Sea Ice Climate Change Initiative: Phase 1

ANT D1.9 Data set & Documentation

Doc Ref: SICCI-ANT-SITDD-06-15

Version: 2.0

Date: 22nd June 2016

Change Record

Issue	Date	Reason for Change	Author

Issue	Date	Reason for Change	Author
1.0	25-06-2015	First Draft	Stefan Kern
1.0	30-06-2015	Final version for SICCI ICESat sea ice thickness data set v0.3	Stefan Kern
2.0	22-06-2016	Update of the SICCI ICESat sea ice thickness data set to v1.07	Stefan Kern

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1 Introduction

1.1 Purpose

This document describes an update to the sea ice thickness prototype dataset for the Sea Ice ECV project, which was produced in Phase 1 of ESA's Climate Change Initiative – Antarctic Sea Ice Thickness Option. The updated was product in June 2016.

1.2 Scope

The scope of this document is a description of the content of the prototype data set. It refers to other ESA documents once it comes to details about how the data set is derived. This document can be understood as a Product User Guide (PUG).

1.3 Document Structure

After this introduction the user will be guided where to find important information about the product in the ESA reports. The user then learns about caveats and limitations of the data before the content of the data set with respect to the sea ice thickness is visualized and the technical description of the data set is given. Some relevant references are given at the end of this document.

1.4 Document Status

This is issue 2.0 of the PUG for version v1.07 of the ESA CCI Sea Ice ECV Antarctic Sea Ice Thickness Option sea ice thickness data set.

1.5 Applicable Documents

The following table lists the Applicable Documents that have a direct impact on the contents of this document.

Acronym	Title	Reference	Issue

Table 1-1: Applicable Documents

1.6 Applicable Standards

Acronym	Title	Reference	Issue

Table 1-2: Applicable Standards

1.7 Reference Documents

Acronym	Title	Reference	Issue

Acronym	Title	Reference	Issue
RD-01	D1.8 Report on Antarctic sea ice thickness retrieval and assessment	SICCI-ANT-SITRA-06-15	1.0
RD-02	D1.4 Report on Envisat RA2 Antarctic freeboard retrieval and assessment	SICCI-RERA2AFRA-12-14	1.1
RD-03	D1.5 Report on Cryosat-2 Antarctic freeboard retrieval and assessment	SICCI-RCS2AFRA-10-14	1.1
RD-04	D1.6 ICESat ANT Freeboard	SICCI-ICESatANT-14-03	1.0
RD-05	D1.1 Passive microwave snow depth on Antarctic sea ice assessment	SICCI-Ant-PMW-SDASS-11-14	1.1
RD-06	D1.3 Product User Guide for Antarctic AMSR-E snow depth on sea ice product	SICCI-ANT-SD-PUG-14-08	2.1
RD-07	D1.2 Antarctic snow depth from alternative sources	SICCI-ANT-SD-AS-14-04	1.0
RD-08	Uncertainties in Antarctic sea-ice thickness retrieval from ICESat	Kern, S., and G. Spreen, Ann. Glaciol. 56(69), 107-119, 2015, doi:10.3189/2015AoG69A736	n.a.
RD-09	Antarctic sea-ice thickness retrieval from ICESat: Inter-comparison of different approaches	Kern, S., B. Ozsoy-Cicek, and A. P. Worby, Rem. Sens., 8, 2016, accepted	n.a.

Table 1-3: Reference Documents

1.8 Acronyms and Abbreviations

Acronym	Meaning
EO	Earth Observation
PDGS	Payload Data Ground System

Table 1-4: Acronyms

2 Data Set & Documentation

2.1 Introduction

This part of the Product User Guide (PUG) provides the entry point to the European Space Agency Climate Change Initiative (ESA CCI) Antarctic Sea Ice Thickness Option sea ice thickness (SIT) prototype product, both from a scientific and a technical point of view. Details of the scientific description of the processing chain and algorithms are however willingly kept out of this PUG, and the interested readers are rather directed to the documents / deliverables D1.8: Antarctic Sea Ice Thickness Retrieval and Assessment [RD-01], D1.4 Envisat RA2 Antarctic freeboard retrieval and assessment [RD-02], D1.5: Cryosat-2 Antarctic freeboard retrieval and assessment [RD-03], D1.6: ICESat ANT Freeboard [RD-04], and D1.1: Passive microwave snow depth on Antarctic sea ice assessment [RD-05] as well as the two papers [RD-08; RD-09]. These documents provide sufficient background to the different approaches to derive Antarctic sea ice thickness in the context of this project.

It is considered essential that users of the SICCI ICESat sea ice thickness product read D1.8 [RD-01] before they use the data set.

This is PUG version 2.0 associated with version v1.07 of the ESA SICCI ICESat sea ice thickness data set made available at http://icdc.zmaw.de/1/projekte/esa-cci-sea-ice-ecv0.html on June 21 2016. In short this data set contains

- ICESat period mean gridded sea ice thickness maps for the Southern Ocean with grid resolution 100 km for ICESat measurement periods between Austral fall 2004 and Austral fall 2008 (in total 12 periods) derived with the SICCI algorithm and the Worby 1-layer algorithm (see [RD-09])
- Data set is based on ICESat laser altimeter data (freeboard) and AMSR-E microwave radiometry data (snow depth)
- Data set is based on SICCI approach described in RD-01, RD-04, RD-08, and RD-09.
- Data set contains in addition maps of number of valid single laser shots per grid cell, the total standard error of the sea ice thickness, the ICESat total freeboard, the standard error of the total freeboard, the snow depth (only for SICCI), and the sea ice concentration used.

2.2 Scientific description of the prototype product

This section gives a summary of the science features of the ESA SICCI ICESat sea ice thickness data set. First we point potential users to the known limitations and caveats which we first describe before we give a recommendation to the user in *italic font.* Note that this version of PUG is written before an extensive validation exercise of the dataset, and that the results described below are based on the investigations and literature review results given in RD-01 and RD-04; see also RD-08 and RD-09.

Note further that it was not intended to provide a mature sea ice thickness data product in the context of the ESA SICCI ANT SIT option.

2.2.1 Known limitations and caveats

The user should be aware of a number of limitations and caveats before considering to using the dataset.

(1) The data set is discontinuous caused by the nature of the ICESat measurements being available only for up to 3 periods per year which have an average length of between 33 and 35 days.
(2) Data coverage is sparse. Only one sea ice thickness map per ICESat measurement period is generated. Reasons for this are i) ICESat's sensor is a laser altimeter which measures every about 170 m with an about 60 m diameter footprint. Hence the "area" covered during one satellite overpass is extremely small; ii) the laser signal is disturbed by clouds which causes many dropouts of data. Both these suggest, that one needs to average over a number of overpasses in a large enough grid cell to get a reasonable number of valid measurements. For the current data set 100 km is chosen. A grid resolution of 25 km would be possible as well as has been done by other authors [Zwally et al., 2008; Yi et al., 2010; RD-08]. However, it remains to be shown that 25 km is large enough to take into account spatial correlations. Also, using 100 km has the advantage that from the 33 to 35 days of one ICESat measurement period more than 2-3 days contribute to the freeboard values (see (3)) in one grid cell [RD-04; RD-08].
(3) The sea ice thickness is computed from the total freeboard which is the elevation of the snow surface above the sea surface. Pending information of the sea surface height with centimetre accuracy on time-scales of hours to days requires to approximating the sea surface height from the ICESat measurements themselves. That this is not a straight-forward thing to do and bears the potential for large uncertainties in the freeboard has been demonstrated in a number of articles, e.g. Kwok et al. [2007]; Markus et al. [2011]; RD-08. To the author's opinion the best way to obtain freeboard from ICESat measurements for Antarctic sea ice has not yet been found and is also difficult to develop because ICESat is not providing data anymore and there is a lack of appropriate validation data. Two additional issues are swell propagating several 100 km into the sea ice cover and a relatively high concentration of small ice bergs. ICESat-2 will improve on that situation [McGill et al., 2013; Kwok et al., 2014].
(4) Computation of the sea ice thickness from ICESat freeboard requires information about the snow depth. Within the SICCI project the NSIDC AMSR-E snow depth product has been assessed [RD-04] with not a too convincing result (see also [RD-10]). Still this is the only snow depth data set – except the newly generated but not yet properly validated SICCI snow depth data set [RD-06] – which provides the required spatiotemporal coverage. Especially over deformed sea ice the NSIDC AMSR-E snow depth under-estimates the actual snow depth. Problems do also occur for wet snow, snow which has undergone melt-refreeze cycles and areas with ice-snow interface flooding. While for some of these flags exist the contribution of these snow property changes to the accuracy of the snow depth product has not yet been quantified. References RD-05 to RD-07 provide an extensive literature compilation regarding this topic. The caveats encountered by the potentially biased snow depth data lead to the derivation of a second sea ice thickness data set within the ESA SICCI project. This is called Worby 1-layer approach and is described in RD-09. In short, it uses a 1-layer system, i.e.

assumes that ICESat measured the elevation of a combined sea-ice snow 1-layer system. In order to compute the thickness of the sea ice of this 1-layer system it is assumed that the impact of the snow load onto the sea-ice buoyancy can be approximated by a modified lower sea-ice density. The modification factors are computed from the ration of the sea ice thickness to the snow depth taken from seasonally average circum-Antarctic ASPeCt sea-ice observations (see [RD-09]). Users should note that this is a climatologically driven approach and might not be able to represent inter-annual variation in sea-ice thickness as the SICCI approach allows us to do by means of using actual snow-depth estimates. However, as the snow-depth estimates used might be biased substantially, we think an approach such as the Worby 1-layer algorithm is a reasonable alternative.

(5) A high percentage of the Antarctic sea ice is flooded, i.e. has an ice-snow interface which is situated below the water line [Yi et al., 2011; Ozsoy-Cicek et al., 2013]. This influences the retrieved snow depth (see 4) but more importantly it violates the validity of the classical equation used to compute sea ice thickness from freeboard. The work-around solution to this problem is a case discrimination of regions with an ice-snow interface above the water line (= positive sea ice freeboard) or an ice-snow interface below the water line (= negative sea ice freeboard). The lack of other independent data forces one to use the snow depth to carry out this discrimination: Sea ice freeboard is negative where the snow depth exceeds the total freeboard and sea ice freeboard is positive as long as the snow depth is smaller than the total freeboard. This methodology has been proposed already by Zwally et al. [2008] and is also used in the SICCI approach [RD-01]. However, whether and under which environmental conditions this discrimination between positive and negative sea ice freeboards is valid depends on the accuracy of the total freeboard and – in particular – of the snow depth in case of ice-snow interface flooding; this has not yet been quantified, though, and remains an open research topic.

(6) The actual snow and sea ice densities (see [RD-01]) might differ quite a bit from those constant ones used in the SICCI approach to convert between freeboard and thickness.

All these points suggest that the ICESat sea ice thickness product should be used with great caution.

- *Users should be careful to draw any conclusions from single grid cells.*
- *Users should be aware of problematic regions such as the marginal ice zone, regions with a high concentration of ice bergs, and regions with an above-normal compact ice cover – e.g. land fast ice – where most likely the identification of the sea surface height fails.*
- *Users should be aware that the applied snow depth under-estimates snow over deformed sea ice and that hence actual sea ice thickness values might be smaller in regions of heavily deformed sea ice than in the product.*
- *The actual amount and location of flooded sea ice is unknown*
- *The users are advised to pay attention to i) the sea ice thickness uncertainty maps and ii) the maps with the total number of single ICESat measurements per grid cell for a proper interpretation of the data*
- *Users being in doubt of the quality are encouraged to read RD-01 and RD-09 and/or to contact the data provider.*

2.3 Technical description of the prototype product

In this section, the sea ice thickness product files are described in terms of content, file name, data format, grid, and others.

2.3.1 Example

To support the reading of the technical specifications, we start this section by giving an overview about the sea ice thickness maps (Figure 2.1) and the sea ice thickness retrieval uncertainty (Figure 2.2) for all ICESat measurement periods considered in the product. These figures aim at giving the potential user a glimpse of how the data product looks like. The user can also see that the sea ice thickness retrieval uncertainty can be quite high and amount of to 50 % of the actual sea ice thickness value.

We refer to RD-01 for a description and discussion of the maps.

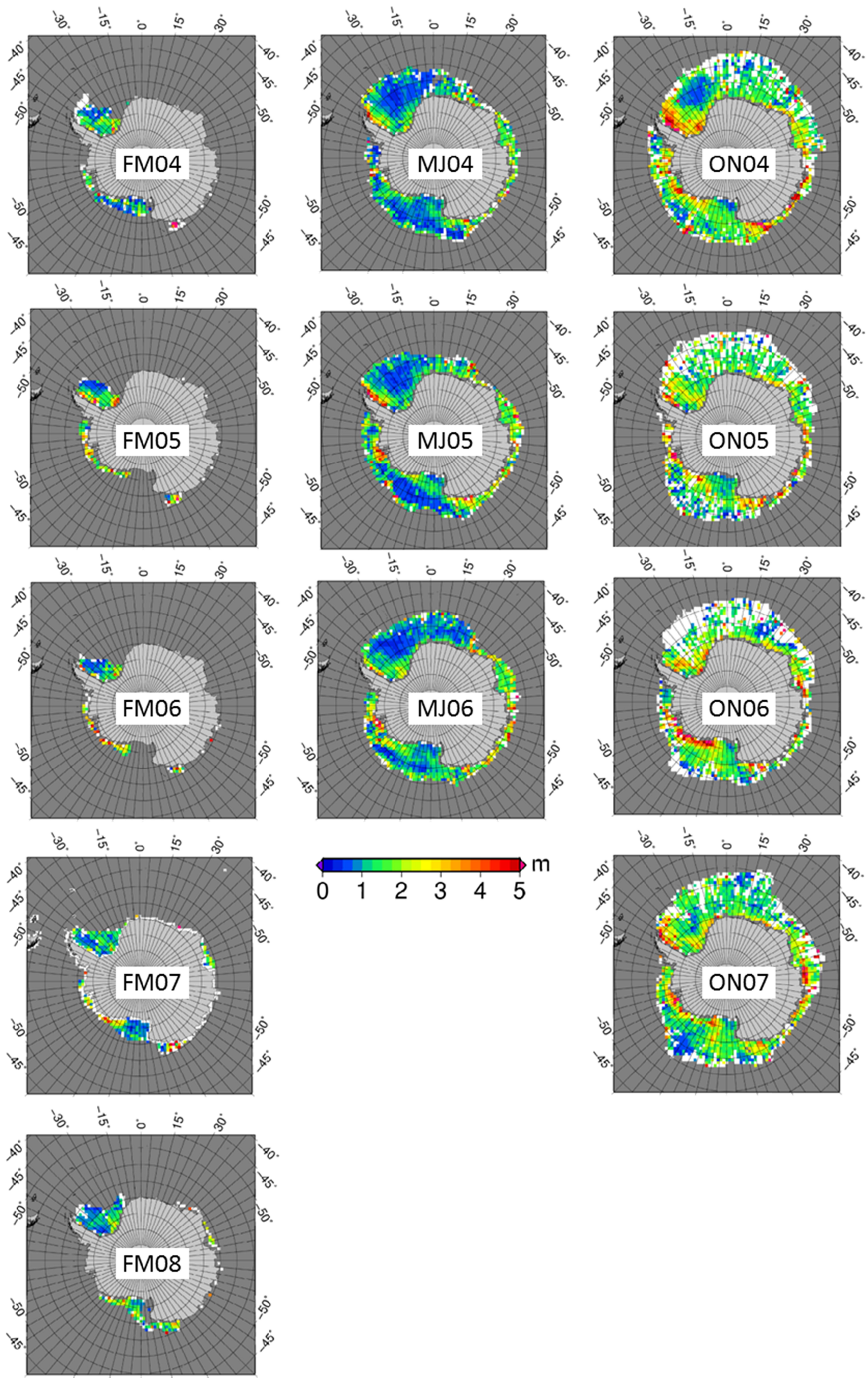

Figure 2.1: Sea ice thickness distribution around the Antarctic for ICESat SICCI for all ICESat periods considered; the left, middle, and right column gives FM, MJ and ON periods, respectively. White areas in the maps show grid cells with sea ice but without enough valid sea ice thickness data. Grid cell size is 100 km. Only grid cells with a sea ice concentration above 60% are shown.

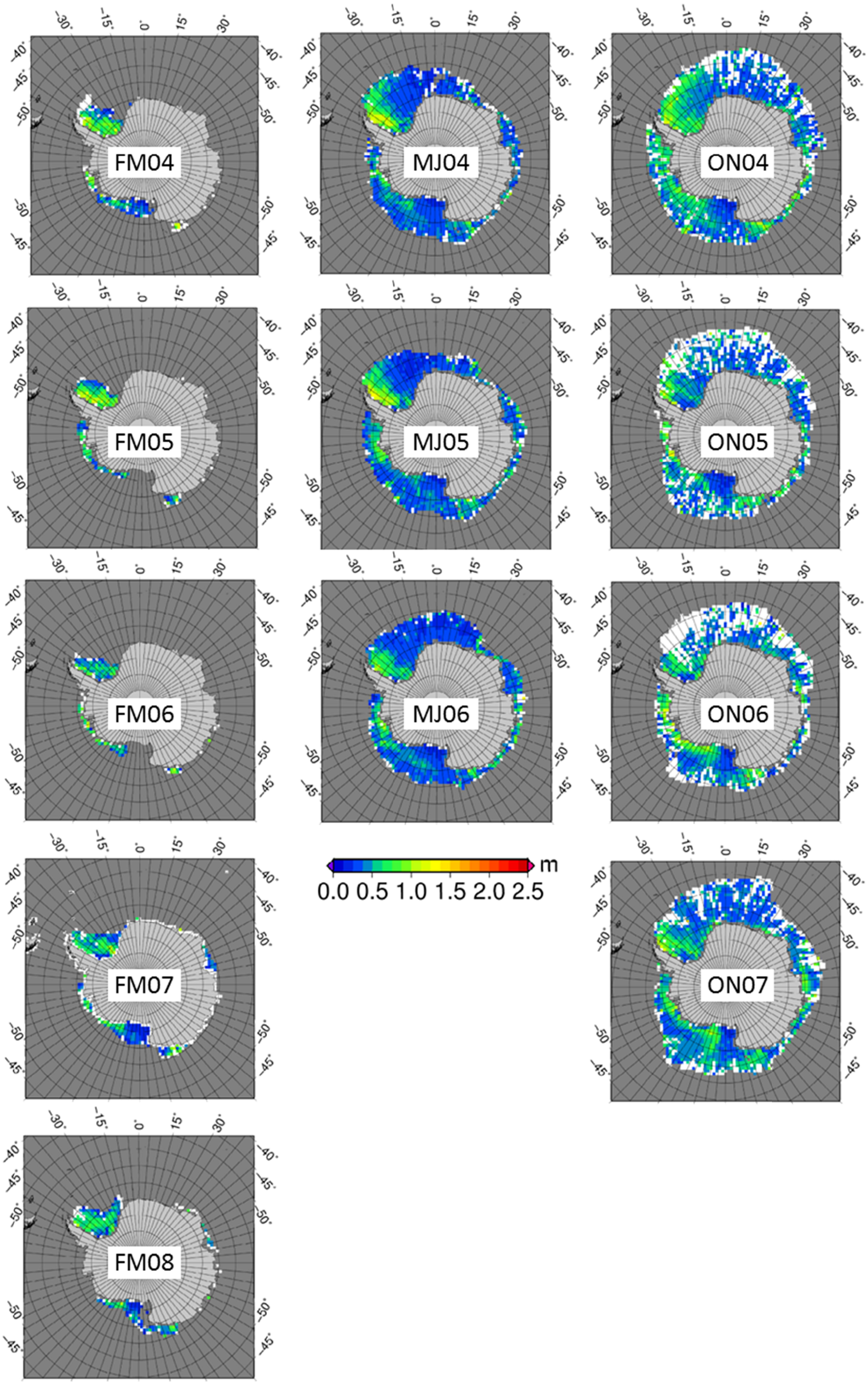

Figure 2.2: As Figure 2.1 but for the SICCI sea ice thickness retrieval uncertainty. Note the different scaling of the legend.

2.3.2 Content of product files

The distributed product files are so called "Level 4" files that are gridded maps for the 12 ICESat measurement periods considered with one map of the sea ice thickness and its retrieval uncertainties for the Southern Hemisphere per period. Each map has dimension 79 (x-coordinate, number of columns) times 83 (y-coordinate, number of rows). Each file contains (in the same order as listed here):

- Latitude and longitude for each grid point. Name of the variable is Latitude and Longitude. These are based on the NSIDC grid with 100 km x 100 km grid resolution, in degrees north and degrees east, respectively

- ICESat period average total freeboard. Name of the variable is TOTAL_FREEBOARD. This variable has the unit m and provides the total freeboard estimate wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0 and -1.0, respectively. Total freeboard is set to 0.0 over open water. Values above 1.0 m are set to missing value.

- ICESat period average total freeboard standard error. Name of the variable is TOTAL_FREEBOARD_STANDARD_ERROR. This variable has the unit m and provides the freeboard retrieval uncertainty estimate wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0 and -1.0, respectively. The uncertainty is set to 0.0 over open water. Values where the total freeboard is above 1.0 m are set to missing value. Note that this is basically the average single laser shot uncertainty.

- ICESat period average sea ice thickness. Name of the variable is SEA_ICE_THICKNESS. This variable has the unit m and provides the sea ice thickness estimate wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0 and -1.0, respectively. Sea ice thickness is set to 0.0 over open water. Values where the total freeboard is above 1.0 m are set to missing value.

- ICESat period average sea ice thickness retrieval uncertainty. Name of the variable is SEA_ICE_THICKNESS_STANDARD_ERROR. This variable has the unit m and provides the sea ice thickness uncertainty estimate wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0 and -1.0, respectively. Sea ice thickness is set to 0.0 over open water. Values where the total freeboard is above 1.0 m are set to missing value. We refer to [RD-09] for a discussion of this uncertainty. *)

- ICESat period average sea ice concentration. Name of the variable is SEA_ICE_AREA_FRACTION. This variable has the unit percent and provides the sea ice concentration from 15% to 100%. Values blow 15% are set to 0%. estimate wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0.

- ICESat period average snow depth on sea ice (only for the SICCI approach because the Worby 1-layer approach does not require snow depth data [RD-09]). Name of the variable is SNOW_DEPTH_ON_SEA_ICE. This variable has the unit m and provides the snow depth wherever the ICESat period average sea ice concentration is > 60%. Missing and fill values are -10.0 and -1.0, respectively. Snow depth is set to -0.1 over open water to not mix with real 0.0 m snow depth over sea ice. Grid cells where on less than 3 days of the ICESat period snow depth was valid are set to missing value.

- The number of valid data per grid cell. Name of the variable is NUMBER_OF_VALID_DATA. This variable has not units. Missing and fill value are -10.

*) The uncertainty computation for the Worby 1-layer algorithm is not in given in RD-09 but added to the data set afterwards.

The two equations to be used are:

$$\rho_{ice}^{*} = \frac{R\rho_{ice}+\rho_{snow}}{R+1} \quad (1)$$

Where R is the R-factor, ρ_{ice} , ρ_{snow} , ρ_{ice}^{*} are the densities of sea ice, snow and the 1-layer system (modified ice density), and

$$I = F\,\frac{\rho_{water}}{\rho_{water}-\rho_{ice}^{*}} \quad (2)$$

where I is sea-ice thickness, F is total freeboard, and ρ_{water} is the sea water density.

Error propagation of equation (1) leads to

$$d\rho_{ice}^{*} = \sqrt{\left(dR\,\frac{\rho_{ice}-\rho_{snow}}{(R+1)^2}\right)^2 + \left(\frac{R}{R+1}\right)^2 (d\rho_{ice}^2 + d\rho_{snow}^2)}$$

where dR, $d\rho_{ice}$, $d\rho_{snow}$, $d\rho_{ice}^{*}$ denote the uncertainties of the respective parameters in Equation (1). Input uncertainties for sea ice and snow density are 20kg/m³ and 50kg/m³, respectively. For dR half the difference between the maximum and the minimum seasonal average R-factor for each Antarctic region is taken, that is 1.25 for Feb./Mar., 1.0 for May/June and 1.15 for Oct./Nov. ICESat measurement periods.

Error propagation of equation (2) leads to

$$dI = \sqrt{\left(dF\,\frac{\rho_{water}}{\rho_{water}-\rho_{ice}^{*}}\right)^2 + \frac{F^2}{(\rho_{water}-\rho_{ice}^{*})^4}\left[(d\rho_{ice}^{*}\rho_{water})^2 + (d\rho_{water}\rho_{ice}^{*})^2\right]}$$

where dF and $d\rho_{water}$ are the uncertainties of the total freeboard (which is three times the total freeboard uncertainty, see [RD-08]) and the sea water density: 0.5 kg/m³.

2.3.3 Temporal coverage

The data set is available for the ICESat measurement periods given in Table 2.1

Table 2.1: ICESat measurement periods used. The naming convention in the text is given by the season abbreviation, e.g. "ON" followed by the two last

digits of the year, e.g. "04", so that "spring 2004" reads "ON04" and "winter 2006" reads "MJ06".

Year	Spring (ON)	Fall (FM)	Winter (MJ)
2004	Oct. 3 – Nov. 8	Feb. 17 – Mar. 21	May 18 – June 21
2005	Oct. 21 – Nov. 24	Feb. 17 – Mar. 24	May 20 – June 23
2006	Oct. 25 – Nov. 27.	Feb. 22 – Mar. 27	May 24 – June 26
2007	Oct. 2 – Nov. 5	Mar. 12 – Apr. 14	--
2008	--	Feb. 17 - Mar.	--

The temporal resolution is one map per period.

2.3.4 *Product grid and geographic projection*

The SICCI ICESat sea ice thickness dataset is provided on the NSIDC polar-stereographic grid with 100 km grid resolution.

Grid center is the South Pole. The tangential plane is located at 70°S. The grid is not symmetric around to pole along axis given by the 0°E / 180°E meridians but is covering 4 more rows in the direction centered at the 0°E meridian. The grid coordinates are given in Table 2.2.

Table 2.2: Definition of the Southern Hemisphere grid used for the Snow Depth dataset.

Dimensions	X [km]	Y [km]	Latitude [deg N]	Longitude [deg E]
X: 79 Y: 83 X1 … X78: 7900 km Y1 … Y83: 8300 km	-3950 0 3950 3950 3950 0 -3950 -3950	4350 4350 4350 0 -3950 -3950 -3950 0	-39.7677 -51.8455 -39.7677 -55.1792 -41.9749 -55.1792 -41.9749 -55.1792	317.7633 0.0000 42.2367 90.0 135.0 180.0 225.0 270.0

2.3.5 *Convention for file names*

The ESA CCI ANT SIT v02 dataset widely follows the ESA-CCI convention for file names. The files are named

ESACCI-SEAICE-L4-SEAICETHICKNESS__ICESat-1__SH100km__NSIDCPolstereo__NAME_algorithm__<YYYYMMDD>-<YYYYMMDD>__UHAM-ICDC__fv01.07.nc

where the first and second <YYYYMMDD> denote the start and end date of each ICESat measurement period, respectively with YYYY for the year, e.g. 2004, MM for the month, i.e. 05, and DD for the day, i.e. 19. <SH100km__NSIDCPOLSTEREO> stands for Southern Hemisphere, NSIDC polar-stereographic grid with 100 km grid resolution. NAME is either "SICCI" or "WORBY_1-layer"

2.3.6 File format

The sea ice thickness data files are netCDF files following convention CF1.6.

All variables are stored as floating point (32 bit) except the coordinates which are stored as double precision floating point (double) and the number of valid data points which is stored as short integer (16 bit).

2.3.7 Access to data

The sea ice thickness dataset can be accessed via:

- http://icdc.zmaw.de/projekte/esa-cci-sea-ice-ecv0.html

Note that a registration is required to access the data.

2.3.8 Dataset version history

V1.07: Version associated with this document and put onto the ICDC data server on June 21, 2016; refined freeboard outlier filtering, updated global attributes, data from two different algorithms available.

v0.3: This version, typos in the data description removed.

v0.2: Second release, freeboard, freeboard uncertainty and number of valid data points included.

v0.1: First release; freeboard, freeboard uncertainty and number of valid data missing.

3 Literature

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