# Arctic sea ice freeboard heights from ICESat laser altimetry

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## Introduction

Arctic sea ice extent has been decreasing at a rate of about 10% per decade, since the earliest satellite observations in 1979. This decline is mainly attributed to climate change and variability. The effect of climate change is more pronounced in the Arctic because of the ice-albedo feedback effect which accelerates the melting process.

Sea ice cover plays an important role in the Earth climate system because, i) it controls the ice-albedo feedback mechanism that amplifies the climate response at high latitude regions. ii) growth (melt) rate affects the salt (freshwater) flux from sea ice that is significant to global ocean circulation and deep water formation. iii) due to relatively thin ice floating on the deep ocean, it interacts with winds and ocean currents. Resulting sea ice dynamics and circulation are responsible for the ice and freshwater transport in (and export from) the Arctic Ocean. iv) sea ice alters the surface heat and mass budget in the Arctic Ocean, which greatly depend on ice thickness. Clearly, sea ice processes span a wide range of scales from micrometer to thousands of kilometres and a wide range of disciplines. Despite about 200 years of research and observations, the evolution of sea ice and its position in the climate system is not completely understood. Therefore, the prediction of the future climate is unreliable. More observations are required for small- and large-scale processes at longer and continuous time-series. But, field campaigns in the Arctic are challenging due to the complex extreme environment and its inaccessibility. Hence, remote sensing techniques are crucial as they can provide global homogeneous coverage and continuous time-series.

## Motivation and Objective

In order to understand the changing Arctic sea ice cover, the change in sea ice *volume* must be known (both extent and thickness). Sea ice thickness is an important parameter that moderates the heat exchange between the ocean and the atmosphere which affects the Earth's climate. The objective of this study is to measure Arctic sea ice freeboard heights from satellite laser altimetry data (ICESat - NASA's Ice, Cloud, and Elevation Satellite) and models of geoid (EIGEN-GL04), ocean tides (AOTIM-5), and mean dynamic topography.

## Sea Ice Freeboard from Altimetry

NASA’s ICESat was launched in January, 2003. The primary objective of this laser altimetry mission is to measure the ice sheet elevations changes over Greenland and Antarctica and the secondary objective is to provide sea ice thickness distribution over the polar oceans (Schutz et al., 2005). The Geoscience Laser Altimeter System (GLAS) onboard ICESat has a ~ 70 m footprint, ~ 170 m track spacing, and 40 Hz pulse rate. ICESat operates in a 91-day repeat cycle and provides near-global coverage, up to 86 N.

Sea ice freeboard is the height of the sea ice surface above the sea level. A satellite laser altimeter measures the snow surface height or the sea ice surface height with respect to a reference ellipsoid depending on the physical properties of the overlying snow layer. Thus, by measuring the sea surface height (with respect to the same reference ellipsoid), snow/sea ice freeboard can be directly derived from laser altimetry.

The basic equation for sea ice freeboard height estimation from laser altimetry data products is,

$F = E - N - T - MDT - S - IBE - e$,

where, F is sea ice freeboard, E is ellipsoidal height of snow surface, N is geoid height, T is ocean tides, MDT is permanent mean dynamic topography, S is snow thickness, IBE is inverse barometric effect correction, e contains the errors in each measurement.

*Ellipsoidal height (E)* - The ICESat sea ice altimetry data products contain snow surface heights with respect to the Topex/Poseidon reference ellipsoid (E). They are converted into snow surface heights with respect to the WGS-84 ellipsoid, by subtracting 70 cm. This transformation is accurate to about 1 cm due to latitude depending changes of the 70 cm bias.

*Geoid (N)* - Recent gravity missions GRACE and CHAMP, terrestrial, airborne and ship-borne gravimetry data have significantly improved the geoid models. Best available geoid models have been reported as ArcGP (Forsberg and Kenyon, 2004) and EIGEN-GL04c (Forste et al., 2005) in Forsberg et al. (2007). In this study, EIGEN-GL04c model will be used to estimate N for every ICESat footprint.

*Mean dynamic topography (MDT)* – The Arctic Ocean exhibits spatial, seasonal and inter-annual variations in MDT. Current models are not consistent in predicting the MDT for the Arctic Ocean and show large differences on the order of tens of centimeters (Forsberg et al., 2007). In this study, a MDT model from University of Washington will be used for freeboard estimation. Also, freeboard will be estimated without the MDT correction.

*Inverse barometric correction (IBE)* - Sea level pressure varies in the Arctic Ocean at time scales between few hours to decades, due to changes in wind and atmospheric circulation. The response of the ocean and sea ice surface to changes in sea level pressure is known as the inverse barometric effect. It can be corrected using a simple linear equation described in Kwok et al. (2006). The sea level pressure values for each ICESat footprint are obtained by linearly interpolating the 6-hourly NCEP/NCAR reanalysis products provided by the NOAA-ESRL PSD Climate Diagnostics Center Branch, Boulder Colorado.

*Ocean tides (T)* - Global and regional tide models (CSR 4.0, GOT 00.2, TPXO 6.2, AOTIM-5 (Padman and Erofeeva, 2004)) were evaluated to determine the best model that represents the ocean tides in the Arctic Ocean. Sea ice cover has a damping effect on the ocean tide amplitudes and a phase lag of the co-tidal lines. Current ocean tide models only assimilate data from tide gauge records and altimetry data over open ocean and only during the summer months. In other words, the models are constrained by observations which do not include the sea ice-tide interactions. Consequently, tide models perform less accurately in the presence of sea ice. In order to identify how the performance decreases and if there is a measurable effect, a number of coastal tide gauges records in the Arctic Ocean were compared with tide models. This work is published in Forsberg et al. (2007). It was concluded that the AOTIM-5 model is the best model in the Arctic Ocean as it best predicts the tidal amplitudes in most constituents. Thus, this model will be used to correct the ICESat footprints for the effects of ocean tides. Loading tides are already corrected in the ICESat sea ice altimetry data products using GOT 00.2. AOTIM-5 model was not replaced because the difference between the models for loading tide is not significant.

*Snow thickness (S)* - Snow depth must be known to convert snow freeboard height into sea ice freeboard height. Besides, the snow-loading on sea ice must be known in order to apply hydrostatic equilibrium assumptions and estimate the sea ice thickness from freeboard height. The future mission Cryosat-2 will carry a radar altimeter, therefore, will be able to directly measure the height of the snow-ice interface above reference ellipsoid in dry snow conditions. Co-incident ICESat and Cryosat-2 footprints have the potential to provide snow thickness data, in cold and dry conditions. In this study, only the snow freeboard heights will be derived.

## Results and Discussion

Sea ice freeboard results from ICESat data (GLAS 13, release 28) for mission phases from 2003 to 2008 were derived. Figure 1 shows the sea ice freeboard map in the Arctic during October 2003, where only the geoid and ocean tides were removed from the snow surface height. In the final presentation, results of freeboard heights which will also include corrections for inverse barometric effect and mean dynamic topography will be presented.

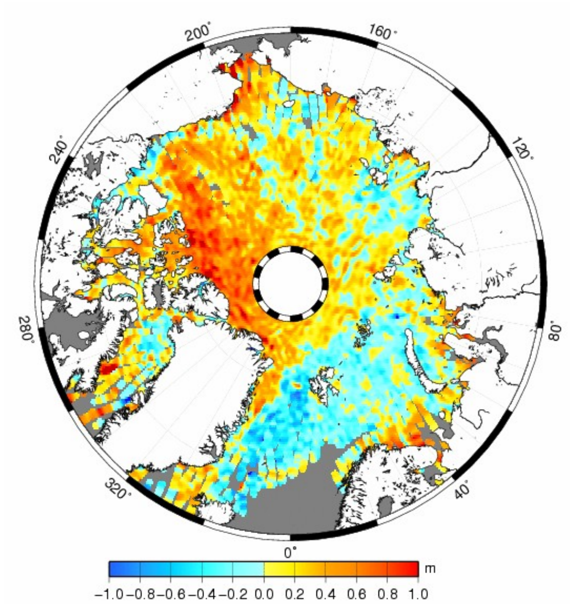


*Figure 1: Sea ice freeboard height (October 2003) estimated from ICESat GLA13 release 28, AOTIM-5 tidel model and EIGEN-GL04c geoid model.*

## Summary

In summary, sea ice freeboard heights are estimated from ICESat by combining various models of the geoid, ocean tides and mean dynamic topography. Current limitations in this method are the lack of information on the depth of the overlying snow layer and the uncertainties in the oceanographic models. Mean dynamic topography models are expected to improve with the launch of GOCE. In the future, sea ice freeboard will be converted into sea ice thickness using physical properties of sea ice under hydrostatic equilibrium assumptions.

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