Sea Ice CCI+

Norwegian Meteorological Institute

ESA CCI+ CLIMATE CHANGE INITIATIVE
PHASE 1: NEW R&D ON CCI ECVS

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SEA ICE THICKNESS
PRODUCT USER GUIDE
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Contract PHASE 1 OF THE CCI+ CLIMATE CHANGE INITIATIVE NEW R&D ON CCI ECVS SEA ICE ECV	**Deliverable** D4.2 Sea Ice Thickness Product User Guide
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1 INTRODUCTION

1.1 Purpose

This document describes the Sea Ice Thickness datasets for the Sea Ice ECV project produced in ESA's (Climate Change Initiative) CCI+. The document is meant for anyone using the product to gain background information. In addition to this document, the details of the processing algorithm and in depth validation results are provided in RD-1 and RD-2.

1.2 Scope

This document is a brief introduction of the relevant product related information for the users. Product variables and their spatial and temporal extents are specified and some known issues are mentioned.

1.3 Document Status

This is the third issue of the PUG released to ESA as part of the project's first phase. The content is in principle an updated version of the PUG in CCI Phase 2 with additional information for the added missions.

1.4 Applicable Documents

Table 1 below lists the Applicable Documents referred to in this document.

Table 1: Applicable Documents

Document ID	Document referred to
RD-1	Algorithm Theoretical Basis Document (ATBD), Issue 3.x,
RD-2	System Specifications Document, Issue 3.0, August 2021
RD-3	Product Validation and Intercomparison Report (PVIR), Issue 3.0, April 2023
RD-4	End 2 End Uncertainty Budget (E3UB), Issue 3.0, August 2021
RD-5	Kurtz, N. T., and S. L. Farrell (2011), Large-scale surveys of snow depth on Arctic sea ice from Operation IceBridge, Geophys Res Lett, 38.
RD-6	CCI Data Standards, Issue 2.3, July 2021
RD-7	Laxon, S. W., K. A. Giles, A. L. Ridout, D. J. Wingham, R. Willatt, R. Cullen, R. Kwok, A. Schweiger, J. Zhang, C. Haas, S. Hendricks, R. Krishfield, N. Kurtz, S. L. Farrell, and M. Davidson (2013), CryoSat-2 estimates of Arctic sea ice thickness and volume, Geophys. Res. Lett., 40, 1–6.
RD-8	Brodzik, M.J.; Billingsley, B.; Haran, T.; Raup, B.; Savoie, M.H. EASE-Grid 2.0: Incremental but Significant Improvements for Earth-Gridded Data Sets. ISPRS Int. J. Geo-Inf. 2012, 1, 32-45.

1.5 Acronyms and Abbreviations

The table below lists the acronyms and abbreviations used in this volume.

Table 2: Acronyms and Abbreviations. Acronyms for the deliverable items (URD, etc…) and partner institutions (AWI,..) are not repeated.

Acronym	Meaning
AMSR-E / AMSR2	Advanced Microwave Scanning Radiometer (for EOS / #2)
AOGCM	Arctic Ocean General Climate Model
AR5, AR6	WMO IPCC Assessment Report series
ASAR	Advanced Synthetic Aperture Radar
C3S	EU Copernicus Climate Change Service
CCI	Climate Change Initiative
CDR	Climate Data Record
CMEMS	EU Copernicus Marine Environment Monitoring Service
CMIP5, CMIP6	Coupled Model Intercomparison Project series
CMUG	Climate Modelling User Group
CRG	Climate Research Group
CS-2	ESA's CryoSat-2
DEWG	CCI Data Engineering Working Group
EASE grid	Equal-Area Scalable Earth Grid
ECMWF	European Centre for Medium-Range Weather Forecasts
ECV	Essential Climate Variable
ENVISAT	ESA's Environmental Satellite
EO	Earth Observation
ERS	European Remote Sensing Satellite
ESA	European Space Agency
ESMR	Electrically Scanning Microwave Radiometer
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites

FoV (*alt* FOV)	Field-of-View
FY3	Feng Yun 3
FYI	First Year Ice
GCOS	WMO's Global Climate Observing System
GCW	WMO's Global Cryosphere Watch
ICDR	Interim Climate Data Record
IMB	Ice Mass Balance buoy
IPCC	WMO's Intergovernmental Panel on Climate Change
L1b, L2, L3C, ...	Satellite data processing Level (Level-1b, …)
MERIS	MEdium Resolution Imaging Spectrometer
EPS, EPS-SG	EUMETSAT's Polar System, EPS Second Generation
MIZ	Marginal Ice Zone
MODIS	Moderate Resolution Imaging Spectroradiometer
MWI	MicroWave Imager (EPS-SG)
MWRI	Micro-Wave Radiation Imager (Feng Yun 3)
MYI	Multi-Year Ice
NASA	National Aeronautics and Space Administration
NOAA	US National Oceanic and Atmospheric Administration
NSIDC	US National Snow and Ice Data Centre
OE	Optimal Estimation
OIB	Operation Ice Bridge
OSI SAF	EUMETSAT Ocean and Sea Ice Satellite Application Facility
OWF	Open Water Filter
PMR	Passive Microwave Radiometer
PMW	Passive Microwave
RA	Radar Altimeter
RRDP	Round Robin Data Package

SIC	Sea Ice Concentration
SIT	Sea Ice Thickness
SAR	Synthetic Aperture Radar
SIRAL	Synthetic Aperture Radar (SAR) Interferometer Radar Altimeter
SOA	Service Oriented Architecture
SMMR	Scanning Multichannel Microwave Radiometer
SMOS	Soil Moisture and Ocean Salinity
SSM/I	Special Sensor Microwave/Imager
SSMIS	Special Sensor Microwave Imager/Sounder
ULS	Upward Looking Sonar
WMO	World Meteorological Organisation
WSM	Wide Swath Mode

1.6 Executive Summary

This is the third version of the CCI+ Phase 1 Product User Guide document for Sea Ice Thickness. This PUG is meant as an entry point for interested users of the sea-ice thickness product. It briefly describes the scientific basis for the product and known limitations. It details the product file format including main variables, status flags, filenaming convention and data access.

2 PRODUCT USER GUIDE

This Product User Guide (PUG) provides an entry point to the European Space Agency Climate Change Initiative+ (ESA CCI+) Sea Ice Thickness (SIT) dataset, both from a scientific and a technical point of view. The data set comprises the prototype version of a consistent climate data record of sea-ice thickness from the Envisat and CryoSat-2 radar altimeter missions in both hemispheres. Details of the scientific description of the processing chain and algorithms are however deliberately kept out of this PUG, and the interested readers are rather directed to the Algorithm Theoretical Basis Document [RD-1], System Specifications Document [RD-2] and peer-reviewed scientific literature [RD-7]. Validation and evaluation results are not contained in this PUG either, but in a Product Validation and Intercomparison Report [RD-3].

In short, the SICCI SIT dataset is:

- Monthly gridded (Level-3) sea ice thickness (SIT), radar freeboard (RFB) and freeboard (FB) fields with 25 km grid spacing for the Arctic and 50 km grid spacing in the Antarctic. Gridded geophysical parameters based on radar altimeter measurements are

available for the freezing season (October-April) for the Arctic and year-around in the Antarctic.

- Daily summary files (Level-2) that contain the geophysical parameters (SIT, RFB, FB) at full resolution of the altimeter missions.

Examples of Level-3 SIT, RFB and FB in the SICCI SIT are given in Figure 1.

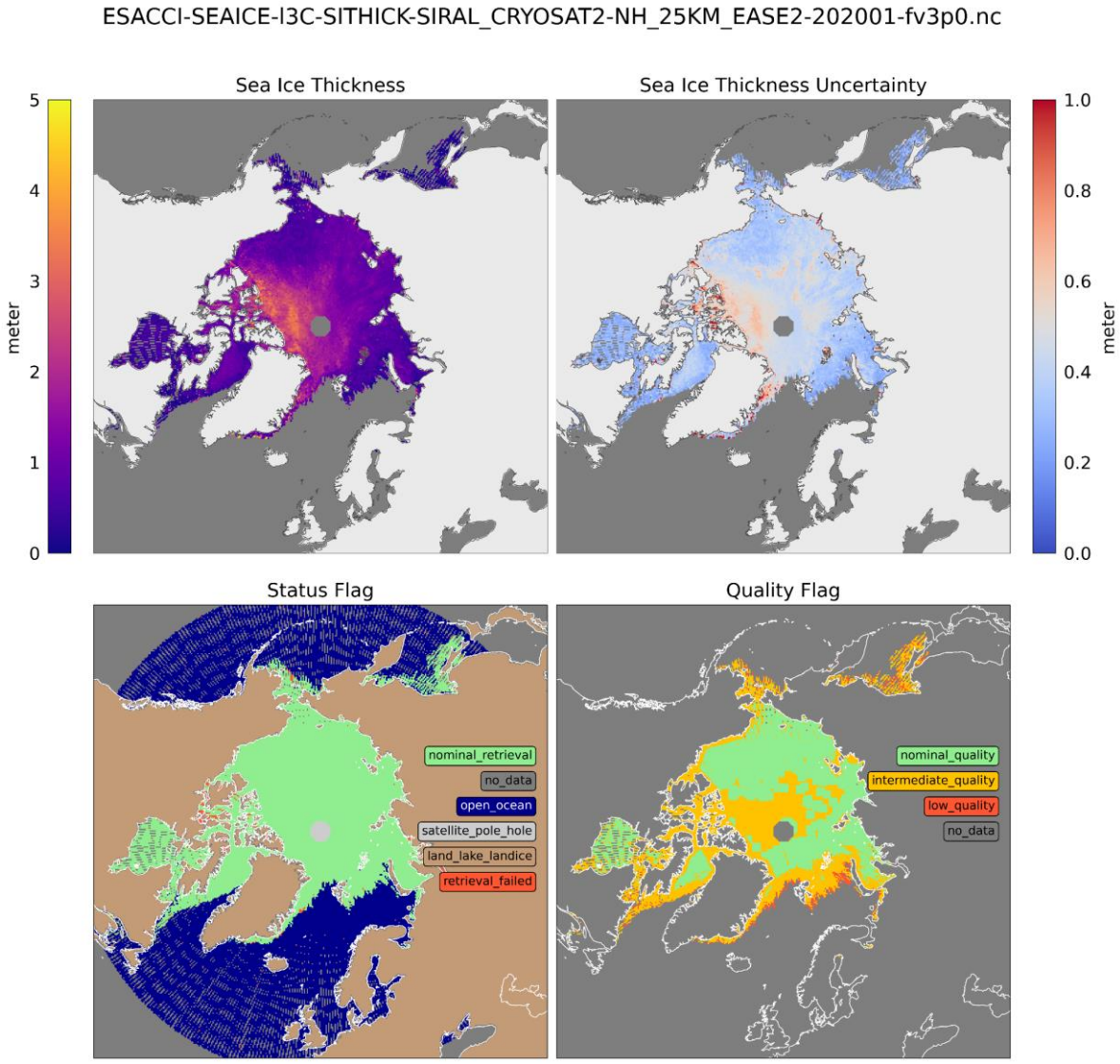

Figure 1: Arctic maps for sea ice thickness and uncertainty (top left and right respectively), status flag and quality flag (bottom left and right) for April 2020 (CryoSat-2).

The ESA CCI+ SIT v3p0 is closely related to the Copernicus Climate Change Service Sea Ice Thickness CDR, Version 3.0. The two products are similar in file format and content, but the users should always refer to the ATBD (in our case RD-1) of the corresponding products for the details of the processing.

2.1 Scientific Description of the Product

This section gives a summary of the science features of the SIT dataset, and describes first the known limitations and caveats the potential users should be aware of before analysing the dataset.

2.1.1 Known limitations and caveats

Subsections below describe the main limitations and caveats of SIT estimation from radar altimetry. These should be taken into account by all users of the product. Users wanting more detailed information on limitations and uncertainties of our products should refer to the E3UB and PVIR documents [RD-4 and RD-3].

2.1.1.1 Speckle

All radar echoes exhibit a form of signal distortion known as 'speckle'. As the speckle de-correlates between consecutive echoes, summing over several echoes reduces the noise due to speckle. Therefore, for gridded ice thickness products, the errors depend on the number of observations in a particular grid cell. The effect of speckle in a single measurement is considerable when compared to expected freeboard, which should be kept in mind when using individual measurements from the Level-2 orbit data.

2.1.1.2 Snow radar backscatter

For the Arctic, we assume that during cold winter months the dominating scattering surface for the radar is the snow/ice interface. However, one of the outcomes of the Round Robin Exercise in Phase 1, as well as results from recent scientific literature indicate that this is not always the case. Thus the user is reminded that the freeboard given in the SICCI+ Arctic SIT product files is the freeboard which we assume to be the elevation of upper surface of ice measured from local sea level due to the lack of a robust parametrization of the regional and temporal variability of a snow backscatter bias. If the dominating scattering surface lies somewhere within the snowpack, e.g. due to multiple backscattering horizons or volume scattering, sea ice thickness retrieval using the radar freeboard with the incorrect assumption will result in too large thickness estimates.

This bias will especially be prominent in the Southern Hemisphere data, with its complex snow layers.

2.1.1.3 Inter-mission consistency

The SICCI+ SIT data records consist of primary input data from two missions with different radar altimeter concepts. The RA-2 sensor on Envisat was a pulse-limited altimeter, while CryoSat-2's SIRAL employs SAR beam sharpening. This has an impact on the radar footprint size and consequently the waveform based surface type classification and freeboard retrieval as different surface types do not equally contribute to the radar return. Specifically, the larger Envisat footprint will be more susceptible to specular lead returns. The SIT algorithms are designed to minimize any inter-mission bias in the surface type classification and freeboard retrieval, however the user should be aware that a residual bias is to be expected in regions with significant surface type mixing.

2.1.1.4 Errors associated with the conversation of freeboard to thickness

The freeboard is converted into thickness by assuming the ice to be in hydrostatic equilibrium. This requires estimates of snow thickness as well as snow, ice and water densities. Uncertainty in all of these will contribute to the uncertainty of the thickness estimate.

Arctic snow depth and density is estimated using the merged monthly W99-AMSR2 snow depth climatology [further described in RD-1] for CryoSat-2 and Envisat. This is a product where snow depth estimates of Warren et al. are merged with AMSR-2 derived estimates to account for the changed snow conditions for the past two decades. The snow depth values are modified depending on ice type (50% Warren for first-year sea ice) [RD-5], though the use of a climatology means that interannual and local spatial variability are underrepresented – as is also shown in the PVASR [RD-4].

Potential changes in the seasonal cycle of the snow density as provided by the Warren et al. climatology in comparison to conditions today might exist but have not yet been investigated. We recommend to keep using the seasonally varying snow density as provided by the Warren climatology.

The sea ice density is estimated as a linear interpolation between the density of first-year and multi-year sea ice based on the multi-year ice fraction over the whole Arctic regardless of the ice type.

In the Antarctic, less information does exist on spatial and temporal variability on snow depth as well as snow and sea ice density. There are sea ice type (first and multi-year) sea ice products available by OSI-SAF for the recent years, however their coverage is incomplete for the Envisat observation period.

If users have access to alternative sources of snow information and/or ice density, they are encouraged to calculate their own thicknesses from SICCI radar freeboard or freeboard estimates.

2.1.1.5 Fitness-for-purpose of the Southern Hemisphere data

The numerous issues of the retrieval of freeboard and the freeboard-to-thickness conversion in the Southern Hemisphere has led to the decision by the data producers to label all Southern Hemisphere data sets as an experimental climate data record.

All users of the Southern Hemisphere RFB, FB & SIT data should be aware that the geophysical variables are very likely biased high to a significant degree.

2.1.2 Technical Description of the processing chain and algorithm

For a detailed description of the algorithm, users should refer to the ATBD [RD-1]. The algorithm is based on distinguishing altimeter echoes from leads and ice floes, retracking elevations for both surface types, interpolating local sea level height from lead elevations and subtracting it from floe elevations. This results in the radar freeboard. Freeboard is then obtained by applying a geometric correction based on the slower wave propagation speed through the snow layer. The thickness is thereafter calculated from the freeboard with independent estimates of snow loading and ice density, which are parametrized based on the multiyear ice fraction.

2.2 Technical Description of the Product

2.2.1 Content of product files

Product files are distributed for each combination of satellite platform, hemisphere and the two product levels. Product level 2 (L2P: Level-2 pre-processed) contains the daily orbit data at full sensor resolution, along with geophysical parameters with associated uncertainty information and auxiliary data, while product level 3 (L3C: Level-3 collated) contains the gridded geophysical parameters, their uncertainty information, auxiliary data, status flag and the relevant grid information.

2.2.1.1 The sea ice thickness and freeboard variables

There are variables for sea ice thickness, radar freeboard and freeboard (sea_ice_thickness, radar_freeboard and freeboard, respectively) in the products for both level 2 and level 3.

Note that the given values in the level 3 product are mean values of successful altimeter measurements inside the grid cell. They do not consider the fraction of open water – if only one 3 m floe is measured in one grid cell, it will result in the sea_ice_thickness of 3 m.

2.2.1.2 The uncertainty variables

Uncertainty values are given for all geophysical parameters (RFB, FB, SIT, SD) in both product levels (L2P and L3C). The uncertainty is derived from error propagation for each data record in the Level-2 files. These are in turn used in deriving the Level-3 uncertainty.

The Level-3 uncertainty is a composite of both random and systematic uncertainties. Uncertainty due to auxiliary snow estimates (depth and density) as well as sea ice density is considered systematic whereas uncertainty due to range noise and sea surface interpolation is considered random. For the details of uncertainty estimation, the users should refer to the E3UB document [RD-4].

2.2.1.3 Auxiliary Data

The Level-3 data sets also contain a variable for sea ice concentration in order to allow the computation of mean ice thickness including the open water area by the user. Also snow depth (and uncertainty) used in the radar freeboard to thickness conversion is included.

Level-3 files also contain region code to enable quick extraction of geophysical variables for certain areas. The possible values and corresponding areas are described in tables below:

Table 3: Description of region code values:

Region code value	Arctic Meaning	Antarctic Meaning
0	Undefined region	Land ice
1	Central Arctic	Ice free ocean
2	Beaufort Sea	Indian Ocean

3	Chukchi Sea	Western Pacific Ocean
4	East Siberian Sea	Ross Sea
5	Laptev Sea	Bellinghausen & Amundsen Sea
6	Kara Sea	Weddell Sea
7	Barents Sea	Not Used
8	East Greenland Sea	Not Used
9	Baffin Bay & Labrador Sea	Not Used
10	Gulf of St. Lawrence	Not Used
11	Hudson Bay	Not Used
12	Canadian archipelago	Not Used
13	Bering Sea	Not Used
14	Sea of Okhotsk	Not Used
15	Sea of Japan	Not Used
16	Bohai Sea	Not Used
17	Baltic Sea	Not Used
18	Gulf of Alaska	Not Used
20	Not Used	Land

2.2.1.4 Status and Quality Flags

The status_flag and quality_flag fields are only applicable for the Level-3 data products. The possible values and their explanations are given in Table below and an example plot shown in Figure 1:

Table 3: Description of status_flag values.

Flag value	Meaning	Comment
0	no input data	Ocean, but no FB measurements available. Most likely open water.
1	no valid retrieval	Outside sea ice concentration mask, no SIT, RFB or FB.
2	polehole	No SIT data is provided because missing satellite input data due to the pole hole (lat > 81.5N for Envisat, lat>88N for CryoSat-2).

3	land, lake or land ice	No SIT data is provided because there is land, lake or land ice in the grid cell (either full or fractional cover).
4	FB but no SIT	Sea ice thickness retrieval failed.
5	nominal	SIT, RFB and FB values given

Table 4: Description of quality_flag values.

Flag value	Meaning	Criterion
3	No data	No FB measurements available
2	Low quality	● Less than 10 Level-2 thickness data points per grid cell, or ● Negative thickness fraction > 40%, or ● Median of marginal ice zone filter flag value is 2
1	Intermediate quality	● CryoSat-2 in SIN mode (CryoSat-2 specific), or ● Area lead fraction (the maximum lead fraction in grid cells with 75 km search radius) < 10%, or ● Less than 50 Level-2 thickness data points per grid cell, or ● Negative thickness fraction between 20% - 40%, or ● Median of marginal ice zone filter flag value is 1
0	Nominal	No criterion above met

2.2.2 Temporal coverage

The dataset covers the Arctic winter months (October, November, December, January, February, March and April) and the full annual cycle in the Antarctic, for both levels 2 and 3. Envisat data products are available from 2002 (Arctic: October, Antarctic: June) through March 2012. CryoSat-2 data products are available from November 2010 through April 2020.

2.2.3 Level-3 product grid and geographic projection

All SIT datasets are delivered on a polar EASE2 grid, with a grid spacing of 25 km (Arctic) and 50 km (Antarctic). The EASE2 projection is defined in [RD-8]. The grid is defined by:

Table 4: Grid definition

Grid ID	PROJ4 string	X,Y boundaries and spacing [m]	Latitude-Longitude bounding box [deg]
NH25 km EASE2	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=+90.0 +lat_ts=+70	x_min: -5400000 x_max: 5400000 dx: 25000 y_min: -5400000 y_max: 5400000 dy: 25000	:geospatial_lat_min = 16.42 :geospatial_lat_max = 90.0 :geospatial_lon_min = -180.0, :geospatial_lon_max = 180.0 ;
SH50 km EASE2	+proj=laea +lon_0=0 +datum=WGS84 +ellps=WGS84 +lat_0=-90.0 +lat_ts=-70	x_min: -5400000 x_max: 5400000 dx: 50000 y_min: -5400000 y_max: 5400000 dy: 50000	:geospatial_lat_min = -16.42 :geospatial_lat_max = -90.0 :geospatial_lon_min = -180.0, :geospatial_lon_max = 180.0 ;

2.2.4 Convention for file names

The Sea Ice Thickness dataset file naming follows the form:

ESACCI-SEAICE-<PRDLVL>-SITHICK-<INSTR>-<REGION>-<YYYYMM>-fv<VER>.nc

where the values for each <FIELD> can be:

- <PRDLVL> : Product Level (L2P or L3C)
- <INSTR> : RA2_ENVISAT, SIRAL_CRYOSAT
- <REGION> : L2P: NH, SH
  L3C: NH25kmEASE2, SH50kmEASE2
- <PERIOD> : date string of the data period
  L2P: YYYYMMDD, L3C: YYYYMM
- <VER> : product version (<XpY>)

2.2.5 File format

Following [RD-6], the Sea Ice Thickness datasets are netCDF files that follow the Climate and Forecast (CF) convention (*http://cfconventions.org*).

2.2.6 Data Access

The SIT CDR data products can be accessed via the search function at the ESA CCI Open data portal (http://cci.esa.int/data) with the search text “sea ice thickness”.

Direct anonymous ftp access is also possible with the following address:

ftp://anon-ftp.ceda.ac.uk/neodc/esacci/sea_ice/data/sea_ice_thickness/

The data is structured in a sub-folders:

1. Product level “l2p” or “l3c”
2. Platform “envisat” or “cryosat2”
3. Version “v3.0”
4. Hemisphere “NH” or “SH”
5. Year YYYY
6. Month MM (*L2P only*)

2.2.7 Digital Object Identifiers

The SIT data has been archived at the Centre for Environmental Data Analysis (CEDA) and linked to a doi. A product is defined as all netcdf files with common platform, product level and hemisphere. In the table (Table 5) below.

Table 5: SIT data product DOI's

SIT dataset	DOI
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Northern** hemisphere sea ice thickness from **Envisat** on the satellite swath (**L2P**), v3.0	10.5285/92eb2ba942074bec804af6a8b5436bee
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Southern** hemisphere sea ice thickness from **Envisat** on the satellite swath (**L2P**), v3.0	10.5285/af96a1ec493f49caa39dc912d15f2b17
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Northern** hemisphere sea ice thickness from the **Envisat** satellite on a monthly grid (**L3C**), v3.0	10.5285/83b11005a3d7472eb57df4f90933c462
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Southern** hemisphere sea ice thickness from the **Envisat** satellite on a monthly grid (**L3C**), v3.0	10.5285/ab6a05baacce4c848d137a0bc9921e6e

ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Northern** hemisphere sea ice thickness from **CryoSat-2** on the satellite swath (**L2P**), v3.0	10.5285/c6504378f78c4ecd9f839b0434023eff
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Southern** hemisphere sea ice thickness from **CryoSat-2** on the satellite swath (**L2P**), v3.0	10.5285/861ad3c7f3a34ebd8be6f618a92bd8e3
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Northern** hemisphere sea ice thickness from the **CryoSat-2** satellite on a monthly grid (**L3C**), v3.0	10.5285/45b5b1e556da448089e2b57452f277f5
ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): **Southern** hemisphere sea ice thickness from the **CryoSat-2** satellite on a monthly grid (**L3C**), v3.0	10.5285/67b003a864cd4e9ebeccd29fbdf4447e

2.2.8 Data Citation

Users should cite the data in their publication with the template

Hendricks, S.; Paul, S.; Rinne, E. (2024): ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): [***Northern|Southern***] hemisphere sea ice thickness from [***Envisat|CryoSat-2***] on [***the satellite swath (L2P)|a monthly grid (L3C)***], v3.0. Centre for Environmental Data Analysis, ***date of citation***. ***DOI***, ***LINK***

Depending on the used data product, e.g., gridded data form Envisat in the Southern Hemisphere, should be cited as:

Hendricks, S.; Paul, S.; Rinne, E. (2024): ESA Sea Ice Climate Change Initiative (Sea_Ice_cci): Southern hemisphere sea ice thickness from Envisat on the satellite swath (L2P), v3.0. NERC EDS Centre for Environmental Data Analysis, *2024-03-01*. Doi: 10.5285/af96a1ec493f49caa39dc912d15f2b17, https://catalogue.ceda.ac.uk/uuid/af96a1ec493f49caa39dc912d15f2b17