Seasonal Change in Satellite-Retrieved Lower-Tropospheric Ice-Cloud Fraction Over the Southern Ocean

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Abstract This study investigated the temperature and fraction of lower-tropospheric ice cloud over Antarctica and the Southern Ocean (SO) using Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation satellite data. Over the SO, the maximum low-level ice-cloud fraction below 2 km is observed at cold temperatures (≤−25°C); however, local maxima of low-level ice-cloud fraction are observed at temperatures >−7.5°C (≥−17.5°C) during summer (winter). High fractions of low-level ice cloud observed at higher temperatures over near-coastal Antarctic sea ice areas in summer, coincident with the highest chlorophyll-a concentrations, and over coastal Antarctic ice-covered areas in winter, suggest that marine aerosols act as ice-nucleating particles for ice-cloud formation during summer and winter.

Plain Language Summary Clouds over Antarctica and the Southern Ocean (SO) play an important role in Earth's climate. Although climate models are useful for investigating Southern Hemisphere clouds, overestimation of the modeled ice-cloud fraction over the SO causes large uncertainties regarding atmospheric and oceanic circulations. Therefore, improved understanding of cloud characteristics over Antarctica and the SO would enhance projections of the climate system. We investigated ice-cloud fractions over Antarctica and the SO using satellite data. Although ice cloud generally occurs under very cold conditions (e.g., <−38°C), low-level ice cloud is observed over the SO under higher temperature conditions because various aerosols influence ice-cloud formation. During summer, high fractions of low-level ice cloud at higher temperatures (≥−7.5°C) are observed over coastal Antarctic sea ice areas, coincident with the highest chlorophyll-a concentrations, an indicator of phytoplankton abundance in the upper layer of the ocean. During winter, the highest fractions of low-level ice cloud at higher temperatures (≥−17.5°C) are observed near coastal Antarctic ice-covered areas, coincident with considerable heat exchange from the ocean to the air. These findings suggest that oceanic aerosols contribute to low-level ice-cloud formation over the SO at higher temperatures during summer and winter.

1. Introduction

Polar region cloud, which plays a major role in the climate system, is very sensitive to sea ice distribution (Sato et al., 2012), lower-tropospheric stability (Taylor et al., 2015), and atmospheric circulation (Inoue & Hori, 2011; Sato & Simmonds, 2021). The microphysical and macrophysical structures of cloud control longwave/shortwave radiation transmission to the surface, while top of the atmosphere reflection of solar radiation depends on lower- and mid-level cloud phase (Vergara-Temprado et al., 2018). Furthermore, cloud over Antarctica modulates the ice mass balance and surface conditions via precipitation (Gorodetskaya et al., 2014). Therefore, many previous studies have investigated cloud over Antarctica (Jolly et al., 2018; Kawai et al., 2015; Lawson & Gettelman, 2014; Scott et al., 2017), the Southern Ocean (SO; Alexander & Protat, 2018; Kuma et al., 2020; McFarquhar et al., 2020; Sato et al., 2018), and the entire high-latitude region of the Southern Hemisphere (SH; Adhikari et al., 2012; Bromwich et al., 2012; Wall et al., 2017).

Poleward of 60°S, total cloud cover over the SO is greater than that over Antarctica in all seasons (Bromwich et al., 2012; Listowski et al., 2019), and low-level cloud (base height: <2.0 km) occurs most frequently (Adhikari et al., 2012). Huang et al. (2012) reported little difference in low-level cloud fraction over the Indian sector of the SO between summer and winter, whereas such seasonal difference was found over the Pacific sector (Jolly et al., 2018). During winter, sea ice extent reduces heat and moisture transport from the ocean to the air, resulting in less low-level cloud over sea ice areas (Adhikari et al., 2012). Near the ice edge, contrast exists in low-level cloud cover between open water and sea ice areas during off-ice flow because of anomalous heat and moisture

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release from the ocean (Wall et al., 2017). Radar and lidar products revealed that sea ice variability influences lower-tropospheric cloud phase (Listowski et al., 2019). During autumn-winter, the occurrence of low-level supercooled liquid water cloud decreases with increasing sea ice concentration (SIC), whereas no difference in low-level cloud extent is found between open water and sea ice areas in summer, meaning that cloud properties are unaffected by sea ice variability (Frey et al., 2018; Listowski et al., 2019). However, variation in mixed-phase cloud extent exists between regions outside and inside the Antarctic Polar Front (near 55°S) owing to the strong meridional sea surface temperature (SST) gradient (Mace et al., 2021).

Ice crystal numbers are enhanced by secondary ice-production processes, for example, rime splintering, collision fragmentation, and droplet shattering (Hallett & Mossop, 1974; Scott & Hobbs, 1977; Vardiman, 1978). However, over Antarctica and the SO, various aerosols (e.g., mineral dust, organic aerosols, and bioaerosols) that originate from local and remote areas are considered active ice-nucleating particles (INPs) at higher temperatures (McCluskey et al., 2018; Vergara-Temprado et al., 2018). Listowski et al. (2019) reported that an increase in bioaerosols associated with high biological activity influences the low-level mixed-phase cloud fraction in spring and summer over coastal Antarctic regions. During sea ice melting seasons, phytoplankton blooms in the marginal ice zone (Arrigo et al., 2008; M. H. Taylor et al., 2013) introduce marine bioaerosols into the lower troposphere via sea spray (DeMott et al., 2015). In numerical climate models, biases toward higher numbers and larger sizes of INPs promote enhanced formation and growth of ice cloud in global numerical climate models, causing excess shortwave radiation and warm temperature biases at the surface over the SO (Vergata-Temprado et al., 2018). Furthermore, the occurrence frequency of low-level cloud below 2 km over the SO is underestimated in general circulation modeling and reanalysis data (Kuma et al., 2020; Wall et al., 2017). Therefore, investigation using observational data is required to elucidate the relationship between the fraction of ice cloud and INPs over the SH.

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) data from the Northern Hemisphere revealed that INPs allow ice-cloud formation at temperatures >−20°C, particularly in the lower troposphere (Yamauchi et al., 2018, 2020). Therefore, this study used CALIPSO data to investigate the temperature and fraction of ice cloud in the troposphere over Antarctica and the SO, and to elucidate the relationship between SO lower-tropospheric ice-cloud fraction and phytoplankton numbers.

2. Data and Methods

2.1. Satellite Cloud Data

The CALIPSO satellite with a Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument, launched in April 2006 (Winker et al., 2007), measures backscatter profiles with high vertical resolution (30 [60] m below (above) 8.2 km altitude), which can be used to estimate cloud properties. Using data from this satellite, the JAXA EarthCARE program developed a cloud data set with 240 m horizontal resolution covering June 2006 to August 2015 (except for January 2011, May 2011 to June 2012, and January–June 2015; Hagihara et al., 2010; Okamoto et al., 2010; Sato & Okamoto, 2011; Yoshida et al., 2010). This data set comprises approximately 37,081 pixels before 2011 and 20,678 pixels after 2012 (horizontal resolution: 1.1 km) with 83 vertical bins (vertical resolution: 240 m) for each orbit. An example of a CALIPSO cloud particle type scene over Antarctica and the SO from orbit No.07 on January 21, 2009 is shown in Figure S1a in Supporting Information S1. Cloud particles are classified into seven types: warm water, supercooled water, horizontally oriented plates (2D-plate), randomly oriented ice crystals (3D-ice), mixture of 2D-plate and 3D-ice, unknown1 (likely ice crystals containing horizontally oriented plates with weak specular reflection), and unknown2 (liquid droplets or randomly oriented ice crystals).

Using CALIOP data, this study defined ice cloud as 2D-plate, 3D-ice, and mixture of 2D-plate and 3D-ice; water cloud was defined as warm water and supercooled water; and unknown1 and unknown2 were excluded from further analysis to avoid ambiguity. Following Yamauchi et al. (2020), fractions of ice cloud ($F_{\text{ice}}$) and water cloud ($F_{\text{water}}$) relative to the total cloud in the target layer were calculated as follows:

$$F_{\text{ice}} = \frac{N_{\text{ice}} \times 100}{N_{\text{ice}} + N_{\text{water}}}$$ (1)

$$F_{\text{water}} = \frac{N_{\text{water}} \times 100}{N_{\text{ice}} + N_{\text{water}}}$$ (2)
where $N_{\text{ice}}$ and $N_{\text{water}}$ are the numbers of bins for ice and water cloud in the target layer, respectively, detected successfully in the total cloud cover by CALIOP (Figure S1a in Supporting Information S1). Cloud below 8 kilometer (km) was classified into high-, mid-, and low-level layers (cloud altitude: >6, 2–6, and <2 km, respectively; altitude is defined as height above mean sea level). Over high latitudes of the SH, approximately 15 passes are available daily (Figure S1b in Supporting Information S1), and $F_{\text{ice}}$ and $F_{\text{water}}$ were calculated for 3.0° × 3.0° grids for each season during 2006–2015 (Figure S2 in Supporting Information S1). Summer has the highest fraction of $F_{\text{ice}} + F_{\text{water}}$ over Antarctica and the SO (Figure S2b in Supporting Information S1). Note that the change in CALIPSO viewing angle from 0.3 to 3 in November 2007 reduced the influence of high reflectance from horizontally oriented ice, which meant that ice-cloud detection was lower after November 2007 (Hu et al., 2009).

CALIPSO data have been used to investigate the effect of dust load on the ice-cloud fraction over the Northern Hemisphere (Filioglou et al., 2019; Kawamoto et al., 2020). To estimate vertical profiles of extinction coefficients of water-soluble, dust, and sea salt aerosols, an algorithm developed by Nishizawa et al. (2011) was applied to backscattering coefficient and depolarization ratio data obtained by CALIPSO. Using the derived extinction coefficients, aerosol optical depth (AOD) was calculated for the three aerosols. This investigation focused on cases where the vertical distance between observed cloud and aerosol layers was within 1 km.

The CloudSat product from the European Centre for Medium-Range Weather Forecasts was used for the temperature profiles (Partain, 2007). However, relative to observations, this product has a warm temperature bias during all seasons (Candlish et al., 2013); therefore, we used bias-corrected data.

### 2.2. Satellite Radiation and Chlorophyll-a Data Sets

This study used Clouds and the Earth’s Radiant Energy System-Energy Balanced and Filled (CERES EBAF Ed4.1) data to assess downward longwave and shortwave radiation (Kato et al., 2018; Loeb et al., 2018). Monthly mean downward longwave and shortwave radiation data are available on 1.0° × 1.0° grids from 2000 to the present. Phytoplankton presence over the SO was investigated using MODIS-Aqua satellite monthly mean chlorophyll-a concentration data available on a 0.1° × 0.1° grid. Full details of the data are available in Hu et al. (2012). Over sea ice areas, error in the water-leaving radiance, which is required for estimating chlorophyll-a concentration, causes overestimation (underestimation) of daily chlorophyll-a concentration for some pixels when the chlorophyll-a concentration is relatively low (high) (Bélanger et al., 2007). To overcome this, we used monthly mean data averaged over 3.0° × 3.0° grids.

### 2.3. Reanalysis Data

Open water and sea ice areas were distinguished using monthly mean SIC and SST data from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data sets, available on 1.0° × 1.0° grids from 1981 to the present. Over sea ice areas, SST was estimated using SST–SIC statistical relationships. Further details are available in Rayner et al. (2003).

For atmospheric parameters (2 m air temperature, 10- m wind speed, and sensible heat flux), we used monthly mean ERA5 data on 0.5° × 0.5° grids from the European Centre for Medium-Range Weather Forecasts (Hersbach et al., 2020). To reduce the parameter uncertainty in the ERA5 data, we used 10-ensemble mean data. Sensible heat flux at each grid is considered an indicator of marine aerosol emission from the ocean to the air. However, because this value over sea ice areas might be underestimated, we defined the indicator of air-sea exchange as follows:

$$\text{ASE index} = (\text{SST} - \text{T2m}) \times \text{WS10m}$$

where T2m and WS10m are the ERA5 2 m air temperature and 10 m wind speed, respectively, and SST is the HadISST sea surface temperature.
3. Results

3.1. Ice-Cloud Fraction Over Antarctica and the Southern Hemisphere

The seasonal distribution of $F_{\text{ice}}$ below 8 km over Antarctica and the SO is shown in Figures 1a–1d. $F_{\text{ice}}$ over Antarctica and the SO is highest in winter (Figure 1d), and the distribution and magnitude of $F_{\text{ice}}$ in spring are similar to those in autumn (Figures 1a and 1c). $F_{\text{ice}}$ in summer is smaller than in winter because of the warmer summer temperatures (Figure 1b). Difference in $F_{\text{ice}}$ between Antarctica and the SO is evident in all seasons. $F_{\text{ice}}$ over Antarctica is larger than over the SO (Figures 1a–1d). Over East Antarctica, $F_{\text{ice}}$ is larger than over West Antarctica in all seasons, reflecting the very cold conditions over interior East Antarctica at high elevations. Over the SO, $F_{\text{ice}}$ is relatively high over Drake Passage, near-coastal regions, and the Indian sector (90°–150°E) compared with other regions in the same latitudinal band. Conversely, the Weddell, Ross, and Amundsen seas have relatively low $F_{\text{ice}}$ in all seasons, particularly summer.

We examined the seasonal cycles of $F_{\text{ice}}$ in low-, mid-, and high-level layers over Antarctica (Figure S3 in Supporting Information S1) and the SO (poleward of 50°S). High-level $F_{\text{ice}}$ does not vary seasonally over Antarctica and the SO because all liquid cloud droplets freeze under very cold conditions (temperature: $<-38°C$) in the upper troposphere (Figures 2a and 2d). Conversely, clear seasonal variation in $F_{\text{ice}}$ is evident in low- and mid-level layers (Figures 2b and 2c). In winter, cold conditions contribute to the highest $F_{\text{ice}}$ over Antarctica and the SO at these levels (Figures 2e and 2f). In summer, although $F_{\text{ice}}$ is smaller than in other seasons, ice cloud is observed even under conditions with relatively high temperatures. These results indicate large differences between summer and winter regarding the temperature at which ice clouds are present, particularly in the lower troposphere, consistent with Jolly et al. (2018).

To examine the zonally averaged $F_{\text{ice}}$ of low-level cloud over Antarctica and the SO (poleward of 50°S) at different temperatures at 2.5°C intervals as a function of latitude during summer and winter (Figure 3 and Figure S4 in Supporting Information S1), the SO was divided into three regions, that is, Indian, Pacific, and Atlantic sectors (Figure 1a and Figure S3 in Supporting Information S1). During winter, low-level cloud over all regions has the highest $F_{\text{ice}}$ at very cold temperatures, i.e., $<-35°C$ (Figures 3a–3c; Figures S4a and S4b in Supporting Information S1).
Additionally, high F\text{\textsubscript{ice}} occurs under relatively warm temperatures (−17.5°C to −10°C) over Antarctica and the SO sectors, especially poleward of 66°S. High F\text{\textsubscript{ice}} over the SO sectors at temperatures >−10°C indicates conditions more favorable for ice-cloud formation near the surface compared with those over Antarctica (Figures 3a–3c; Figures S4a and S4b in Supporting Information S1). In contrast, during summer, ice cloud over all regions occurs at temperatures >−35°C (Figures 3d–3f; Figures S4c and S4d in Supporting Information S1). Specifically, over the SO sectors, the local maximum F\text{\textsubscript{ice}} occurs at temperatures >−7.5°C (Figures 3d–3f and Figure S4d in Supporting Information S1). Although differences exist in the magnitude of F\text{\textsubscript{ice}} of low-level cloud, relatively high F\text{\textsubscript{ice}} occurs at warmer temperatures over the different SO sectors in summer.

### 3.2. Relationship Between Low-Level Ice Cloud and Surface Conditions in Summer and Winter

During summer, lower-tropospheric INPs over the SO are mostly of oceanic origin (Uetake et al., 2020). In all seasons, marine organic aerosols act as INPs for ice-cloud formation over the SO (Vergara-Temprado et al., 2018). The various aerosols that act as INPs for ice-cloud formation over Antarctica and the SO have different ice nucleation onset temperatures (organic aerosols: <−20°C, mineral dust: <−10°C, bioaerosols: >−10°C; Hoose & Möhler, 2012). Therefore, SIC variability influences seasonal differences in biological activity and the release of marine aerosols into the lower troposphere (Figures 1e–1h), presumably resulting in differences in INP type available for low-level ice-cloud formation, particularly between summer and winter.

We examined the relatively high F\text{\textsubscript{ice}} of low-level cloud associated with higher temperatures (i.e., −7.5°C to 0°C and −17.5°C to −10°C for summer and winter, respectively), chlorophyll-\text{a} concentration, SIC, AOD, and ASE index poleward of 50°S (Figure 4). Chlorophyll-\text{a} concentration, used to estimate phytoplankton numbers, can be considered an indicator of the number of marine bioaerosols in the lower troposphere (Richert et al., 2019;
Williams et al., 2016). Figures 4a–4c show the $F_{\text{ice}}$ of low-level cloud under higher temperatures (i.e., between $-17.5^\circ C$ and $-10^\circ C$) at different ASE indexes with 10 intervals as a function of latitude during winter. Under a relatively high ASE index condition, when cold advection from Antarctica dominates, the highest $F_{\text{ice}}$ for low-level cloud at higher temperatures is observed over near-coastal Antarctic regions with high SIC over all sectors (Figures 4a–4c and 4e). Over sea ice areas, open water within pack ice (e.g., leads and polynyas) and the marginal ice zone represent sources of organic carbon emitted into the atmosphere (Inoue, Tobo, Taketani, & Sato, 2021; Kirpes et al., 2019). Over the marginal ice zone, marine organics, supplied to the atmosphere via strong air-sea
exchange during strong cold advection, act as INPs for ice-cloud formation at temperatures >−15°C in cold seasons (Inoue, Tobo, Taketani, & Sato, 2021). Leads and polynyas are potential sources of marine aerosols in sea ice areas of all SO sectors near the Antarctic coast (Figure 4e). When strong cold advection from Antarctica prevails over coastal Antarctic regions of the Indian and Pacific sectors (under high ASE index conditions), a clean Antarctic air mass induces low AOD for all aerosols (Figures 4a and 4b; Figures S5a and S5b in Supporting Information S1). However, marine aerosols emitted from Antarctic coastal polynyas cause relatively high $F_{\text{ice}}$ for low-level cloud over the SO at temperatures between −17.5°C and −10°C. Over the near-coastal Antarctic region of the Atlantic sector, the highest $F_{\text{ice}}$ for low-level cloud at higher temperatures is observed under a high ASE index condition, coincident with the highest AOD (Figure 4c and Figure S5c in Supporting Information S1). However, aerosols transported from remote regions would influence ice-cloud formation over the Atlantic sector. Mineral dust from remote (e.g., mid-latitude) regions, acting as INPs at temperatures of <−10°C (Hoose & Möhler, 2012), are responsible for ice-cloud formation over the SO. The highest AOD with higher $F_{\text{ice}}$ of low-level cloud under a low ASE index condition over near-coastal Antarctic regions of the Indian and Pacific sectors...

Figure 4. Dependence of averaged low-level ice-cloud fraction relative to total cloud ($F_{\text{ice}}$) at higher temperatures (−17.5°C to −10°C) as a function of latitude and ASE index (shading: %) with aerosol optical depth for all aerosols (contours) averaged over the (a) Indian, (b) Pacific, and (c) Atlantic sectors of the Southern Ocean in austral winter 2006–2015. Values are correlation coefficients between monthly mean $F_{\text{ice}}$ at warm temperatures and ASE index for each region. (d) Chlorophyll concentration (mg/m²) and (e) Sea ice concentration (SIC: %) as function of latitude averaged over the Indian (blue), Pacific (red), and Atlantic sectors (green) of the Southern Ocean. Values are correlation coefficients between monthly mean $F_{\text{ice}}$ at higher temperatures and each parameter for each region. (f–j) Same as (a–e) but for $F_{\text{ice}}$ at higher temperatures (−7.5°C to 0°C) in austral summer.
suggests that aerosols transported from lower latitudes promote ice-cloud formation over near-coastal Antarctic regions (Figures 4a and 4b; Figures S5a and S5b in Supporting Information S1). However, over such regions, the $F_{\text{ice}}$ of low-level cloud under a high ASE index condition is larger than that under a low ASE index condition. These results indicate that emission of marine aerosols in high-latitude areas is more important in ice-cloud formation over near-coastal Antarctic regions than transportation of mineral dust and other aerosols from remote regions.

During summer, $F_{\text{ice}}$ of low-level cloud at higher temperatures ($-7.5^\circ C$ to $0^\circ C$) over near-coastal Antarctic regions of all SO sectors is larger than that over the ocean (Figures 4f–4h). Moreover, the chlorophyll-$a$ concentration is higher in high-latitude areas with sea ice than in open water (Figure 4i). Over the Pacific and Atlantic sectors, high AOD near coastal Antarctic regions under low ASE index conditions suggests transportation of aerosols from lower latitudes. However, transportation from mid-latitudes has little impact on lower-tropospheric INP numbers over the SO (Uetake et al., 2020). Therefore, marine bioaerosols emitted from high-latitude oceans presumably contribute to the higher $F_{\text{ice}}$ for low-level cloud at higher temperatures ($>-7.5^\circ C$) over coastal Antarctic regions (Figures 4g and 4h, Figures S5e and S5f in Supporting Information S1). Over the Indian sector, high $F_{\text{ice}}$ for low-level cloud at higher temperatures with relatively low AOD is observed over near-coastal Antarctic regions (Figure 4f and Figure S5d in Supporting Information S1). Therefore, an increase in marine bioaerosols from the ocean at the same latitude leads to the highest $F_{\text{ice}}$ for low-level cloud when cold clean air is advected from Antarctica. High $F_{\text{ice}}$ for wintertime low-level cloud at temperatures between $-7.5^\circ C$ and $0^\circ C$ is also observed over all SO sectors (Figures 3a–3c). Despite the unavailability of chlorophyll-$a$ concentration data over high latitudes during winter, leads and polynyas represent potential sources of marine INPs (Hartmann et al., 2020) that could influence low-level ice-cloud formation as INPs, even during winter (Figures 3a–3c and 4d).

### 4. Conclusions and Discussion

Seasonal changes of $F_{\text{ice}}$ of tropospheric cloud over Antarctica and the SO (poleward of 50$^\circ$S) were investigated using CALIOP data. Seasonal variation of $F_{\text{ice}}$ in low- and mid-level layers is evident with summertime minima and wintertime maxima. The $F_{\text{ice}}$ of low-level cloud over Antarctica and the three SO sectors in winter is highest at temperatures of $<-35^\circ C$; however, $F_{\text{ice}}$ is relatively large at temperatures between $-17.5^\circ C$ and $-10^\circ C$ under high ASE index conditions, particularly over near-coastal Antarctic regions. During summer, the local maximum $F_{\text{ice}}$ of low-level cloud occurs at higher temperatures ($>-7.5^\circ C$) over near-coastal regions of the three SO sectors, coincident with high chlorophyll-$a$ concentrations under a low ASE index. These results indicate that marine aerosols emitted from high-latitude oceans promote ice-cloud formation over near-coastal Antarctic regions during summer and winter.

Unlike phytoplankton, bacteria act as primary INPs for low-level ice-cloud formation at relatively high temperatures (i.e., $>-10^\circ C$; Hoose & Möhler, 2012). However, bacteria numbers in the ocean increase with phytoplankton concentration (Richert et al., 2019; Williams et al., 2016). Therefore, chlorophyll-$a$ concentration could be an indicator of the number of marine bacteria emitted into the air. During winter, stronger and more numerous cyclones over the SO (Sato et al., 2021; Simmonds et al., 2003) promote transportation of mineral dust from lower latitudes. Additionally, over polar regions, open water within pack ice represents a source of aerosol particles emitted into the atmosphere (Hartmann et al., 2020; Inoue, Tobo, Taketani, & Sato, 2021). Therefore, Antarctic coastal polynyas could potentially introduce marine aerosols into the lower troposphere (Tamura et al., 2016).

Variation in total tropospheric $F_{\text{ice}}$ influences surface longwave/shortwave radiation budgets because the optical depth of ice cloud is thinner than that of water cloud (Figures S6e–S6l in Supporting Information S1). In summer, shortwave radiation over coastal East Antarctica is greater than that over the SO Pacific sector in the same latitudinal band (Figure S6f in Supporting Information S1). Although ice crystal and water cloud droplet size distributions affect outgoing solar radiation, a relatively small total tropospheric water cloud content is considered the main cause of decrease in solar radiation reflection over these regions. Increased incoming shortwave radiation at the surface enhances the number of bioaerosols contributing to increased ice-cloud formation through positive ice cloud-bioaerosol feedback during summer. Moreover, an extended ice-free ocean with higher wave conditions (Waseda et al., 2018) is favorable for producing more sea spray, which promotes marine aerosol emission into the atmosphere during all seasons.
This study was based on a Japanese satellite product; however, differences exist in the detection of ice cloud tops among satellite cloud-phase products owing to different algorithms and instruments (Villanueva et al., 2021). Moreover, the CALIOP signal is attenuated by thick cloud. Therefore, further investigation of the relationship between low-level $F_{\text{ice}}$ and marine aerosols in the SH will require direct observations. In recent Arctic field campaigns, Inoue, Tobo, Sato, et al. (2021) and Inoue, Tobo, Taketani, & Sato (2021) used a cloud particle sensor sonde (Meisei Electric Co., Ltd.) to obtain vertical profiles of cloud properties. A number of austral summer cruises have been conducted by the Japanese icebreaker Shirase (Hirano et al., 2020; Sato et al., 2020), and further cruises during 2022–2027 will provide opportunities to investigate the relationship between bioaerosol numbers and ice-cloud formation over the SO.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The Lidar Cloud Particle Type product and Lidar Aerosol Property product provided by the Japan Aerospace Exploration Agency (JAXA) were obtained from the EarthCARE Research Product Monitor (https://www.eorc.jaxa.jp/EARTHCARE/research_product/ecare_monitor_e.html). Sea ice concentration and sea surface temperature data were derived from the Hadley Centre Sea Ice and Sea Surface Temperature (HadISST) data sets (available from https://www.metoffice.gov.uk/hadobs/hadisst). The Clouds and the Earth's Radiant Energy System-Energy Balanced and Filled (CERES EBAF Ed4.1) data were provided by the National Aeronautics and Space Administration (NASA; available from https://ceres.larc.nasa.gov/data). Chlorophyll-a concentration data were based on MODIS–Aqua satellite data obtained from NASA (available from https://neo.sci.gsfc.nasa.gov/view.php?dataset-Id=MY1DMM_CHLORA). ERA5 reanalysis data were obtained from the European Centre for Medium-Range Weather Forecasts (available from https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5).

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