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RE	Restricted to a group specified by the consortium (including the Commission)	
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SUMMARY

NASA's Ic,Cloud and land Elevation Satellite (ICESat) provided measurements of sea ice from January 2003 to October 2009. We have derived sea ice freeboard heights and sea surface heights for the Arctic Ocean from ICESat data. The sea ice freeboard heights can be converted into thicknesses by multiplying the freeboard heights by a factor of 4-4.5.

We find that some ICESat campaigns contain too sparse qualitative useful data to estimate reliable freeboard and sea surface height grids, but 13 freeboard grids and 10 grids of sea surface heigths are available.

Overall, we find a decrease of approx. 10-15 cm in the Arctic Ocean mean freeboard heights since 2003.

MONARCH-A CONSORTIUM

Participant no.	Participant organisation name	Short name	Country
1 (Coordinator)	Nansen Environmental and Remote Sensing Center	NERSC	NO
2	The University of Sheffield	USFD	UK
3	Universität Hamburg	UHAM	NO
4	Centre National de la Recherche Scientifique	CNRS	FR
5	Scientific foundation Nansen International Environmental and Remote Sensing Center	NIERSC	RU
6	Universitetet i Bergen	UiB	NO
7	Danmarks Tekniske Universitet	DTU	DK
8	Institut Francais de Recherche pour l'Exploitation de la Mer	IFREMER	FR

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1 Grids of sea thickness and sea surface heights from ICESat measurements 2003-2009

1.1 Grid file

Sea ice freeboard heights and sea surface heights of the Arctic Ocean observed from ICESat altimetry 2003-2009 are available in GRAVSOFT format grids of resolution 0.1°x0.2°. They are available at:

ftp.spacecenter.dk/pub/MONARCH-A/D2.6.1/

The GRAVSOFT grid data are stored rowwise from north to south, like you would read the values if they were printed in an atlas. The grid values are initiated with label of latitude (ϕ) and longitude (λ) limits and spacing, the follows the data in free format:

φ_1 φ_2 λ_1 λ_2 $\Delta\varphi$ $\Delta\lambda$

d_{n1} d_{n2} .... d_{nm}

.....
.....

d_{11} d_{12} .... d_{1m}

The sea ice freeboard heights are here given in m and the sea surface heights in cm above the Arctic Gravity Project (ArcGP) geoid.

1.2 ICESat data

ICESat data release 31 has been downloaded directly from the National Snow and Ice Data Center (NSIDC). The ICESat product GLA13, which is specially adapted to sea ice covered surfaces, was used in this analysis. Filtering and corrections of the ICESat data are performed to remove unreliable ICESat data and to apply corrections to measurements due to e.g. saturation and large off-pointing.

Each grid represent an ICESat period according to table 1. The non available ICESat freeboard grids are due to laser periods where there are very few data in the data set, either due to few days of operation (2D, 2F and 3K) or due to poor data quality (2E and 2C). For the sea surface heights even more ICESat periods (3F, 3G and 3I) are excluded from the analysis due to limitations in the cross-over adjustment program.

Table 1: ICESat's operational periods in chronological order and overview of available grids release 31

Laser ID	# Days	Start Date	End Date	FRB grid	SSH grid
1A	38	2003-02-20	2003-03-29	X	X
2A	55	2003-09-24	2003-11-18	X	X
2B	34	2004-02-17	2004-03-21	X	X
2C	35	2004-05-18	2004-06-21		
3A	37	2004-10-03	2004-11-08	X	X
3B	36	2005-02-17	2005-03-24	X	X
3C	35	2005-05-20	2005-06-23	X	X
3D	35	2005-10-21	2005-11-24	X	X
3E	34	2006-02-22	2006-03-27	X	X
3F	33	2006-05-24	2006-06-26	X	
3G	34	2006-10-25	2006-11-27	X	
3H	34	2007-03-12	2007-04-14	X	X
3I	37	2007-10-02	2007-11-05	X	
3J	34	2008-02-17	2008-03-21	X	X
3K	16	2008-10-04	2008-10-19		
2D	23	2008-11-25	2008-12-17		
2E	34	2009-03-09	2009-04-11		
2F	12	2009-09-30	2009-10-11		

1.3 Method

To estimate the sea ice freeboard heights and the sea surface heights, a lowest-level filtering process is applied to the ICESat data. This procedure picks the lowest levels along an ICESat track after removing a geoid model (ArcGP) from the ICESat heights. These lowest levels are assumed to originate from open water leads in the ice pack. A smooth surface is interpolated to the lowest-level data points, which thus basically represent an estimate of the sea surface height. Using this estimated sea surface height the sea ice freeboard heights can be calculated. The procedures are described in more detail in Skourup (2010).

The data have been corrected for the inverse barometer effect using NCEP/NCAR sea level pressure fields, and ocean tides using the tide model applied to the ICESat elevations in the GLA13 data product. Potential ICESat inter-campaign biases has to be applied to the sea surface heights by the user.

The sea ice freeboard (f) to thickness (t) conversion $(t = (1 + R) * f)$ is debated in many papers and is highly variable (R = 1-10) depending on sea ice type, settings and snow conditions. Recent studies of the relation between freeboard and draft by Doble et al (2011), finds a R-value of 3-3.5 for ICESat measurements. Thus, it is suggested to use these values to convert the sea ice freeboard heights of ICESat presented above into sea ice thicknesses.

1.4 Results

Two examples of Arctic Ocean sea ice freeboard heights are shown in the figure below from ICESat periods October-November 2005 (left) and February-March 2006 (right). The sea ice freeboard heights show good correlation with backscatter values from QuikSCAT scatterometer data (Skourup, 2010). However, as the method depends on the presence of open water, the method is underestimating the sea ice freeboard heights by up to 37 cm in heavy ice conditions, when compared to coincident high resoltuion airborne lidar measurments (Skourup and Forsberg, 2006).

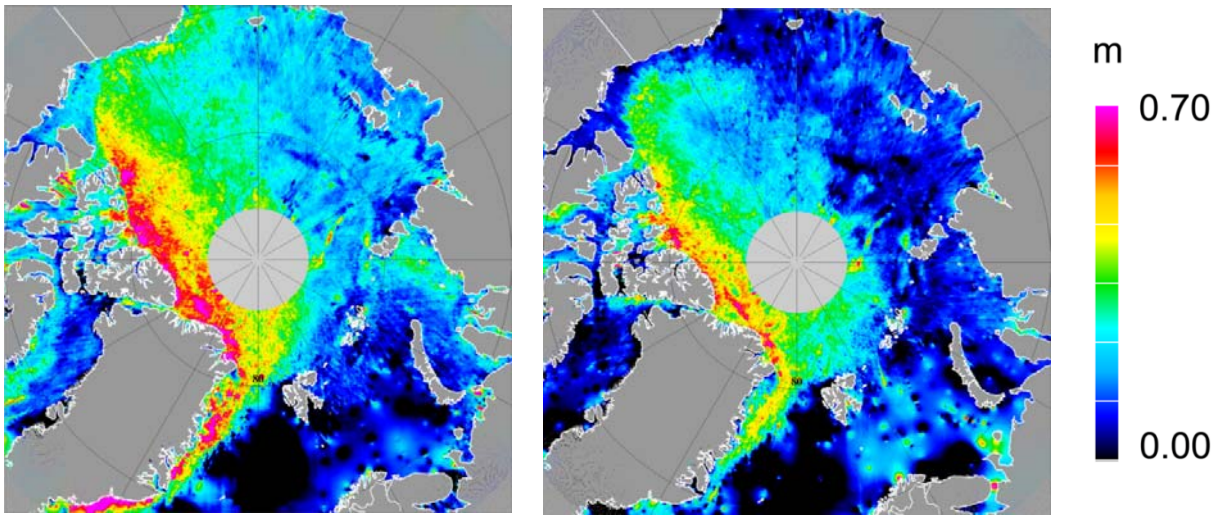

Figure 1: Sea ice freeboard maps February-March 2006 (left) and October-November 2005 (right)

Overall, a decrease in the Arctic Ocean mean freeboard heights of approximately 10 - 15 cm is observed, since the beginning of the ICESat observations in 2003, see figure 2. These are realistic values and can be explained by a combination of a decrease in the perennial sea ice extent together with a general decrease in the ice thickness due to an increased heating of the atmosphere and ocean.

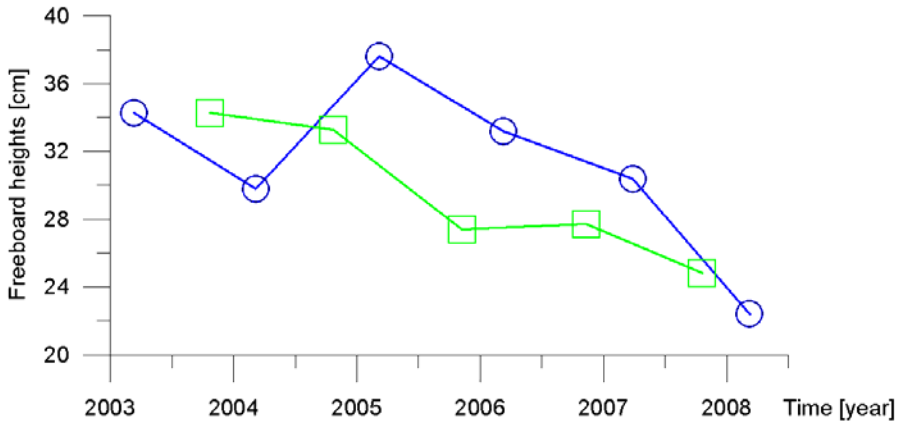

Figure 2: Mean sea ice freeboard heights in the Arctic. Blue circles February-March and green rectangles October-November.

2 References

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