RESEARCH ARTICLE

Relationship between specular returns in CryoSat-2 data, surface albedo, and Arctic summer minimum ice extent

R. Kwok, G. F. Cunningham and T. W. K. Armitage

Specular (mirror-like) reflections in radar altimeter returns are sensitive indicators of flat open water in leads and melt ponds within the Arctic sea ice cover. Here we find increased specular and near-specular returns in CryoSat-2 waveforms as the sea ice cover transitions from a high albedo snow-covered surface to a lower albedo surface dominated by ponds from snow melt. During early melt, mid-May to late June, increases in fractional coverage of specular returns ($F_{SR}$) show spatial correspondence with concurrent decreases in albedo. To examine the utility of $F_{SR}$ we compared its efficacy with that of satellite-derived albedo in forecasting summer minimum ice extent (SMIE). Regression analysis of the area-averaged $F_{SR}$ ($\bar{F}_{SR}$) (2011–2017) shows that ~72% of SMIE variance can be explained by the dates when $\bar{F}_{SR}$ climbs to 0.5 within two latitudinal bands covering 70–80°N and 80–90°N. The lag between the two crossing dates provides a measure of the relative rate of the poleward progression of melt. Approximately 93% of SMIE variance can be explained by the date when albedo drops to 0.6 in these same latitudinal bands. Standard errors for these regressions are 0.37 and 0.19 × 10^6 km², respectively. Calculating the regression coefficients using only 2011–2016, the 2017 SMIE was forecast with residuals of 0.06 (2% of the total extent) and −0.17 × 10^6 km² (~4%). Using only 2011–2015 yielded residuals that are less than 0.5 × 10^6 km² (~10%).

1. Introduction

As incident solar radiation increases and the air warms during the onset of summer, the Arctic sea ice cover undergoes a spectacular transformation from a high albedo (>0.8), snow-covered surface during the winter months to a lower albedo surface dominated by melt ponds and open leads. Perovich and Polashenski (2012) divided the surface changes into distinct stages beginning with the wetting of the winter snow layer and the appearance of ponds as meltwater accumulates on the surface. Several weeks after the onset of melt and rapid increase in pond coverage, melt pond drainage occurs when the higher ice permeability and number of open macroscopic flaws during this stage allow water to be lost to the ocean. As a result of drainage, pond coverage drops significantly on first-year ice, where melt ponds are more extensive and shallower, but only slightly on multiyear ice, where thicker and more deformed ice can retain more surface meltwater. Following this stage, pond coverage continues to increase until the seasonal maximum is reached. The variability in the rate of progression through these stages of melt, however, has received less attention likely due to the lack of direct measurements of pond coverage.

A recent study by Schröder et al. (2014), using a melt pond model with more realistic process representations that include surface topography development (Scott and Feltham, 2010), showed that spring melt pond coverage is a skillful predictor of summer minimum ice extent (SMIE). This skill is thought to be derived from improved simulation of the positive albedo feedback in response to pond formation: reduced surface albedo leads to increased absorption of solar radiation, increased ice melt, and enhanced melt pond formation. These results suggest that variability in the spatial and temporal development of surface albedo, an expression of the initial state of the ice cover and the atmosphere/ocean forcing during the summer, could be useful indicators for SMIE forecasts. Despite this potential, and increased interest in more accurate seasonal sea ice forecasts (Eicken, 2013), we are not aware of any published investigation that utilizes retrieved surface albedo in a statistical forecast of SMIE. This may be due to the infrequent satellite retrievals of surface albedo due to clouds during the melt season, solar elevations at polar
lattitudes, and the latency of these retrievals for use in forecasts. Instead, passive microwave brightness temperatures have been used to provide signals of melt (e.g., onset dates) for the forecast of SMIE (e.g., Petty et al., 2017) rather than measures from albedo changes.

Specular returns from the sea ice cover in CryoSat-2 (CS-2) waveforms are robust indicators of smooth open water or thin ice in leads and melt ponds within the radar-altimeter footprint. This type of distinctive return, easily identified in altimetric waveforms, has been used effectively in ice/water discrimination (e.g., Peacock and Laxon, 2004; Laxon et al., 2013; Armitage and Davidson, 2014) and the identification of local sea levels for the calculation of sea ice freeboard (e.g., Kwok and Cunningham, 2015). Hence, we expect that changes in the density of specular returns in CS-2 data can be compared to surface albedo, as both are dominated by development of melt pond coverage during the melt season.

In this paper, we examine the fractional coverage of specular returns \( F_{\text{sw}} \) as an indicator of open water coverage on the ice cover. The utility of \( F_{\text{sw}} \) is demonstrated by comparing the relative effectiveness of using \( F_{\text{sw}} \) and surface albedo for statistical forecasting of summer minimum ice extent (SMIE). After describing the datasets used (Section 2), we describe the computation of \( F_{\text{sw}} \), the comparison of the time-varying spatial patterns of \( F_{\text{sw}} \) with the development of area-averaged surface albedo during summer, and the skill of using \( F_{\text{sw}} \) and surface albedo to the forecast of the SMIE (Section 3), ending with discussion and conclusions (Section 4).

2. Data Description


We used radar data acquired by the Synthetic Aperture Radar (SAR) Interferometric Radar Altimeter (SIRAL) instrument on CryoSat-2 (CS-2) (Wingham et al., 2006). The altimeter waveforms (Release C) are available through ESA’s data portal (URL: https://earth.esa.int). The synthesized footprint of SIRAL in SAR operation is nominally 0.31 km by 1.67 km in the along- and across-track directions. specular and near-specular returns within the radar footprint are identified using the combined peak power and width at the half-power point of the first return; the details of this approach are described by Kwok and Morison (2016), where they used the procedure to retrieve the heights of the sea surface over ice-covered oceans. Specular and near-specular returns from areas of open water much smaller than the radar footprint typically dominate and mask out diffuse returns from the surrounding ice cover (Drinkwater, 1991), making SIRAL returns highly sensitive to the presence of surface water. Section 3.1 provides a more detailed discussion of the sources of specular returns during early melt.

2.2. Surface albedo fields (2011–2017)

Weekly-mean surface albedo fields of Arctic sea ice (on a 15-km map grid), between 2011 and 2017, are from EUMETSAT’s Satellite Application Facility on Climate Monitoring (CM SAF CLARA-SAL data set). The retrievals are based on the aggregation of radiance data acquired by the Advanced Very High Resolution Radiometer (AVHRR) instrument on board polar-orbiting NOAA and Metop satellites (Karlsson et al., 2012). Raw radiances are corrected for atmospheric, radiometric, and topographic effects and are expanded into hemispherical spectral albedos before shortwave albedo is obtained using a narrow-to-broadband conversion. Expected uncertainty in the albedo estimates is around 5% (or 0.05), and retrievals of temporal mean area-averaged albedo derived from only a few observations are vulnerable to errors in cloud masking. The reader is referred to Karlsson et al. (2012) for a more detailed description of this product.

2.3. Sea ice extent and high resolution imagery

In CS-2 data, we used specular and near-specular returns to show the relationships between specular returns, albedo, and SMIE. The comparison of the time-varying spatial patterns of \( F_{\text{sw}} \) with the development of area-averaged surface albedo during summer, and the skill of using \( F_{\text{sw}} \) and surface albedo to the forecast of the SMIE (Section 3), ending with discussion and conclusions (Section 4).

3. Methods and Results

In this section, we discuss the sources of specular returns in the CS-2 data during early melt, followed by a description of the computation and interpretation of \( F_{\text{sw}} \). The time-varying spatial patterns of \( F_{\text{sw}} \) are then compared to the development of surface albedo during summer. Last, we assess the skill of \( F_{\text{sw}} \) and surface albedo for forecasts of the summer minimum ice extent (SMIE). The objective is to show the relationships between \( F_{\text{sw}} \) albedo, and SMIE.

3.1. Sources of specular returns

During early melt, the period of interest in this work, the surface is composed of open leads and a melting snow cover with increasing coverage of ponds. Specular returns from open leads have been used as a source of sea surface height within the ice cover during winter and summer (e.g., Kwok and Morison, 2016), and also during early melt. The smooth open water surfaces of melt ponds are another source of specular returns as melt progresses and likely the main contributor to the large increases in specular returns seen in early melt. The melting snow surfaces tend to remain rough compared to water surfaces or the wavelength of the radar: ~2 cm, and thus their returns are expected to remain diffused and hence not specular. Away from the marginal ice zone at this stage of melt, the contribution of open leads to the increases in specular returns is not expected to be significant as the break-up of the ice cover does not typically occur until later in the melt season (late July to August). However, in our analysis, specular returns from open leads and melt ponds are indistinguishable from each other; we are not aware of any investigation in the published literature that has characterized the evolution of the relative coverage of open water in leads and ponds after the onset of melt.

In CS-2 data, we used specular and near-specular returns that span a range of 25 dB (~300 times in return power) above the surrounding ice cover (Kwok and Morison,
2016), which translates roughly into a potential sensitivity to specular areas covering less than ~40 m² (i.e., 300 times smaller than the first Fresnel Zone area of ~12,468 m² calculated using the radar altitude and frequency). Even though the specular returns are sensitive to small areas of open water, these returns could be from individual melt ponds (with scales of meters) as well as from the surfaces that contain a collection of ponds and leads.

### 3.2. Fractional coverage of specular returns ($F_{SR}$)

We define $F_{SR}$ as the fractional coverage of specular returns within 25-km segments of CS-2 ground tracks, which are sampled by ~80 contiguous synthetic aperture footprints at a spacing of ~300 m. $F_{SR}$ varies between 0 and 1. Even though the radar returns are highly sensitive to the presence of open water or thin ice, $F_{SR}$ is not an accurate indicator of ice concentration because, as mentioned above, specular returns from areas of open water much smaller than the radar footprint tend to dominate and mask diffuse scattering from the surrounding ice cover. Hence, $F_{SR}$ tends to underestimate ice concentration or overestimate open water fraction.

The maps in Figure 1a show gridded (50 km) composites of $F_{SR}$ constructed from all 25-km along-track segments for consecutive 15-day periods (~210 CS-2 orbits) between June and July for seven years (2011–2017). North-south striping in the composites (see, e.g., 15–30 June 2014) are due to combining data that sampled the surface at different times, as melt progresses rapidly poleward within the 15-day intervals. For each year, the space-time progression of melt is evident in the $F_{SR}$ composites. In early June, $F_{SR}$ is low (~0.1) over most of the central Arctic but slightly higher (~0.2) over the thinner, more deformable ice, with lower ice concentration occupying the peripheral seas (Beaufort, Chukchi, East Siberian and Laptev Seas). As the snow cover melts and ponds develop when the air temperature climbs with the onset of summer, the number of specular returns increases dramatically in the lower latitudes ($F_{SR} > 0.8$). Given the temporal coarseness of the composites, these fields are not able to capture the finer details of the initial stages of surface melt (e.g., decreases in pond coverage associated with drainage) described by Perovich and Polashenski (2012). Increasing $F_{SR}$ progresses from south to north as solar illumination increases and the Arctic warms, peaking after 15 July with high $F_{SR}$ observed over large regions of the Arctic. $F_{SR}$ begins to return to winter values at the end of the summer, progressing southwards as the temperature falls.

This seasonal evolution is also illustrated in the seasonal cycle of area-averaged $F_{SR}$ ($F_{SR}$) within two latitudinal bands: 70–80°N and 80–90°N (Figure 2c) to contrast the progression of melt between the lower and higher latitude Arctic Ocean. As pond coverage increases steadily, higher $F_{SR}$ (>0.8) is seen over most of the Arctic Ocean by the latter half of July, with the higher latitudes lagging the lower latitudes by ~16 days (average over 2011–2017). As the ice cover remains relatively compact during early melt (i.e., low lead fraction), increases in surface water coverage due to melt ponds dominate (see also examples of imagery in Figure 3) while the ice concentration remains high (average ice concentration within the ice in June for seven years is ~96%). By the early half of September, $F_{SR}$ begins its downward trend in the central Arctic and expands southwards as surface meltwater disappears as the air temperature falls.

### 3.3. Comparison of time-varying fields of $F_{SR}$ and surface albedo

To assess the similarity between $F_{SR}$ and albedo fields, we compared the time-varying spatial patterns and the interannual variability of the $F_{SR}$ composites with fields of surface albedo. For this, we constructed gridded albedo composites (Figure 1b) with the same temporal sampling as the $F_{SR}$ composites, i.e., consecutive 15-day periods for seven years (2011–2017). Only the June and July composites are shown in Figure 1. The albedo composites do not cover the month of September due to reduced retrievals as the sun begins to set in high Arctic latitudes. In contrast, the $F_{SR}$ composites span the entire melt period because the CS-2 radar acquisitions are not sensitive to clouds or solar illumination of the surface, though they are less useful in winter.

Although there are differences, the large-scale correspondence between the spatial patterns of the $F_{SR}$ and albedo composites is clear during June and early July (spatial correlations of the 15-day fields are shown in Figure 1b). During early melt, these fields are negatively correlated where increases in $F_{SR}$ correspond to decreases in albedo due to higher pond coverage associated with melt. It is not expected that these fields should have exact correspondence. Differences between the 15-day $F_{SR}$ and albedo composites can be attributable to: 1) the sparsity in altimeter footprints and albedo retrievals during summer; 2) the lack of spatial and temporal coincidence between the two measurements; and 3) the saturation of $F_{SR}$ at low albedos (at ~0.6). Past mid-July, spatial correlations with the albedo composites are reduced and become spurious (see correlation values in Figure 1) as the $F_{SR}$ composites become largely saturated as $F_{SR}$ becomes insensitive to further increase in melt pond coverage. More quantitatively, Figure 2a and 2b compares the evolution of $F_{SR}$ and albedo over seasonal (i.e., multiyear ice fraction [MYF] < 0.7) and multiyear ice (MYF ≥ 0.7), and Figure 2c shows their seasonal cycle in two latitudinal bands: 70–80°N and 80–90°N. $F_{SR}$ climbs to >0.9 in seasonal ice but only to ~0.8 in multiyear ice. Similarly, area-averaged albedo ($\bar{\alpha}$) falls to 0.6 in seasonal ice, and only to ~0.5 in multiyear ice. These behaviors are consistent with lower melt pond coverage over older ice in higher latitudes (i.e., lower $F_{SR}$ and higher albedo).

$F_{SR}$ and albedo can also be used to identify dates delineating the progress of the melt season. Figure 2d shows the dates at which $F_{SR}$ climbs/falls to 0.5, and the dates at which $\bar{\alpha}$ falls to 0.5 in the two latitudinal bands. The selection of 0.5 as a threshold is somewhat arbitrary but is discussed further below. These two dates from $F_{SR}$ can be used to calculate the duration over which $F_{SR}$ remains above 0.5 (we designate as the duration as $D_{0.5}$). Figure 2d shows that 2013 has both the shortest $D_{0.5}$ for both latitudinal bands and the lowest excursions of $F_{SR}$ and albedo during the summer in the 7-year record.
Figure 1: Gridded 15-day composites of specular returns fraction and albedo between June and July (2011–2017). Correlation between the two composites of (a) specular returns fraction ($F_{SR}$) and (b) albedo ($\alpha$) are shown in the bottom left corner of the images in (b). After mid-July (below the dashed line), $F_{SR}$ saturates and the correspondence between the two composites is reduced. DOI: https://doi.org/10.1525/elementa.311.f1
A closer examination of 2013 (composites in Figure 1a and b) shows that there were large areas of lower \( F_{SR} \) and higher albedo over the central Arctic ice cover throughout much of the 2013 melt season, indicative of lower melt pond coverage compared to other years. The notably higher albedo in 2013 in late June through August (compared to other years) can be seen in the high-resolution visible-band imagery in Figure 3: there was a complete absence of melt ponds on 20 and 21 August (in 2013) at a location just north of Ellesmere Island, whereas imagery from 22 August 2011, 16 August 2012 and 18 August 2014 all show at least partial melt pond coverage at the same location (map in Figure 3 shows location of the imagery).

The impacts of the anomalous surface melt conditions on the ice cover in summer 2013 were discussed by Kwok and Cunningham (2015), Tilling et al. (2015), and Kwok (2015). In addition to the cooler summer air temperatures in 2013 (compared to 2011–2014 averages), Kwok (2015) also noted anomalously strong mechanical convergence of the ice cover against the Canadian Arctic Archipelago (CAA) due to persistent on-shore winds, which resulted in a net area decrease of ~23% between June and August. Cooler air temperatures and closing of the ice cover reduced ice melt and the impact of openings on air temperatures (i.e., lower albedo and reduced ice-albedo feedback) in the ice cover. The estimates of \( F_{SR} \) and albedo in this region (Figure 1) are consistent with the reported behavior. Also of note is the joint behavior of \( F_{SR} \) and \( \alpha \) in 2017, which reveals a cooler eastern Arctic during most of the summer. The above comparison with albedo suggests that \( F_{SR} \) is sensitive to surface melt and is a useful geophysical parameter.

### 3.4. Summer minimum sea-ice extent (SMIE): Regression analysis

Here, we compare the relative utility of \( F_{SR} \) and surface albedo by examining the relationship between \( F_{SR} \) and albedo and the Arctic SMIE, then assess the skill of using \( F_{SR} \) and \( \alpha \)
Figure 3: Available high-resolution optical imagery of sea ice north of the Canadian Arctic Archipelago and Greenland. The map (a) shows the location of the imagery in (b). Each high-resolution (1 m) image is 2 km on a side. The imagery used here is described by Kwok (2014) and available through the Global Fiducials Library at USGS (URL: http://gfl.usgs.gov/). DOI: https://doi.org/10.1525/elementa.311.f3

To forecast SMIE, we considered two models wherein the SMIE is dependent on threshold-crossing dates derived from the composites of $F_{sr}$ and surface albedo ($\alpha$):

$$ SMIE(x) = a\Phi_{sr,L}(x) + b\Phi_{sr,H}(x) + c, $$

and

$$ SMIE(y) = d\Lambda_{L}(y) + e\Lambda_{H}(y) + f. $$

The terms $\Phi_{sr,L}(x)$ and $\Phi_{sr,H}(x)$ are the dates at which $F_{sr}$ climbs above the threshold $x$ in the two latitudinal bands, designated here by $L$ (lower, corresponding to the $70$–$80^\circ$N band) and $H$ (higher, corresponding to the $80$–$90^\circ$N band). Similarly, we define $\Lambda_{L}(y)$ and $\Lambda_{H}(y)$ as the dates at which $\bar{\alpha}$ falls below the threshold $y$ in the same two latitudinal bands $L$ and $H$; $a$, $b$, $c$, $d$, $e$, and $f$ are linear coefficients.

These two linear models are used to examine the relationship between SMIE and the progress of surface melt as informed by the crossing dates of the $F_{sr}$ and $\bar{\alpha}$ thresholds (i.e., $x$ and $y$) for the two latitudinal bands during early melt.

Figure 4a and b summarizes results from the regression of SMIE against the independent variables in Equations (1) and (2) for the years 2011–2017. To assess the sensitivity of the regression model, we varied the $F_{sr}$ and $\bar{\alpha}$ thresholds (i.e., $x$ and $y$) for determining the crossing dates $\Phi_{sr,L}(x)$, $\Phi_{sr,H}(x)$, $\Lambda_{L}(y)$, and $\Lambda_{H}(y)$. The regression analysis was carried out for $x = 0.4$, $0.5$, and $0.6$ and for $y = 0.5$ and $0.6$.

As a measure of the fraction of explained variance in the
regression analysis, we show both the squared correlation $\rho^2$ as well as the adjusted squared correlation $\rho^2_A$, where $\rho^2_A$ is always less than $\rho^2$. The adjusted measure takes into account automatic increases in $\rho^2$ when more than one explanatory variable is added (Draper and Smith, 1998), and is based on the number of explanatory terms relative to the number of data samples. For the above — SRF and $-\alpha$ thresholds, the best regression results (i.e., estimated SMIE; Figure 4) were obtained with $x = 0.5$ and $y = 0.6$, where the models explain $\sim$72/57% and 93/89% ($\rho^2/\rho^2_A$) of the variance in SMIE, with standard errors of $0.37 \times 10^6$ km$^2$ and $0.19 \times 10^6$ km$^2$, respectively (the crossing dates for these two cases can be found in the Appendix). For the seven years (2011–2017), the mean crossing dates are 10 June (day of year = 161) and 26 June (177) for $F_{SR,L}(x)$ and $F_{SR,H}(x)$, and 5 June (156) and 19 June (170) for $-\alpha$. Not unexpectedly, in all cases examined, the linear model using the albedo crossing dates was able to explain higher percentages of the SMIE variance than the one using the SRF crossing dates, as the albedo fields provide denser coverage of the surface and are a more direct representation of the pond coverage. Figure 4e shows the crossing dates for these two cases and compares the regression results with the observed SMIE.
3.5. SMIE forecasts with regression models
To examine the effectiveness of the observed crossing dates in forecasting SMIE, we forecast the 2017 SMIE with linear coefficients from a regression analysis using only the crossing dates from 2011–2016 (i.e., excluding 2017). Similar to above, the best regression results for the six years were obtained with $x = 0.5$ and $y = 0.6$ (Figure 4c and 4d). The two models explain $-79/65\%$ and $93/88\%$ ($p^2 / \bar{p}^2$) of the variance in SMIE, with standard errors of $0.37 \times 10^3$ km$^2$ and $0.22 \times 10^3$ km$^2$, comparable to the results using all seven years of crossing dates. With the observed crossing dates from 2017 and Equation 1, the regression coefficients from 2011–2016 were able to forecast the 2017 SMIE with residuals of $-0.06 \times 10^3$ km$^2$ (2% of the 2017 SMIE) and $-0.17 \times 10^3$ km$^2$ (4%), respectively.

We repeated this analysis using only crossing dates from 2011 to 2015 (i.e., excluding those from 2016 and 2017). Again, the best fit for the five years (not shown here) was obtained with $x = 0.5$ and $y = 0.6$, where the regression models explain $-88/56\%$ and $98/93\%$ ($p^2 / \bar{p}^2$) of the SMIE variance, and were able to forecast the 2016 SMIE with residuals of $0.06/0.31 \times 10^3$ km$^2$, and the 2017 SMIE with residuals of $0.5/-0.07 \times 10^3$ km$^2$, for $F_{st}$ and $\bar{a}$, respectively. These comparisons suggest that during early melt (to ~mid-July), using $F_{st}$ from CS-2 altimeter returns as indicators of open water coverage is comparable to using surface albedo to the extent measured by the explained variance. Further, the low SMIE residuals obtained from the forecasts demonstrate that threshold crossing dates from $F_{st}$ or $\bar{a}$ have potential for SMIE forecast.

4. Discussion and Conclusions
In this paper, we examined the relationship between the fractional coverage of specular returns ($F_{st}$) derived from the CryoSat-2 radar altimeter, surface albedo of the Arctic ice cover, and the summer minimum ice extent (SMIE). Specular reflections in altimeter returns are sensitive indicators of open water in sea ice leads and melt ponds within the Arctic sea ice cover. This is evident in the large concurrent increases in specular returns in CS-2 waveforms and decreases in surface albedo as the sea ice cover transitions from a high albedo snow-covered surface to a lower albedo surface dominated by ponds during early melt (Figure 1). Our analysis addressed the geophysical utility of $F_{st}$ by comparing the relative effectiveness of using $F_{st}$ with surface albedo for forecasting SMIE; results show that both $F_{st}$ and surface albedo can be used to forecast SMIE, as summarized below.

Regression analysis of the area-averaged $F_{st}$ and albedo time series, between 2011 and 2017, shows that ~72% and ~93% of the variance in SMIE can be explained by the dates when area-averaged $F_{st}$ climbs to 0.5 and the area-averaged albedo falls to 0.6 in two latitudinal bands ($70^\circ$–$80^\circ$N and $80^\circ–90^\circ$N). The results suggest that these threshold-crossing dates are effective in capturing the temporal and poleward progress of surface melt, and are useful forecasting SMIE. Excluding 2017 from the analysis, we were able to forecast the 2017 SMIE with residuals of 0.06 (~2% of the total extent) and $-0.17 \times 10^3$ km$^2$ (~4%) (see Figure 4). These residuals are comparable to the top two statistical forecasts of SMIE in June (see SIPN report in https://www.arcus.org/sipn/sea-ice-outlook/2017/post-season). Further, excluding both 2016 and 2017 in our analysis yielded forecast residuals that are less than $0.5 \times 10^3$ km$^2$ for both the 2016 and 2017 SMIE. Even though the CS-2 record is only seven years, the analyses here show the relative robustness of the regression models, whether using the full record or only a truncated portion of it.

In an examination of the summer ice cover of 2013, both the $F_{st}$ and albedo fields (Figure 1) captured the lower pond coverage in the central Arctic that summer, as also evident in the later $F_{st}$ and $\bar{a}$ threshold crossing dates. The surface conditions were associated with cooler air temperatures and a convergent ice cover (noted by Kwok, 2015; Kwok and Cunningham, 2015; Tilling et al., 2015). The reduced summer melt left a thicker ice cover at the end of summer that was significant in the relatively insensitive to clouds and solar illumination. Given this insensitivity and the ~2 day latency of Near Real-Time CS-2 products, both $F_{st}$ and surface albedo (with latency of ~1 week) during early melt may be useful parameters to include in forecasts of SMIE, when they are available around the end of June. We also note that even though large-scale change in albedo during summer melt is a characteristic feature of the sea ice surface, the available satellite-derived albedo fields have not been used directly in statistical forecasts of SMIE to date. Here, we used simple regression models to forecast end-of-summer ice extent and demonstrate the utility of $F_{st}$ and albedo; the results also suggest that a more complex model, exploiting the spatial nature of the satellite data, could be explored to investigate the spatial variability of end-of-summer ice coverage.

Data Accessibility Statement
The CryoSat-2 data set is from the European Space Agency data portal (URL: https://earth.esa.int), the albedo data set is from the EUMETSAT Satellite Application Facility on Climate Monitoring (CM SAF, URL: https://www.cmsaf.eu), and the high-resolution visible imagery is from the Global Fiducial Library (URL: https://gfl.usgs.gov, accessed in January 2017, website currently under revision).

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Competing interests
The authors have no competing interests to declare.
Author contributions

- Contributed to conception and design: RK
- Contributed to acquisition of data: RK, GFC
- Contributed to analysis and interpretation of data: RK, GFC, TWKA
- Drafted and/or revised the article: RK, TWKA
- Approved the submitted version for publication: RK

References


Appendix: Summer minimum ice extent (SMIE) and threshold-crossing dates

The threshold crossing dates discussed in Section 3.3:


SMIE = [4.344, 3.387, 5.054, 5.029, 4.433, 4.137] × 10² km²

Φₛₑₘ(0.5) = [162, 156, 163, 166, 158, 158]; day-of-year

Φₛₑₘ(0.5) = [168, 172, 188, 182, 170, 182]; day-of-year

λₛₑₘ(0.6) = [138, 136, 142, 146, 134, 140]; day-of-year

λₛₑₘ(0.6) = [157, 152, 165, 167, 157, 160]; day-of-year