ICESat-2 shows sea ice leads decrease the Arctic cloudiness in cold months

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Article

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Abstract

The effect of leads in Arctic sea ice on clouds is a potentially important climate feedback. We use observations of clouds and leads from the Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) to study the effects of leads on clouds. Newly open leads increase cloudiness while newly frozen leads decrease cloudiness. The latter dominates but the magnitude of the net effect depends on the life cycle of leads. The cloud dissipating effect decrease the Arctic cloudiness by 4-6% in cold months. The cloud increasing effect of open leads is evident in areas with strong sea ice deformation and frequent lead formation. Lead effects can reach beyond the boundary layer to 6 km. The lack of proper representation of lead effect on clouds in current climate models and reanalyses contributes to the overestimation of cloudiness over Arctic sea ice in cold months.

Introduction

Leads are narrow, linear channels formed due to the deformation of sea ice (Kwok, 2001). Despite their small total surface area, leads are a major source of heat and moisture to the lower troposphere over Arctic sea ice during the cold season. Although the areal coverage of leads in the central Arctic Ocean in winter is often less than 1-2% in the perennial ice zone (Kwok, 2002), turbulent fluxes from leads contribute up to 70% of the total heat fluxes from the surface to the atmosphere (Marcq & Weiss, 2012). The enhanced surface fluxes from open water, such as leads, are an important source of moisture for the maintenance of the Arctic mixed-phase clouds (Morrison & Pinto, 2006; Solomon et al., 2014). Cloud plumes associated with leads are frequently observed and hydrometeor plumes can reach as high as 4 km, penetrate the top of the atmospheric boundary layer, and propagate tens of kilometers downwind (Bary et al., 1987; Curry, 1988; Schnell et al., 1989). The plume circulation can affect the local winds and the radiative fluxes from the cloud plume modify the surface energy budget of the leads and the sea ice surface downstream (Zulauf & Krueger, 2003; Lüpkes et al., 2008; Went et al., 2018). The modification of cloudiness by leads is a critical link in the interactions between sea ice and atmosphere due to its impacts on the cloud radiative heating and the sea ice growth.

Many previous studies of the processes and factors of lead effect on clouds focused on the effects of individual leads, especially open leads. The modification of the surface turbulent fluxes, the development of a thermal internal boundary layer within the existing stable boundary layer, and the properties of the resulting cloud plumes over and downstream of the open leads were examined using observations and idealized model simulations (Serreze et al., 1992; Alam & Curry, 1995, 1997; Andreas & Cash, 1999; Zulauf & Krueger, 2003). For example, the surface turbulent heat fluxes averaged across the width of open leads are larger over narrower leads, while wider leads allow the thermal internal boundary layer to develop deeper and affect the cloudiness over a larger area (Alam & Curry, 1997; Andreas & Cash, 1999). Following the findings from these studies, one would expect that more open leads correspond to more open water and contribute to increasing clouds, at least for colder parts of the year (Schweiger et al., 2008; Kay & Gettelman, 2009).

However, some recent studies suggest the importance of the newly refrozen leads on the overall interactions between leads and the atmosphere. As the leads begin to freeze up, the surface turbulent fluxes decrease rapidly with the thickness of the ice over (Maykut, 1978). The surface flux evolution during the refreezing process has significant variability dependent on winds and ice growth within leads (Alam & Curry, 1998). Burk et al. (1997) found that partially refreezing leads must be in an advance stage with enough cold refrozen area to significantly limit the span of the simulated cloud plume. A more recent idealized modeling study of a refrozen lead downwind of an open lead showed that refreezing at the surface cut off the water vapor supply more effectively than the sensible heat flux. The substantial warming of the atmospheric boundary layer is accompanied a decreased relative humidity without the moisture source from below. Such warming and drying of the atmosphere dissipate the existing cloud plumes developed from the open lead upwind (Li, Krueger, Strong, Mace, et al., 2020).

The net effect of leads on clouds results from the contributions by leads of all sizes, orientation, and integrated through their life cycle. Li et al. (2020) computed lead fluxes using the daily lead fraction from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) Aqua satellite (Röhrs & Kaleschke, 2012) and examined lead fluxes and cloud fraction from the CloudSat and CALIPSO joint radar and lidar cloud retrievals (Mace & Zhang, 2014). They found fewer clouds are present when lead fluxes are larger in both the Beaufort Sea and the Siberian sector of the Arctic Ocean over cold months. This finding suggests that drying and cloud dissipating effects from the newly frozen leads compensate and dominate over the increases in cloud cover from open leads in the large-scale mean lead effect on clouds. One limitation of this study is that the contribution of the narrower leads was not included because the AMSR-E lead fraction product has difficulty identifying leads narrower than 3 km due to the constraint of the AMSR-E sensors resolution (Röhrs & Kaleschke, 2012). In addition, because the inclination of the CloudSat and CALIPSO satellites, their cloud observations in the Arctic are limited to south of 82 °N and the central Arctic Ocean in this area is not included in this study. Uncertainties also arise from radar ground clutter that may introduce inconsistency in cloud retrievals and may result in a sudden reduction of cloud occurrence below 720 m due to the lack of cloud radar information to identify the clouds missed by lidar due to attenuation (Y. Liu et al., 2017).

The Ice, Cloud, and Land Elevation Satellite-2 (ICESat-2) was launched in September 2018. The photon-counting Advanced Topographic Laser Altimeter System (ATLAS) on board ICESat-2 measures the Earth surface and clouds heights using three pairs of laser beams with unprecedented resolution and accuracy (Markus et al., 2017; Neumann et al., 2019). With an inclination of 92 °, ICESat-2 provide simultaneous observations of leads and snows between 88 °N and 88 °S. The capability to observe leads with width of several meters and a much smaller data gap near the poles, the ICESat-2 present us with the unique opportunity to investigate the effects of leads on clouds in the Arctic, including the central Arctic Ocean, for the first time.

Another challenge for assessing lead effect on clouds is that the occurrence of both clouds and leads are connected to the synoptic weather conditions (Stramler et al., 2010; Barton et al., 2012; Y. Wang et al., 2016; Z. Liu & Schweiger, 2017). Li et al. (2020) chose leads and clouds in a specific synoptic condition, from the east side of surface high pressure system, to limit the influence of synoptic conditions to their evaluation of lead effect on clouds. The high resolution of simultaneous observations of leads and clouds allowed us to examine the lead effects on a smaller spatial scale and exclude the biases introduced by synoptic variability. This way, the aggregated lead effect from ICESat-2 observations include contribution from all synoptic conditions.
In this study, we examine the spatial distribution of clouds in the Arctic and the spatial distribution of lead effect on clouds in cold months since 2018. We find leads are associated with lower cloud fraction on the pan-Arctic scale and the areas with weaker lead effects are likely associated with the frequent new open lead production due to the strong sea ice deformation in these areas.

Results

The seasonal variability and spatial distribution of low-level cloud cover from ICESat-2 (Fig. 1) is consistent with active satellite observations, such as CloudSat and CALIPSO (Y. Liu et al., 2012; Cesana et al., 2012; Kay et al., 2016), passive satellite observations, and in-situ based climatologies (Warren et al., 1988; Schweiger et al., 1999; X. Wang & Key, 2005). The cloud fraction is over 0.7 in most of Greenland, Iceland, and Norwegian (GIN) and Barents Seas but only 50% in the Beaufort, Chukchi, and Eastern Siberian Seas. The larger cloud fraction in the GIN seas and the Barents Sea are associated with the warm open water surface and the frequent storm passages in this area (Seneze et al., 1993; Simmonds et al., 2008; Sorteberg & Walsh, 2008; Crawford & Seneze, 2016). This spatial contrast in cloud cover weakens significantly in summer, likely due to weakened air-surface coupling by smaller air-sea temperature contrast, temperature inversions (Kay and Gettelman, 2009) and the relatively subdued cyclogenesis and storm activity (Seneze et al., 1993; Simmonds et al., 2008). Low-level cloud fractions reach a maximum in autumn and cloud cover differences between sea ice and open water begin to show up again, with more cloud cover over the marginal seas than further north over the Arctic Ocean. Low cloud fractions over the GIN and Barents Sea remain higher relative to the central Arctic in all seasons because of the location of the major storm tracks that cross these areas.

To isolate the effects of leads on clouds, we examine the occurrence of “cloud plumes” defined as the first layer of clouds above surface with a base height below 750m (see Methods). The idea is to only capture clouds that are likely influenced directly by leads through moisture or turbulent fluxes from leads. The co-location with leads of any stage in their lifecycle) or compact sea ice is determined from the ICESat-2 cloud and sea ice products (see Methods). The cloud plume fraction over leads is lower than over sea ice floes in most places, but the differences are smaller in some areas, such as to west of the Banks Island and in the Beaufort Gyre (Fig. 2). Over the entire Arctic region, the mean cloud plume fraction over leads is 0.28 compared to 0.37 over sea ice floes. The cloud dissipating effects of leads range from -0.2 to 0 in most of the 200 × 200 km² grid boxes containing sea ice, with a peak occurrence at -0.1 (Fig. 3). Over 3% of the boxes have dissipating effects over -0.2. This result suggests that as new leads freeze quickly in winter, the overall dissipating effects of the newly frozen leads on clouds dominate in the Arctic Ocean. If all low-level clouds (not just plumes) below 2 km are included, a larger dissipating effect of 0.17 is found, with a mean low-level cloud fraction of 0.32 over leads and 0.48 over sea ice. The observations of leads and clouds from ICESat2 do not support the common assumption of increased cloudiness from leads on the pan-Arctic Ocean scale, which corroborates the findings by Li et al. (2020) using different sea ice lead and cloud observations.

About 50% of the grid boxes covered with sea ice has lead effect weaker than -0.1 and 8% of the grid boxes has lead effect weaker than -0.05. The grid boxes with less negative lead effect on cloud plume fraction occurs in the areas that exhibit strong sea ice deformation (Herman & Glowacki, 2012; Hutter & Losch, 2020; Zhang, 2021). The areas with stronger sea ice deformation are favorable for producing more new, open leads and maintaining the open leads longer. This provides more moisture to the atmospheric boundary layer and increases cloud plume fraction. With more new and longer lasting open leads, the increase in cloudiness from their cloud plumes can compensate for the drying and dissipating effects of the newly frozen leads in these areas.

Although the mean vertical profile of lead effect does not have an as pronounced low-level peak as the vertical profiles of cloud fraction, the lead effect is still most evident in low levels below 2 km from the grid boxes with strongest and weakest lead effect. Here, we examine the vertical profile of lead effect in the grid boxes from the two ends in the lead effect distribution in Fig. 3. Relative to the mean profile of lead effect, in the grid boxes in the first quartile (smaller absolute values of lead effect in Fig. 3), leads are associated with more clouds at all levels and the low-level differences are more than twice of the differences above 2 km (Fig. 4). Positive values indicate the production of clouds by the open leads. Relative to the mean profile of lead effect, in the grid boxes in the fourth quartile (stronger dissipating lead effect), the reduction in cloud fraction is seen at all levels with the most decreases below 2 km.

Overall, the cloud dissipating effect is demonstrated by a strong local effect in the vicinity of leads and reduces cloudiness over leads by 0.14 (30%) at low levels below 2 km, 0.18 (48%) at middle levels from 2 km to 6 km, and 0.07 (34%) at high levels above 6 km. Besides the strong local effect, the presence of leads has significant influences on the Arctic-wide cloudiness as well. Taking into account of the spatial coverage of leads, the pan-Arctic mean cloud fraction including cloud profiles over both leads and sea ice is lower than the mean cloud fraction over sea ice, by 4% at low levels, 6% at middle levels, and 5% at high levels.

Discussion And Conclusions

Using collocated ICESat-2 cloud and sea ice information we find a strong impact of leads on the Arctic cloudiness in cold months from December to April. Open leads in high sea ice deformation areas enhance low-level clouds, while refrozen leads tend to reduce low-level cloudiness. The cloud dissipating effect dominates on spatial scales larger than hundreds of kilometers. Both cloud generating effect from open leads and the cloud dissipating effect from newly frozen leads are most evident in the low level below 2 km. The net lead effect is relatively uniform with height up to 6 km as a result of the compensating effects in low levels. Despite the small spatial coverage of leads, their presence leads to decreases of the pan-Arctic cloudiness ranging from 4% at low levels to 6% at middle levels, due to the strong local effect in the vicinity of leads. Our study adds to an emerging body of research that shows that leads are critically important for clouds. It provides strong support for prior more limited studies that challenge the conventional wisdom that associates Arctic leads with increases in cloud fraction.

Currently, lead effect on the cloudiness in the Arctic have not been parameterized in global models and are difficult to resolve in most regional models. Neglecting the lead drying effect in climate models and global reanalyses may contribute to the substantial biases and uncertainties in the modeled wintertime cloud cover, especially low cloud over in the Arctic (Kay et al., 2012, 2016; Y. Liu & Key, 2016). Most previous efforts to parameterize the lead effect...
assume open leads using a mosaic approach (Zulauf & Krueger, 2003). The findings of this study suggest that the frequency of occurrence and lifetime of both open and frozen leads need to be included to properly parameterize the lead effect. The coincidence between the spatial distribution of lead effect and the sea ice deformation suggests the sea ice deformation is likely a key proxy to estimate the subgrid-scale lead effect on clouds.

The lead effect above the atmospheric boundary layer is evident when only leads and clouds on the east side of surface high pressure system are considered (Li, Krueger, Strong, & Mace, 2020). The high vertical extent of the lead effect (Fig. 3) suggests that the lead effect can potentially be involved with processes above the boundary layer and interact with the cyclones in the Arctic. The longwave cloud radiative heating of the warm front may help keep leads open to produce more clouds, while the cold and dry air behind the cold front may speed up the freezing of leads and enhance the lead drying effects. The contrasting behavior of leads during the passage of Arctic cyclones is another factor to consider when accounting for the total lead effect on clouds and the nearby surface energy budget.

To assess the net effect of lead cloud interaction as a potentially important climate feedback, models that accurately represent this interaction need to be constructed. At this point, we can only speculate on important parameters and outline questions to answer. As the climate warms further and sea ice thins, winter sea ice will become more mobile and subject to increased deformation. There is solid evidence that sea ice speed has increased and deformation is increasing (Rampal et al., 2009; Spreen et al., 2011; Itkin et al., 2017). Whether the “open water cloud producing” or the “refrozen cloud dissipating” effect will ultimately dominate, will depend on the timing and frequency of new lead formation and the state of other surface energy budget parameters that determine how quickly the leads refreeze. While a warming climate may produce more deformation and open leads, it also takes longer for the refrozen ice cover on leads to grow thick enough to effectively reduce the sensitive heat flux and the dissipating effects on cloudiness. However, given that current high deformation areas such as the Eastern Beaufort Sea are currently net cloud enhancers, it appears likely that with increased deformation the cloud enhancing effect of leads may dominate. Given that low clouds constitute a positive feedback on the surface energy balance in winter (Schweiger & Key, 1994; Cronin & Tziperman, 2015), the resulting feedback mechanism would likely further reduce sea ice.

**Declarations**

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**Methods**

The ICESat-2 sea ice height (ATL07) product provides along track information of surface height and type from the 6 laser beams in ice covered polar seas (Kwok et al. 2019a). We only use the three strong beams to be consistent with the choice of the ICESat-2 cloud product ATL09. The ATL07 product assigns surface type and surface height for segments of the 150 geolocated photons in each beam. The strong beams of the ICESat-2 are capable of detecting surface segments of specular leads with the length of meters. Following Petty et al. (2021), adjacent surface segments of sea surface are connected to identify leads. The total length of the adjacent lead segments is used as the lead width for simplicity, although the leads are not always perpendicular to the ground track of satellite. The cloud mask is derived from the calibrated backscatter and cloud characteristics ATL09 data product (Palm et al. 2019). The ICESat-2 ATLAS laser shots are summed to 25 Hz profiles in ATL09, which corresponds to a horizontal resolution of 280 m for atmospheric retrievals. Each profile contains the top and bottom height of up to 10 cloud layers. The cloud mask is created using the height of cloud boundaries on the ATL09 vertical grid with a resolution of 30 m.

To examine the clouds associated with leads, we use cloud profiles direct over leads and close to leads to account for downwind cloud plume development and moistening of the atmospheric boundary layer. The cloud profiles are collocated with leads and sea ice segments using their time stamps. This simple approach includes profiles from the upwind side, which will reduce the differences in cloud fraction over leads and sea ice but circumvent the difficulties in matching the local winds with the lead orientation and the direction of the ICESat-2 ground tracks. To simplify the problem further, we used fixed distance, or “plume search distance” on both side of the lead along the ICESat-2 ground tracks. The robustness of the simplified approach is examined by comparing results using three plume distance, 500 m, 1 km, and 2 km. The cloud fraction over sea ice is constructed using only profiles that collocate with sea ice segments of the ATL07 data and does not include the profiles when the underlying surface features cannot be identified due to the attenuation of laser beams. To focus on clouds that are likely directly associated by leads, we define a “cloud plume” as clouds detected in the lowest layer by ICESat-2. This corresponds to a maximum cloud base height of 750 m which corresponds to the typical low-level cloud base height observed by ground-based cloud radars at Arctic observatories (Shupe et al., 2011). The frequency of occurrence of the ICESat-2 profiles containing cloud plumes is defined as the “cloud plume fraction”. The sensitivity to the choice of maximum cloud base height is examined and discussed in Uncertainty Analysis.

The surface features, sea ice and leads, and their associated cloud profiles are gridded on a Lambert Azimuthal Equal Area grid centered at the North Pole, with a grid spacing of 200 km × 200 km. The gridded mean cloud fraction over leads and flos are computed using the mean cloud fraction over individual surface features weighted by their width. Three years of the ICESat-2 observations of over 5000 granules from October 2018 to April 2021 are used in this study. The most recent version of the ICESat-2 data, R004, is used, which fixed the erroneous, sometimes negative, surface segment length in the previous version of the ATL07 dataset. A mask is applied using the number of ATL09 profiles over sea ice normalized by the number of granules in each grid box to remove poorly sampled grid boxes with broken water ways, such as over part of the Canadian Archipelagos east of the Banks Island.
In the Arctic, the clouds are closely associated with the synoptic weather conditions (Stramler et al., 2010; Barton et al., 2014; Z. Liu & Schweiger, 2017). The connection between the occurrence of leads and synoptic conditions may introduce differences in cloud fraction over leads and sea ice that are unrelated to the effects of leads on clouds. Li et al. (2020) focused on leads and clouds from the east side of surface high pressure system to limit the influence of synoptic conditions. To mitigate this problem and include lead effects in all synoptic conditions, we compute the differences in cloud fraction between leads and sea ice for each ICESat-2 granule in the 200 × 200 km² grid boxes and use the cloud fraction differences of each granule to compute the mean lead effect. In this way, the sampling biases due to the synoptic variability of clouds and leads are mostly removed. Without lead effect on clouds, the mean lead effect computed using this method will be zero regardless of the synoptic variability of leads and clouds. The biases due to synoptic variability of leads and clouds can be found by comparing the lead effect computed using this method and computed using the differences between the mean cloud fraction over leads and sea ice. Compared to the mean lead effect, the biases due to synoptic variability are negligible even if the second approach is used (not shown).

Uncertainty Analysis

The observations of Arctic clouds from space are challenging for both passive microwave sensors and active sensors. The ICESat-2 also suffers from the same difficulties faced by other space-borne lidars such as the CALIOP on board CALIPSO. The ICESat-2 ATLAS will not detect surface and low-level clouds under an opaque cloudy scene due to the attenuation by cloud particles. Such opaque clouds are usually associated with liquid clouds or synoptic conditions such as the warm sector of Arctic cyclones instead of the low-level plumes and boundary layer clouds around leads. We would not expect the lead effect on clouds in cold months to be biased by excluding these profiles.

The height segment sea surface height flag is used to classify leads and sea ice in the ICESat-2 ATL07 data product. The leads identified using this flag include both specular leads and dark leads. Under cloudy scenes, some dark leads might be misclassified due to the lower photon rate due to the attenuation by clouds and there is ongoing research to address this issue in the future version of the ATL07 data (Kwok et al., 2021). The inclusion of the misclassified “dark leads” under clouds results in an overestimation of cloud cover near leads. Without this bias, the overall drying effects of leads on cloudiness in the pan-Arctic Ocean scale will be more evident.

Because the lead plume search distance does not match the actual extent of the lead effect from cloud plume or the drier internal boundary later, the lead effect is underestimated. The inaccurately defined cloud plumes misclassify clouds over leads to over sea ice, or vice versa, which decreases the differences in cloudiness over leads and sea ice and leads to underestimation of lead effect. In addition, the cloud plume fraction associated with leads includes profiles from the upwind side where a lead is not expected to influence the cloud directly. The average cloud plume fraction defined this way will likely underestimate lead impacts. A more rigorous delineation of cloud profiles that includes wind direction and lead orientation would likely emphasize our findings and show an even stronger lead impact.

The smaller cloud plume fraction over leads than over sea ice on the pan-Arctic Ocean scale is robust with different threshold of maximum cloud base height as well as different plume search distances (Table 1). The domain mean differences decrease with increasing lead plume search distance because more cloudy profiles over sea ice are accounted as lead plumes. As the cloud base height threshold increases from 500 m to 1 km, the cloud plume fraction over leads increased by 0.04 on average while the cloud plume fraction over sea ice decreased by 0.08, which produces larger cloud fraction differences between sea ice and leads.

Table 1. The mean differences in wintertime cloud plume fraction over leads and sea ice in the Arctic using ICESat-2 observations from 2018 to 2021.

| Cloud base height threshold | Lead plume search distance |
|-----------------------------|---------------------------|
|                             | 0 m | 500 m | 1 km | 2 km |
| 500 m                       | -0.11 | -0.07 | -0.06 | -0.05 |
| 750 m                       | -0.13 | -0.09 | -0.08 | -0.07 |
| 1000 m                      | -0.15 | -0.11 | -0.10 | -0.09 |

Data Availability

The ICESat-2 datasets are hosted by the National Snow and Ice Data Center for public access. The ATLAS/ICESat-2 L3A Sea Ice Heights product version 4 is available at the ATL07 webpage (https://nsidc.org/data/ATL07) and the L3A Calibrated Backscatter Profiles and Atmospheric Layer Characteristics product is available at the ATL09 webpage (https://nsidc.org/data/ATL09).

Code Availability

The codes used to process and analyze the ICESat-2 data to produce the results here are available from the GitHub page of this study (https://github.com/liuzheng-arctic/lead-effect).

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**Figures**
Figure 1

Seasonal Distribution of Low Cloud Fraction from ICESat-2. The occurrence of low-level clouds (color) in the Arctic in winter (upper left), spring (upper right), summer (lower left), and autumn (lower right) using ICESat-2 observations from October 2018 to April 2021.
The Lead effect on Clouds in Cold Months. The mean cloud "plume" fraction of the lowest cloud layer over leads (left), sea ice (middle), and their differences (right) in the Arctic using ICESat-2 observations in cold months, from December to April, for three years since 2018. The cloud "plume" is defined as the lowest layer of cloud with a cloud base below 750 m and within the along-track distance of 1 km around the lead in the ICESat-2 observations. The color scale in c) is not centered to highlight the areas where the two effects nearly cancel.

Figure 3

The histogram of lead effect in cold months. The histogram of mean lead effect of in the Arctic using ICESat-2 observations in cold months, from December to April, for three years since 2018. The lead effect is defined as the difference of cloud plume fraction over leads from over sea ice. The cloud "plume" is defined the same as in Fig. 2.
Figure 4

The Vertical Profile of Lead Effect on Clouds in Cold Months. Left: The mean vertical profiles of cloud fraction over sea ice (blue), leads (green), and their differences (lead-sea ice; red). Right: The differences of the mean lead effect profiles in grid boxes from the first quartile (weak; black solid line) of lead effect on cloud plume fraction in Fig. 3 and in grid boxes from the fourth quartile (strong; black dashed line), relative to the mean vertical profiles of cloud effect in all grid boxes covered by sea ice (red line on the left). The ICESat-2 observations in cold months, December to April since 2018, are used to compute the mean profiles.