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Ice, Cloud, and land Elevation Satellite (ICESat) over Arctic sea ice: Retrieval of freeboard

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[1] Total freeboard (snow and ice) of the Arctic Ocean sea ice cover is derived using Ice, Cloud, and land Elevation Satellite (ICESat) data from two 35-day periods: one during the fall (October–November) of 2005 and the other during the winter (February–March) of 2006. Three approaches are used to identify near-sea-surface tiepoints. Thin ice or open water samples in new openings, typically within 1–2 cm of the sea surface, are used to assess the sea surface estimates. Results suggest that our retrieval procedures could provide consistent freeboard estimates along 25-km segments with uncertainties of better than 7 cm. Basin-scale composites of sea ice freeboard show a clear delineation of the seasonal ice zone in the fall. Overall, the mean freeboards of multiyear (MY) and first-year (FY) ice are 35 cm and 14 cm in the fall, and 43 cm and 27 cm in the winter. The increases of ~9 cm and ~12 cm on MY and FY sea ice are associated with the 4 months of ice growth and snow accumulation between data acquisitions. Since changes in snow depth account for >90% of the seasonal increase in freeboard on MY ice, it dominates the seasonal signal. Our freeboard estimates are within 10 cm of those derived from available snow/ice thickness measurements from ice mass balance buoys. Examination of the two residual elevations fields, after the removal of the sea ice freeboard contribution, shows coherent spatial patterns with a standard deviation (S.D.) of ~23 cm. Differencing them reduces the variance and gives a near random field with a mean of ~2 cm and a standard deviation of ~14 cm. While the residual fields seem to be dominated by the static component of unexplained sea surface height and mean dynamic topography (S.D. ~23 cm), the difference field reveals the magnitude of the time-varying components as well as noise in the ICESat elevations (S.D. ~10 cm).

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1. Introduction

[2] At this writing, Ice, Cloud, and land Elevation Satellite (ICESat) has successfully completed ten data acquisition campaigns since its January launch of 2003. Each operational campaign consists of a laser-on period that spans approximately one 33-day subcycle of the 91-day repeat orbit. The interval between campaigns is ~3 months. This sampling strategy is employed to allow for detection of seasonal and interannual changes of the global ice cover. Overviews of the ICESat mission are given by *Zwally et al.* [2002] and *Schutz et al.* [2005]. A compilation of the recent scientific results can be found in a special section on ICESat in the *Geophysical Research Letters*.

[3] The subject of this paper pertains to the use of ICESat data for Arctic Ocean studies. Previous examinations of the ICESat data set of Arctic sea ice given by *Kwok et al.* [2004, 2006] have provided general overviews. Of particular geophysical interest is the potential of obtaining estimates of sea ice freeboard and thickness from the altimetric profiles. Because of the importance of thickness in sea ice mass balance and in the surface heat and energy budget, remote determination of ice thickness at almost any spatial scale has long been desired. Current spaceborne sensors, however, can see only radiation emitted or scattered from the top surface or the volume within the top few tens of centimeters of the ice and do not see the lower surface; this is an obstacle to the direct observations of ice thickness. An alternative approach has been to use altimetric freeboard along with the assumption of hydrostatic equilibrium to determine ice thickness. The first geophysical results of ice freeboard/thickness estimates from spaceborne radar altimeters are given by *Laxon et al.* [2003]. Specular radar returns from open water/thin ice provide the necessary sea surface references: this forms the algorithm basis for derivation of freeboard estimates for the planned CryoSat-2 mission. For ICESat, one approach of freeboard retrieval in

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the published literature is discussed by *Kwok et al.* [2004] and another by *Forsberg and Skourup* [2005]; these are presented as part of an initial assessment of ICESat data. Many investigators are working toward accurate freeboard and thickness retrievals for addressing current gaps and for providing future estimates of these key climate parameters.

[4] The focus of this paper is on the retrieval of freeboard from two Arctic Ocean ICESat data sets, one acquired during the fall of 2005 and the other during the winter of 2006. The objectives are to provide a detailed description of the geophysical issues and to determine what is achievable in terms of the estimation of this parameter. The topic of conversion to sea ice thickness is not addressed. A crucial first step is to identify local tiepoints of the sea surface in the altimeter data because of the large uncertainties our knowledge of sea surface height compared to that required for accurate determination of freeboard. We offer three approaches for acquiring such tiepoints. The geophysical basis for identifying such points and the uncertainties associated with their acquisitions are addressed. The first approach uses young ice in new openings identified in ICESat profiles and SAR imagery while the other two are derived solely from ICESat data. Their relative merits are discussed and the resulting fields of freeboard estimates are assessed.

[5] This paper is organized as follows. Section 2 describes the ICESat products and ancillary data sets used in our analyses. The relationships between ICESat elevation, freeboard, sea surface height and tiepoints are described in section 3. The next section discusses the data filters used in removing the unreliable and contaminated ICESat data samples. The three approaches for acquiring sea surface tiepoints and their uncertainties are discussed in section 5. In section 6, basin-scale maps of the freeboard and their distributions are constructed using the available sea level tiepoints. The consistencies of these two freeboard composites are examined in terms of their spatial variability and changes during the three months between acquisitions. The retrieved freeboards are compared with those derived from available snow and ice thicknesses reported by ice mass balance buoys. Section 7 discusses the variance associated with the unexplained static and time-varying components of the sea surface that are obtained after the sea ice freeboard is removed. The last section summarizes the paper.

8. Summary and Conclusions

[54] In this examination of ICESat data, we focus on the identification of sea surface tiepoints for the retrieval of freeboard and the assessment of their uncertainties. The two ICESat data sets that are used allow us to assess the seasonal consistency in the retrieved freeboard fields. Three approaches that yield tiepoints of different qualities are discussed. The best quality tiepoints are from those of young ice in new openings identified in ICESat profiles and SAR imagery. An intermediate quality category of tiepoints is obtained by comparing the reflectivity of the samples with that of the background ice and the expected deviation of these samples from a mean surface. A third category uses only the expected deviation of these samples from a mean surface as the selection criterion. The strength of the second and third approaches is that they do not depend on SAR imagery and offer a larger number of tiepoints for providing a more complete view of the spatial pattern of sea ice freeboard over the Arctic Basin. However, because of the nature of these tiepoints, they are expected to underestimate the freeboard by up to several centimeters (<4 cm) on the basis of our assessment. Using the tiepoints from new openings as a reference, the uncertainty in the individual tiepoints from these two approaches is ~5 cm. We would like to emphasize, however, that one has a choice of quality over density if only sparsely distributed tiepoints of the highest quality (like those in Figure 3) are of interest.

[55] The preferred estimate of sea surface is created from the weighted average of the two categories of tiepoints within 25-km ICESat segments. Estimates from these segments are binned to construct gridded fields of mean freeboard. The within-bin variability of ~3 cm indicates that not only are the 25-km estimates consistent, but that the spatial and temporal variability of the mean freeboard estimates are relatively small at this length scale. Our present assessment provides one indication of what could be achievable. The results suggest that our retrieval procedures could provide consistent freeboard estimates along 25-km segments with uncertainties of better than 7 cm (i.e., $\sqrt{(4^2 + 5^2)}$ cm); the actual uncertainties are, of course, dependent on the number of tiepoints available within each segment. Pointwise absolute estimation freeboard uncertainties, however, are more difficult to obtain. It is subject to systematic (instrument and processing) and nonsystematic errors (e.g., variability in surface returns, sea surface variability) that are often difficult to quantify. Spatial averaging would reduce these errors only if they are well behaved.

[56] Separating the freeboard distributions of the seasonal and perennial ice, we find that the mean freeboards of multiyear (MY) and first-year (FY) ice to be 35 cm and 14 cm in the fall, and 44 cm and 27 cm in the winter. The increases in mean freeboard of ~9 cm and ~12 cm on MY and FY sea ice are associated with ice growth and snow accumulation during the four months between data acquisitions. The freeboard distributions of the seasonal ice cover (with S.D.s of ~5 cm) are sharply peaked in both the fall and winter because of ice of similar age (within weeks). The higher variability in the age and deformation of the MY ice cover contribute to the larger S.D. (of ~15 cm).

[57] The ICESat freeboards are compared with the freeboard derived from the snow and ice thickness measurements reported by ice mass balance buoys. For the five data points available, the agreement seems remarkable considering the ICESat estimates are on a fairly coarse spatial scale compared to the point measurements provided by IMBs; but enthusiasm should be tempered by the fact that the errors in freeboard is multiplied tenfold in the conversion to errors in ice thickness. The placement of these buoys on relatively level MY ice helps since the measured ice thickness and snow cover could be expected to be somewhat closer to the larger-scale average. It is also interesting to note (from the IMB measurements) that changes in snow depth accounts for 90% of the increase in freeboard of MY ice between late October and late February since the contribution of ice growth to the overall freeboard is lower over thick ice. Thus seasonal changes in ICESat freeboard over old ice are good estimates of changes in snow depth. Conversely, accurate estimates of snow depth are critical for detecting seasonal changes in MY ice thickness. This also highlights the fact that a time series of ICESat freeboard provides a good indicator of seasonal changes in snow depth. Over FY ice, however, the contribution of ice growth to freeboard would be higher.