, shipboard observations are important for investigating maritime cloud behavior.

Norris (1998) investigated the global frequency of individual low-level cloud types over the ocean during daytime summer and winter seasons over 1954–1992 from synoptic surface cloud observations primarily made by volunteer ships. The study showed the seasonal climatology of June, July, and August as well as December, January, and February, based on 2° × 2° monthly summaries from the Comprehensive Ocean–Atmosphere Data Set (COADS). The COADS project has archived a long-term global data record of cloudiness encompassing more than a century of shipboard visual observations. Despite this, observations around Antarctica are sparse compared with other regions (Woodruff et al. 1987). The cloudiness statistics from volunteer observation ships appeared to be moderate compared with oceanic weather stations, which suggests that visual observations were dependent on observer experience (Norris 1998). Therefore, it is important to compare visual observations and optical measurements with onboard whole-sky camera and ceilometer observations.

Furthermore, Lachlan-Cope (2010) pointed out that seasonal variations in cloud fractions observed from passive satellite observations and ground-based visual observations were out of phase at the South Pole. A comparison of the latitudinal variation in cloud fractions between satellite and visual observations was also performed, and the results were comparable to coastal and inland regions. However, a few visual observations around Antarctica still hinder the comparison of cloud properties over the circumpolar Antarctic Ocean. The study also highlighted the fact that the isolation of Antarctica and the extreme nature of its climate account for the study of clouds in the region being less advanced than in many other regions of the world.

According to an extended review on tropospheric clouds over Antarctica by Bromwich et al. (2012), necessary future studies should focus on remedying the lack of data over sea ice and/or oceans. Equipping ships that routinely work within the Southern Ocean with more numerous and sophisticated radiation and cloud sensors could provide important data for determining how cloud properties vary according to the environment where they form and persist. Consistent cloud measurements over more varied surfaces coupled with (at a minimum) the complete radiative field would significantly contribute to radiative budget models, including potential cloud contributions to the cryospheric melt.

Protat et al. (2017) investigated the radiation budget with the shipboard observation campaign for ten days at the Southern Ocean. They mentioned that cloud treatment in the model simulation was important, but there were not enough observation sites even over land in the southern hemisphere compared with the northern hemisphere. Thus, satellite observations are important in the southern hemisphere. However, cloud fractions near the surface between active and passive sensor products are different from each other. Therefore, it is necessary to validate the cloud properties from satellite observations using shipboard surface observations.

Accordingly, routine shipboard cloud observations over the sea ice or ocean regions between Japan and Antarctica will contribute to future investigations of the global cloud radiation budget.

Clouds are one of the largest factors that affect the radiation budget over the sea surface. For example, shipboard measurements of shortwave radiation and cloud cover were simultaneously collected over the Atlantic Ocean in 2006 and 2007. Using automated and temporal high-resolution observations of the cloudy atmosphere, Kalisch and Macke (2008) tested and improved the existing insolation parameterization. The ship tracks crossed many climate zones and spanned several seasons; thus, the observations covered a wide variety of cloud, temperature, and humidity conditions. They focused on the variation of short-term shortwave radiation with atmospheric characteristics caused by clouds. The conclusion that total cloud cover was the most important factor for shortwave radiation was deduced from images taken by a full-sky imager without a shadow band, which is composed of commercially available standard components. They also found that their parameterization on
Cloud types significantly improved the standard deviation between the calculated and measured shortwave fluxes for a broken cloud scheme.

Cloud fraction is a primary parameter in model simulations, but it is necessary to validate any results with other instruments, such as satellite observations. Recently, it has been demonstrated that sea surface temperatures (SSTs) influence long-term global warming. Specifically, not only the SST value but also the pattern of SST is important to cloud feedbacks. Simulations and observations now show that changing SST patterns could affect cloudiness and thereby dampened simulations. Specifically, not only the SST value but also the temperatures (SSTs) influence long-term global warming (Mauritsen 2016; Zhou et al. 2016). Furthermore, artificial shifts caused by a change in satellite instruments could easily exceed the long-term trend (Mauritsen 2016; Norris and Evan 2015). Therefore, satellite observations require validation that compares them with other shipboard observations, even though spaceborne observations are suitable to understand cloud climatology over the global ocean.

Letu et al. (2014) validated cloud detection schemes with satellite remote sensing over land using a whole-sky camera and a similar method of image brightness and spectral contrast. They estimated error propagation caused by the cloud mask and found that errors in the cloud mask significantly influence the monthly mean reflectance and brightness temperature for cloudy pixels. They demonstrated that a ground-based sky camera was complementary to satellite observations.

Kuji et al. (2016) described an overview of an observation system with a whole-sky camera and ceilometer onboard the R/V Shirase. They showed the initial results of spatiotemporal variations in cloud fractions between Australia and Antarctica during the Japan Antarctic Regional Expedition 55 (JARE 55). Furthermore, they found that the cloud fractions from both observation methods were consistent, and the cloud fractions were larger at higher latitudes over the limited season and region.

However, an accurate estimate of cloud fractions over a sea ice region remains a challenge. In this study, we made periodical shipboard observations with a whole-sky camera and a ceilometer onboard the R/V Shirase to investigate maritime cloud behavior between Japan and Antarctica over the Pacific Ocean.

Thus, our objective was to investigate the variation in cloud fractions along the ship transect. We show observations and initial results from the dataset in terms of cloud fraction using a whole-sky camera. A previous study found that a constant classification parameter was sufficient for an open water region (Kuji et al. 2016). However, this parameter was determined as a function of sun elevation over a sea ice region, because higher surface albedo was usually observed owing to the presence of sea ice in higher latitudes near Antarctica. A validation of this was thus also performed using a ceilometer and visual observations onboard the R/V Shirase over both open ocean and sea ice regions; as a result, cloud fractions were described along the ship tracks of JARE 55 and 56, both on the R/V Shirase.

2. Observations and collected data

The fundamental specifications of the observations and data for JARE 55 were described in Kuji et al. (2016). Shipboard observations and the analyzed data from JARE 55 and 56 are described further in this section.

2.1 R/V Shirase expeditions

The Japanese Maritime Self-Defense Force operates the Japanese icebreaker R/V Shirase (AGB-5003); its length and displacement are 138 m and approximately 20,000 tons, respectively.

The R/V Shirase conducts round-trip expeditions between Japan and Antarctica, with Fig. 1 showing the ship track during the annual Antarctic cruise. The ship traveled from Japan to Antarctica via the western coast of Australia and returned past eastern Australia during JARE 55. The ship took almost the same course via western Australia for both the outgoing and returning tracks during JARE 56. The R/V Shirase observations took place over approximately 35°N to 70°S and included the circumpolar sea ice region. This circumpolar coverage is one of the unique features of our shipboard observations and is comparable to the observations over approximately 60°N to 60°S in the Atlantic Ocean from Kalisch and Macke (2012).

Table 1 summarizes the R/V Shirase cruises of JARE 55 and 56. Shipboard observations were performed using a whole-sky camera and a ceilometer onboard the R/V Shirase (Kuji et al. 2016); visual observation data were available only during JARE 56. The entire journey takes several months from November to March or April of the following year. The sea ice regions ranged around the Antarctic continent, and the duration of the cruises was approximately two months each. Hence, the number of observation events in the sea ice region is comparable to that of the way to or from Antarctica generally. One of the specific features of R/V Shirase cruises is that the ship travels both open ocean and sea ice regions with identical platforms during a serial cruise for several
2 months.

2.2 Whole-sky camera

The system mainly consists of a digital camera (NIKON D7000, NIKON Corporation) and a circular fisheye lens (4.5 mm F2.8 EX DC Circular Fisheye HSM, SIGMA Corporation) that photographs the whole sky. The observation interval was 5 min in duration. In total, we produced 32,503 images from 8 November 2013 to 6 April 2014 (JARE 55) and 39,053 images from 11 November 2014 to 1 April 2015 (JARE 56). The number of observation events for the sea ice region was 13,395 from 9 December 2013 to 25 February 2014 (JARE 55) and 18,443 from 15 December 2014 to 17 February 2015 (JARE 56) (Table 1). We note that the number of observation events for the sea ice region amounted to approximately half of the entire observations made on both JARE 55 and 56.

Kuji et al. (2016) estimated the cloud fraction for the open ocean region between Australia and Antarctica using a whole-sky camera during JARE 55 (November to December 2013). They found that the cloud fraction estimates between the whole-sky camera and the ceilometer were consistent with a correlation coefficient of 0.86.

2.3 Ceilometer

Feedbacks involving low-level clouds remain a primary cause of uncertainty in global climate model projections (Clement et al. 2009). The analysis of low-level clouds has provided observational evidence that this feedback is positive in the Northeast Pacific on decadal time scales.

The cloud base height is also one of the controlling parameters of the Earth’s radiation budget. For example, it has recently been recognized that a significant lack of clouds over the Southern Ocean is a serious problem in most climate models and causes huge biases in shortwave radiative flux, especially in the summer months (Kawai et al. 2015; Trenberth and Fasullo 2010). Abe et al. (2016) investigated this in the Arctic region using the general circulation model MIROC5 in the summer and fall during the period 1976–2005. They found that the decrease in sea ice in autumn led to the increase in cloud fraction and the increase in cloud base height.

In this study, cloud base height data were utilized to derive the temporal cloud fraction. The cloud base height is determined based on the return time of a laser beam (Vaisala CL51) (Vaisala 2010) with an observation interval of 36 s. We produced 270,314 profiles from 27 November 2013 to 6 April 2014 (JARE 55) and 163,012 profiles from 11 November 2014 to 1 April 2015 (JARE 56).
from 9 February 2015 (JARE 56). From these profiles, we obtained up to three cloud base heights with the system software. The lowermost cloud base heights were analyzed in this study. The number of observation events for the sea ice region was 187,025 from 9 December 2013 to 25 February 2014 (JARE 55) and 115,469 from 15 December 2014 to 9 February 2015 (JARE 56). We noted that this represents more than a half of the total in both JARE 55 and 56.

The cloud detection accuracy was investigated by Liu et al. (2015). They compared the cloud bottom heights between two ceilometers (Vaisala CL31 and CL51) and an infrared cloud imager. They found that cloud base heights are consistent between the two types of ceilometers, but cloud base heights estimated with an infrared cloud imager may be influenced by the amount of water vapor and atmospheric temperature profiles.

2.4 Visual observation

Visual observations of cloud amounts were also conducted every 1 h onboard the R/V Shirase by the Japanese Maritime Self-Defense Force, as one of the standard meteorological elements such as weather, air temperature, wind speed, and direction. The cloud amount was compiled as an octa format from 0 to 8. The number of cloud amount data was 3,050 from 11 November 2014 to 31 March 2015 (JARE 56), but no data are available for JARE 55. The number of observations for the sea ice region was 1,537 from 15 December 2014 to 17 February 2015 (JARE 56), which represents more than half of the total observations.

3. Analyses

The cloud detection scheme for the whole-sky imagery is based on the sky index–brightness index (SI–BI) method (Yoshimura and Yamashita 2008), in principle, and improved for shipboard observations (Kuji et al. 2016). On the basis of the red, green, and blue features of the light spectrum in the whole-sky image, we defined SI using Eq. (1), which is sensitive to sky color (i.e., blue or white). Furthermore, we estimated BI as sky brightness defined in Eq. (2).

\[
SI = \frac{Blue - Red}{Blue + Red},
\]

\[
BI = \frac{Red + Green + Blue}{255 \times 3},
\]

where Red, Green, and Blue are the digital numbers corresponding to the three colors of red, green, and blue, and these numbers range from 0 to 255; i.e., they are capable of expressing 256 levels.

When we plot the SI–BI domain, there are generally two distinctive clusters corresponding to cloudy and clear sky pixels in the whole-sky image based on the visual examination. We thus specified a classifica-
tion curve between the cloudy and clear sky clusters:

\[ BI = e^{-k \times SI}, \quad (3) \]

where \( k \) is some coefficient, determined by the following processes.

We know that we can fit the cloudy and clear sky clusters with the same exponential function as Eq. (3). We called them the cloudy and blue sky curves, and they had the coefficients \( k_c \) and \( k_b \), respectively. Because the classification curve must lie between the cloudy and blue sky clusters in principle, we determined the coefficient \( k \) for the classification curve based on the coefficients \( k_c \) and \( k_b \).

At first, we selected the data from 27 November 2013 14:00 UTC to 9 December 2013 13:30 UTC from JARE 55 for analysis, which corresponded to the period after the ceilometer operation was initiated and before the R/V Shirase moved into the sea ice region (Kuji et al. 2016). In other words, we divided the open ocean and sea ice regions because the higher surface albedo from sea ice affects the sky brightness and spectral contrast. Furthermore, we chose the overcast images and fully clear sky images by visual examination. We then constructed the \( SI - BI \) diagram and performed curve fitting for the overcast or fully clear sky images to determine the exponential coefficients \( k_c \) and \( k_b \), respectively.

Figure 2a shows the scatter plot of the cloudy and fully clear sky coefficients over the open water region. We determined the coefficient \( k \) from Eq. (3) as follows:

\[ k = \frac{k_c, \text{min} + k_b, \text{max}}{2}, \quad (4) \]

where \( k_c, \text{min} \) and \( k_b, \text{max} \) were estimated within 1 degree bin. The minimum of \( k_c \) was 4.5, and the maximum of \( k_b \) was 2.8. Therefore, we set the exponential coefficient \( k \) at a constant value of 3.7 for the open water region.

Figure 2b shows the scatter plot of the cloudy and fully clear sky coefficients within the sea ice region. It is clear that the coefficients highly depend on the sun elevation compared with the open ocean region. We estimated averages of the minimum of \( k_c \) and the maximum of \( k_b \) for each sun elevation with 1 degree bin and then performed a linear fitting to determine the classification coefficient \( k \) over the sea ice region:

\[ k = -0.038 \times \eta_0 + 3.6 \quad (10.0^\circ \leq \eta_0 \leq 44.6^\circ), \quad (5) \]

where \( \eta_0 \) is sun elevation (\(^\circ\)). It is noted that the valid range of sun elevation in Eq. (5) is between 10.0\(^\circ\) and 44.6\(^\circ\) in this study.

We classified the pixels as cloud or clear sky based on Eq. (3) with the coefficient \( k \) from Eqs. (4) and (5) for the open water and sea ice regions, respectively. Finally, the cloud fraction \( CF_{\text{cum}}(\%) \) from the whole-sky camera was estimated as the fraction of cloudy \( \text{Pixels}_{\text{cloudy}} \) to the whole sky \( \text{Pixels}_{\text{total}} \) pixels:

![Fig. 2. Scatter plots of coefficients \( k \) vs. sun elevation (\(^\circ\)), where \( k_c \) and \( k_b \) indicate cloudy (gray) and clear sky (light blue) pixels, respectively, over (a) open water and (b) sea ice regions during JARE 55. The red lines are the classification coefficients from Eqs. (4) and (5). Note that the valid range of sun elevation in Eq. (5) is between 10.0\(^\circ\) and 44.6\(^\circ\) over the sea ice region in this study.](image-url)
The cloud fraction $CF_{cell}$ (%) from the ceilometer was defined as a frequency of cloud appearance for a given time bin (5 min in this study), i.e., the ratio of cloudy $Profiles_{cloudy}$ to total $Profiles_{total}$ profiles:

$$CF_{cell} = \frac{Profiles_{cloudy}}{Profiles_{total}} \times 100,$$

where $Profiles_{cloudy}$ means the number of cloudy profiles for which cloud bottom heights were detected and $Profiles_{total}$ represents the number of available profiles between $±2.5$ min of the observation time of the whole-sky image.

Finally, the cloud fraction $CF_{vis}$ (%) from visual observations was estimated from the cloud amount $N_{vis}$ that ranged from 0 to 8:

$$CF_{vis} = \frac{N_{vis}}{8} \times 100.$$

4. Results

Figure 3 shows the spatial variation of the cloud fraction retrieved with the whole-sky camera along the ship track during JARE 55 and 56. The plots represent every 6 h. There were some gaps in the series of plots because the analyses were performed when the sun elevation was higher than $10°$. We found that the cloud fraction is approximately 100 % at latitudes higher than $40°S$ whereas it is less at the middle and lower latitudes.

From Figs. 3a and 3b, it appears that the R/V Shirase traveled across the Southern Ocean ($40°–60°S$) along $110°E$ from Australia to Antarctica during the outgo-

![Fig. 3. Cloud fractions estimated from the whole-sky camera every 6 h along the ship tracks of (a) JARE 55, (b) JARE 56 from Japan to Antarctica, and (c) JARE 56 from Antarctica to Japan.](image-url)
Cloud fraction was 70% with a higher value for the period 2007–2009. As a result, the cloud fraction over the Southern Ocean (0°–360°E, 45°–60°S) for the period 2007–2009. The R/V Shirase traveled from 40°E to 110°E across the Antarctic Sea during the returning cruise of JARE 55 in Fig. 3a, whereas it moved to 110°E almost linearly during JARE 56 in Fig. 3c. It is found that the cloud fractions were even higher along 60°S during JARE 55 and 56 across the Southern Ocean and the Antarctic Sea.

The cloud fraction statistics from the whole-sky camera are shown in Table 2. The daily-averaged cloud fraction over the sea ice region was 83.7% overall, whereas those over the open ocean were 53.1% and 57.4% for the outward and returning cruises, respectively, during JARE 55. In contrast, during JARE 56, the daily-averaged cloud fraction over the sea ice region was 57.4%, which is lower (higher) than 65.9% (52.1%) along the outward (returning) ship track over the open ocean.

Kawai et al. (2015) investigated the cloud top height via the spaceborne light detection and ranging (LIDAR) system based on 20 km mesh global monthly climatologies. They also investigated the cloud fractions observed by CALIPSO. Our whole-sky cloud fraction was higher, which is a finding that is consistent with the tendency of higher daytime cloud fractions observed by CALIPSO.

Figure 4 also illustrates the spatial variation of the cloud fraction estimated from the ceilometer observations during JARE 55 and 56. The operation of the ceilometer started offshore Fremantle, Australia in JARE 55, whereas during JARE 56 it was halted after the start of the return track in the sea ice region because the ceilometer was damaged during a severe blizzard. Therefore, there are no plots between Japan and Australia (Fig. 4a) and only a few plots near Antarctica (Fig. 4c). Except for operational difficulties, cloud fractions were continuously obtained every 6 h from the cloud base height measurements, which were taken every 36 s.

The spatial distributions of cloud fractions estimated from the ceilometer are similar to those from the whole-sky camera (Fig. 3). It is clearly seen that the cloud fraction was particularly higher in latitudes greater than 40°S. However, the cloud fraction was lower between 20°N and 20°S in the tropical region (Figs. 3a, b).

The cloud fraction statistics from the ceilometer are shown in Table 2. The daily-averaged cloud fraction over the sea ice region was 80.2%, whereas those over the open ocean were 85.2% and 57.6% for the outward and returning cruises, respectively, during JARE 55. It is found that the cloud fractions from the whole-sky camera and the ceilometer observations were consistent with each other within several percent for the sea ice and returning cruises. However, they were different by more than 30% along the outward track during JARE 55. This discrepancy is attributable to the ship track of the two measurements. Because the operation of the ceilometer started from Australia (Fig. 4a), the observation was deficit between Japan and Australia where the cloud fraction was smaller than that over the Southern Ocean. During JARE 56, the daily-averaged cloud fraction over the sea ice region was 50.5%, which is less than the 63.6% estimated during the outward cruise over the open ocean. The cloud fractions from the ceilometer were consistent with those from the whole-sky camera within several percent for the outgoing and sea ice cruises.

Figure 5 shows the spatial variations of the cloud fraction observed visually shipboard during JARE 56, which is similar to the general cloud fraction observed visually shipboard during JARE 55.
Fig. 4. Cloud fractions estimated from the ceilometer. Note that the ceilometer observations started offshore Fremantle, Australia during JARE 55. We also note that the operation of the ceilometer ceased after the start of the return cruise from Antarctica to Japan during JARE 56.

Fig. 5. Cloud fractions estimated from visual observations during JARE 56 only. Cloud fractions estimated from visual observations during JARE 56 only.
distribution obtained by the other mechanical sensors. The cloud fraction ranged between 20% and 80%, as a whole. Compared with the cloud fraction estimates obtained from the whole-sky camera and the ceilometer, human observation was moderate, i.e., the upper (lower) values of the cloud fraction were less (more) than those from the mechanical sensors. This tendency is also highlighted by Norris (1998), who investigated the global cloud amount from ship observations over several years.

The cloud fraction statistics from the visual observations are shown in Table 2. Overall, the daily-averaged cloud fraction over the sea ice region was 59.5%, whereas those over the open ocean were 69.8% and 60.9% for the outward and returning cruises, respectively, during JARE 56. It is found that the cloud fractions by visual observation were overestimated by several percent compared with the other mechanical sensors during JARE 56. Furthermore, the standard deviation is approximately 30%, which is smaller by around 10% than those of the whole-sky camera and ceilometer observations. The difference clearly supports the tendency by human observation.

5. Discussion

Figure 6 illustrates the temporal variations of the daily-averaged cloud fraction from the whole-sky camera, ceilometer, and visual observations during JARE 55 and 56.

Figure 6a is a time series of the cloud fraction from whole-sky camera and ceilometer observations during JARE 55. In this figure, the cloud fraction from the
whole-sky camera was estimated using Eq. (3) with the constant coefficient $k = 3.7$. The cloud fraction in Fig. 6b corresponds to the coefficient that depends on sun elevation with Eq. (5). Comparing both Figs. 6a and 6b, the variations in cloud fractions from the whole-sky camera (red markers) and the ceilometer (blue markers) are more consistent in Fig. 6b over the sea ice region. The cloud fraction from the whole-sky camera greatly improved by approximately several percent with Eq. (5) in Fig. 6b compared with the constant coefficient in Fig. 6a over the sea ice region in particular.

Figure 6c shows the temporal variation of the daily-averaged cloud fractions from the whole-sky camera, ceilometer, and visual observations during JARE 56. The cloud fraction from the whole-sky camera was estimated using Eq. (5) over the sea ice region. We found that the three kinds of cloud fraction estimates were consistent generally, even though no ceilometer data were available during the returning cruise from Antarctica to Japan during JARE 56.

Figure 7 shows the scatter plots of the daily-averaged cloud fractions between whole-sky camera and ceilometer observations for the open ocean and sea ice regions during JARE 55 and 56 in Figs. 6b and 6c, respectively. All the regression lines lie almost along the one-to-one lines in Fig. 7. The plots during JARE 55 are more scattering than those during JARE 56. Furthermore, the plots in red of the cloud fraction over the open ocean also lie with a wider range than those in blue over the sea ice region. These tendencies could be confirmed with the root mean square errors (RMSEs) summarized in Table 3: the RMSE over the sea ice region is 9.3 (9.1), and this is also better than 13.9 (12.1) over the open ocean during JARE 55 (JARE 56). Furthermore, the correlation coefficient over the sea ice region is 0.93 (0.96), and this is higher than 0.87 (0.93) over the open ocean during JARE 55 (JARE 56). The correlation coefficient over total regions is 0.90 (0.95) during JARE 55 (JARE 56).

Even though cloud fractions were influenced by weather conditions where the R/V Shirase conducted observations, one of the reasons for the difference in cloud fractions between the open ocean and sea ice regions may be attributed to the spatial distribution of the clouds. When clouds appeared without a zenith direction, for example, the ceilometer might miss it because the ceilometer inherently observes only the zenith direction. Hence, the difference in cloud fractions possibly suggested that the dominant cloud type was different between the open ocean and sea ice regions.

In terms of the visual observations, the correlation coefficients were 0.91, 0.92, and 0.92 for the open ocean, sea ice, and total regions, respectively, during JARE 56. The correlation coefficients to visual observation were comparable to, but slightly smaller than, those to the ceilometer observation.

One of the reasons why the correlation of the whole-sky camera to visual observations was high is possibly related to the observation field of view. The whole-sky camera observes the sky with a zenith angle up to 90° whereas the observed image was analyzed with a zenith angle up to 70°. By trimming the

![Fig. 7. Scatter plots of daily-averaged cloud fractions between the whole-sky camera and ceilometer: (a) JARE 55 and (b) JARE 56. Red and blue correspond to open ocean and sea ice regions, respectively. Solid and dashed lines are regression and one-to-one, respectively. The regression lines are (a) $y = 0.82x + 9.07$ and $y = 0.91x + 10.77$, (b) $y = 0.93x + 3.79$ and $y = 0.89x + 10.39$ for open ocean and sea ice regions, respectively.](image-url)
edge of the images, we suppressed the influence of sea surface contamination on the images because the ship fluctuation was up to 20°. The ceilometer observed only the zenith direction, whereas visual observations cover a zenith angle up to 90°. The field of view for visual observations was similar to that for the whole-sky camera.

The fact that the cloud fractions differ from the field of view suggests the importance of cloud type. The dataset for the visual observations provides only the cloud fraction estimate, whereas the whole-sky camera compiles a two-dimensional image; thus, the whole-sky camera has the potential to detect cloud type. Heinle et al. (2010) estimated the cloud fraction for each cloud type as part of a radiation budget study over the Atlantic Ocean. Cloud type classification using whole-sky camera observation is one of the future areas of research for subsequent cruises on board the R/V Shirase.

The RMSEs are also almost identical for both the open ocean and sea ice regions in Table 3. This indicates that the visual observation automatically took into consideration whether the surface condition was an open ocean or sea ice region, and that the analysis of whole-sky camera data well corresponds to the surface condition. On comparing the ceilometer and visual observations during JARE 56, the RMSEs of the visual observation were larger than those of the ceilometer. This fact again supports the issue that the cloud fraction observed by humans has a tendency to be moderate compared with the mechanical sensors (Norris 1998).

As mentioned by Bromwich et al. (2012), cloud observations over sea ice regions remain challenging. Shipboard observations have certain advantages over satellites because the crew can precisely identify sea surface conditions such as whether one is in an open ocean or sea ice region. The periodical shipboard observations are suitable platforms to investigate cloud climatology over sea ice regions as well as the open ocean.

Cloud occurrences for the higher latitudes over polar regions are one of the important products from active orbital observations because passive spaceborne observations are impeded by the similarity of clouds and the underlying snow/ice surface, which have higher albedo and lower temperatures. Cloud properties using spaceborne active remote sensing with CloudSat and CALIPSO were investigated for approximately four years between June 2006 and May 2010 over the southern high latitudes poleward of 60°S (Adhikari et al. 2012). That study performed a sector analysis for Antarctic seas, the Antarctic Plateau, and coastal regions in terms of cloud cover, cloud top and bottom heights, and microphysics. They found that low-level cloud occurrence was higher in summer over the circumpolar sea region because heat and moisture were transported from the sea to the atmosphere as the sea ice shrank. Even though the active sensors are useful for cloud detection over Antarctica, performing validation studies using ground-based observations is still encouraged, particularly for low-level cloud systems.

The shipboard observation is expected to validate cloud fraction from geostationary satellite observations in future. For example, the Japan Meteorological Agency has operated the geostationary meteorological satellite Himawari-8 from 7 July 2015 (Bessho et al. 2016). Himawari-8 carries the Advanced Himawari Imager, which observes the Earth and its atmosphere, covering the western Pacific Ocean every 10 min for a full disk from geostationary orbit at 140.7°E. The cloud mask, also known as cloud occurrence, is also obtained from the operation of Himawari-8.

### Table 3. Statistics of daily-averaged cloud fractions between whole-sky camera and other observations: correlation coefficient ($R^2$), root mean square error (RMSE), and number of data (N).

| Observation | Region   | JARE 55 |       |       | JARE 56 |       |       |
|-------------|----------|---------|-------|-------|---------|-------|-------|
|             |          | $R^2$   | RMSE  | N     | $R^2$   | RMSE  | N     |
| Ceilometer  | Open ocean| 0.87    | 13.9  | 52    | 0.93    | 12.1  | 29*   |
|             | Sea ice  | 0.93    | 9.3   | 47    | 0.96    | 9.1   | 49*   |
|             | Total    | 0.90    | 12.6  | 99    | 0.95    | 10.5  | 78*   |
| Visual      | Open ocean| —      | —     | —     | 0.91    | 12.4  | 57    |
|             | Sea ice  | —      | —     | —     | 0.92    | 12.4  | 65    |
|             | Total    | —      | —     | —     | 0.92    | 12.5  | 122   |

* Mainly for its way from Japan to Syowa Station, Antarctica. See Figs. 4b and 4c.
The cloud mask detection accuracy was 85% over the sea region, based on a validation study spanning two weeks in each of the four seasons. The whole-sky camera observations onboard the R/V Shirase are higher frequency with measurements every 5 min. Most of the R/V Shirase's ship tracks were covered with Himawari-8. The cloud fraction derived from R/V Shirase data in this study will contribute to the validation of the observations from Himawari-8 in the future.

6. Summary

Shipboard cloud observations were performed to investigate the cloud fractions using a whole-sky camera and a ceilometer onboard the R/V Shirase, traveling between Japan and Antarctica from November 2013 to April 2014 (JARE 55) and from November 2014 to April 2015 (JARE 56).

The daily-averaged cloud fractions ranged from 52% to 66% with the whole-sky camera and from 58% to 85% from ceilometer estimates for the open ocean during JARE 55 and JARE 56. We found that cloud fractions were generally larger in latitudes higher than 40°S, in particular, compared with the lower latitudes.

Furthermore, we analyzed the whole-sky camera data over the sea ice region in addition to the open ocean. The classification curve is expressed as a function of solar elevation over the sea ice region, whereas a constant parameter is applicable over open water. As a result, we found that the cloud fractions over the sea ice region were 84% and 57% during JARE 55 and 56, respectively.

The cloud fractions estimated from the whole-sky camera were consistent with the ceilometer and visual observations for both the open ocean and sea ice regions during JARE 55 and 56; the correlation coefficients were approximately 0.9 overall.

However, there still exists a discrepancy of cloud fraction estimates from whole-sky camera, ceilometer, and visual observations because of their field-of-view differences. This suggests that cloud type, which was not considered in this particular study, could allow us to improve the cloud fraction estimates because the cloud fractions are dependent on the cloud field (e.g., stratus or broken).

It is likely that a combination of whole-sky camera and ceilometer data could provide cloud fractions for each cloud type, which is one of the future tasks and a research area where we will continue shipboard observations.

Finally, Yoshimura and Yamashita (2013) attempted to compare ground-based cloud detection with satellite observations directly from the moderate resolution imaging spectroradiometer (MODIS) 250 m imagery. Thus, continued cloud fraction estimates made onboard the R/V Shirase will also help validate satellite observations as well as whole-sky camera observations at Syowa Station on the Antarctic coast.

Supplements

Supplement contains maps of cloud base heights from the ceilometer during JARE 55 and 56; maps of cloud fractions from the whole-sky camera, ceilometer, and visual observations around sea ice regions during JARE 55 and 56.

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