Cryo-TEMPO

Product Handbook

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Acronyms and Abbreviations

AD	Applicable Document
ADT	Absolute Dynamic Topography
AMSR	Advanced Microwave Scanning Radiometer
AO	Announcement of Opportunity
ATBD	Algorithm Theoretical Basis Document
C3S	Copernicus Climate Change Service
CCI	Climate Change Initiative
CCN	Contract Change Notice
CLS	Collecte Localisation Satellites
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National des Etudes Spatiales (French Space Agency)
CNR	Consiglio Nazionale delle Ricerche
CO	Coastal Ocean
CPOM	Centre for Polar Observation & Modelling
CR	Change Request
CRISTAL	Copernicus Polar Ice and Snow Topography Altimeter
DAHITI	Database for Hydrological Time Series of Inland Waters
DEM	Digital Elevation Model
DOT	Dynamic Ocean Topography
DTU	Technical University of Denmark
DUACS	Data Unification and Altimeter Combination System
EGM	Earth Gravitational Model
EO	Earth Observation
ERR	Evolutions Recommendation Report
ESA	European Space Agency
GIMP	Greenland Ice sheet Mapping Project
GLWD	Global Lakes and Wetlands Database
GOP	Geophysical Ocean Products
GSFC	Goddard Space Flight Centre
GSHHG	Global Self-consistent, Hierarchical, High-resolution Geography
GSWE	Global Surface Water Explorer
G-REALM	Global Reservoirs and Lakes Monitor
IAG	International Association of Geodesy
IMBIE	Ice Sheet Mass Balance Intercomparison Exercise
IMEDEA	Instituto Mediterráneo de Estudios Avanzados
IPCC	Intergovernmental Panel on Climate Change
IRPI	Istituto di Ricerca per la Protezione Idrogeologica
ISO	International Organization for Standardization
ISRO	Indian Space Research Organisation
ITT	Invitation To Tender
IW	Inland Water
JPL	Jet Propulsion Laboratory
L1	Level-1
LEGOS	Laboratoire d'Étude en Géophysique et Océanographie Spatiale
LRM	Low Resolution Mode
LU	Lancaster University
MDT	Mean Dynamic Typography
MSS	Mean Sea Surface
MSSL	Mullard Space Science Laboratory (part of UCL)
NASA	The National Aeronautics and Space Administration
NERSC	Nansen Environmental and Remote Sensing Center
NSF	National Science Foundation
OCOG	Offset Centre Of Gravity retracker

PEG	Polar Expert Group
POCA	Point of Closest Approach
PO	Polar Oceans
PRF	Pulse Repetition Frequency
PSMSL	Permanent Service for Mean Sea Level
RD	Reference Document
REAPER	Reprocessing of Altimeter Products for ERS
REMA	Reference Elevation Model of Antarctica
RMSD	Root mean square difference
SAMOSA	SAR Altimetry Mode Studies and Applications
SAR	Synthetic Aperture Radar
SARAL	Satellite with Argos and AltiKa
SARIn	Synthetic Aperture Radar Interferometric
SI	Sea Ice
SIRAL	SAR Interferometric Radar Altimeter
SLA	Sea Level Anomaly
SSH	Sea Surface Height
TAI	Temps Atomique International
TCOG	Threshold Centre of Gravity
TDP	Thematic Data Product
TFMRA	Threshold First Maximum Retracker Algorithm
TUG	Thematic User Group
UCL	University College London
UCM	User Consultation Meeting
UTC	Coordinated Universal Time
WGS	World Geodetic System
WSH	Water Surface Height
WTC	Wet Troposphere Correction

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1 SUMMARY

The Cryo-TEMPO project brings together a team of radar altimetry scientific experts and software engineers to generate agile and state-of-the-art Thematic Data Products (TDP's), which aim to open up CryoSat-2 datasets to new sectors and user groups.

The TDP's produced by Cryo-TEMPO will provide dedicated, bespoke satellite altimetry products for the following five thematic areas:

This handbook is designed to support both novice and more advanced users, and to serve as a reference guide for anyone wishing to make use of the European Space Agency (ESA's) Cryo-TEMPO suite of thematic products. It provides fundamental information on the theory underpinning the products, and the technical specifications of the data that can be accessed. It also provides links to the more in-depth literature and information on the theory and technical aspects of the products being distributed. The handbook is structured as follows.

Within **Section 2** of this handbook, newcomers to satellite altimetry data can find basic information on altimetry, including how to interpret and understand the Cryo-TEMPO data files distributed by ESA. For more expert users, the overview information is presented here, with more technical, and in-depth information available in the referenced literature.

Section 3 of this handbook describes the Thematic data products for each thematic area.

Section 4 of this handbook describes the technical specifications of each thematic product, including the format, content and structure of the Cryo-TEMPO data files.

1.1 Document Scope

This Product Handbook document comprises the Deliverable D1b for the *CryoSat-2 ThEMatic PrOducts* (*Cryo-TEMPO*) study, Ref: ESA AO/1-10244/2-/I-NS, and describes products from Cryo-TEMPO Baseline-B. The Document has been written by Ole Baltazar Andersen, DTU Space, with contributions from all members of the Cryo-TEMPO consortium. Lancaster University as the prime contractor is the contact point for all communications regarding this document.

1.2 Applicable and Reference Documents

Applicable documents

Reference	Title
AD1	Statement of Work ESA Express Procurement Plus - EXPRO+ CryoSat-2 ThEMatic PrOducts | Cryo-TEMPO, Issue 1, Revision 0, Date of Issue 01/04/2020 [Ref. ESA-EOPG-EOPGMQ-SOW-10].
AD2	Invitation to Tender for CryoSat-2 ThEMatic PrOducts | Cryo-TEMPO REF.: ESA AO/1-10244/2-/I-NS [Ref. SA-IPL-POE-NS-sp-LE-2020-313].

Reference documents

Reference	Title
RD1	Copernicus Polar and Snow Cover Applications User Requirements Workshop, http://www.copernicus.eu/polar-snow-workshop
RD2	PEG-1 Report, User Requirements for a Copernicus Polar Mission, Step 1 Report, Polar Expert Group, Issue: 12th June 2017
RD3	PEG-2 Report, Polar Expert Group, Phase 2 Report on Users Requirements, Issue: 31st July 2017
RD4	Baseline-C CryoSat Ocean Processor – Ocean Product Handbook, Version 4.1, 5 December 2019, https://earth.esa.int/documents/10174/125272/CryoSat-Baseline-C-Ocean-Product-Handbook

2 INTRODUCTION

2.1 The CryoSat-2 Mission

Cryo-TEMPO provides data products based upon data acquired by the CryoSat-2 satellite, since its launch on 8 April 2010. CryoSat-2 is an ESA Earth Explorer mission dedicated to precise monitoring of the changes in the thickness of marine sea-ice floating in the polar oceans and variations in the elevation of the vast ice sheets of Greenland and Antarctica. CryoSat-2 carries an advanced radar altimeter specifically designed to monitor the most dynamic sections of Earth's cryosphere. It has an orbital inclination of 92 degrees (allowing measurements to within 2 degrees of the poles) and a long quasi orbital repeat of 369 days. It borrows synthetic aperture radar (SAR) and interferometry techniques from standard imaging radar missions to sharpen its accuracy over rugged ice sheet margins and sea ice in polar waters. The primary payload is the SAR Interferometric Radar Altimeter (SIRAL) which has extended capabilities to meet the measurement requirements for ice sheet elevation and sea ice freeboard.

After more than 10 years in orbit, CryoSat-2 has now far surpassed its initial design lifetime of 3.5 years, providing a decade of measurements with which to monitor and understand our changing planet. Furthermore, going beyond its primary mission objectives of both land and sea ice (Laxon et al., 2013; McMillan et al., 2014, 2016; Tilling et al., 2015), CryoSat-2 is now also a valuable source of data for the oceanographic and hydrological communities. The satellite's radar altimeter can measure high-resolution geophysical parameters not only over Earth's cryosphere, but also from the open ocean to the coast; meaning that its measurements are of great value to a broad spectrum of climate research communities.

2.2 Operating Modes

SIRAL (CryoSat-2's radar altimetry instrument) has been designed with three different operating modes: Low Resolution Mode (LRM), Synthetic Aperture Radar (SAR) mode, and SAR Interferometric mode (SARin). These are specifically designed to monitor different types of surfaces, each with its own topographic characteristics, namely sea ice (SAR), rugged ice sheet margins (SARIn), and flat ice sheet interiors and open ocean (LRM). In practice, the precise mode of operation (LRM, SAR or SARIn) at any point in space and time is selected based upon a predefined mask of geographical zones, which is updated every two weeks to account for changes in sea ice extent (see RD4 for more details).

In LRM mode, pulses are sent at intervals of about 500 µs (equivalent to a Pulse Repetition Frequency (PRF) of about 2 kHz) ensuring that the returning echoes are uncorrelated. This mode of measurement is suitable over flat surfaces (ocean and ice-sheet interiors).

In SAR mode, complex bursts are transmitted to the ground at a PRF of about 18 kHz, to allow on-ground delay-Doppler processing. This mode is used to achieve high resolution in the along-track direction.

In SARIn mode, complex bursts are received by two antennas mounted ~ 1 meter apart on the spacecraft, allowing the precise retrieval of the location of the surface echo in the across-track plane, using interferometric techniques. As with the SAR mode of operation, through delay-Doppler processing, SARIn mode also provides improved along-track resolution. SARIn mode is generally used across the ice sheet margins and over mountain glaciers, where the surface topography is complex.

2.3 Satellite Altimetry Basics

Like all altimetry satellites, CryoSat-2 emits radio-wave pulses and records their reflection from Earth's surface, converting the timing, power and shape of the received echo waveform into range from the satellite center of mass to Earth's surface, as well as providing an indication of its roughness at various scales, and penetration depth (Figure 1). Timing, power and shape are obtained by fitting a physical or statistical model to the observed return echo, a process known as "retracking". To convert the timing of the reflected echo into a range from the satellite to Earth's surface, a series of geophysical corrections are applied in order to account for factors such as the varying propagation speed of the radio-wave pulse through Earth's troposphere and ionosphere. As the satellite's orbital position is known with very high degree of accuracy with respect to a reference datum, one can then compute the height of the reflecting surface relative to that datum by differencing the altitude of the satellite and the measured corrected range. For further information relating to the underlying principles of radar altimetry, the reader is referred to dedicated texts, such as Fu and Cazenave (2001) and Stammer and Cazenave (2018), and references therein.

While the working principle of altimetry is simple, the practical application is complicated by the required level of precision, which is typically a few cm, from a satellite orbiting at an altitude of ~700 km – a precision greater than one part in ten million. As an analogy, it is as if you went to the bakery to buy a standard loaf of bread (about 1 kg) and wanted to know its weight to an accuracy of less than 0.1 mg. This "one part in ten million" precision needs not only to be achieved, but also to be maintained through time, which places challenging requirements upon the entire altimeter system (e.g. both the instrument and the processing chain, including the various geophysical corrections). It is also a requirement in order to be able to precisely track long-term sea level rise, which is currently measured with an accuracy of 0.5 mm/y (ESA, 2020).

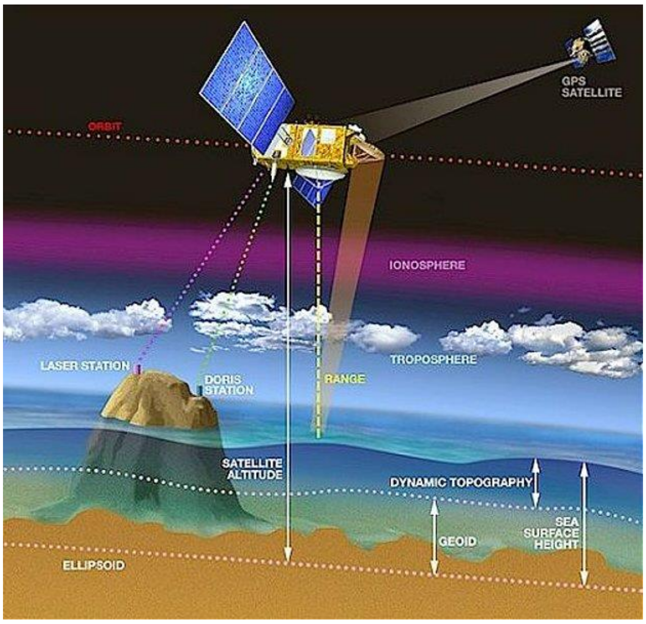


Figure 1. Example of altimetry principle over the ocean surface. The same principle is also valid over the others geophysical surfaces (e.g. ice and inland water surfaces). Image credit: https://www.aviso.altimetry.fr/en/techniques/altimetry/principle/basic-principle.html

2.4 Cryo-TEMPO Thematic Products

Cryo-TEMPO aims to deliver state-of-the-art, domain-specific, and simple-to-use products, derived from dedicated CryoSat-2 radar altimetry processing. For each thematic area, the product is designed with the following objectives in mind, namely to deliver:

a) A limited set of parameters to the non-expert user.
b) A product that maintains the native high along-track sampling rate of the altimeter.
c) Dedicated, traceable uncertainties.
d) Domain-specific parameters that are relevant to each individual thematic area.

In the following sections, we outline – for each thematic area – potential use cases for the Cryo-TEMPO products. These examples are not exhaustive, but are aimed at illustrating to the reader the range of applications for which these datasets are suited.

2.5 Cryo-TEMPO Thematic Use Cases

2.5.1 Land Ice

The Cryo-TEMPO Land Ice thematic product provides a 12-year, quality-controlled record of surface elevation of the Greenland and Antarctic Ice Sheets. As such, it has a wide range of potential uses for both the specialist and non-specialist user, including the production of timestamped Digital Elevation Models (DEM's), surface slope models, and calculation of rates of ice sheet surface elevation and volume change. In turn, these data can be used to study a diverse range of climatological and glaciological processes. Below several potential use cases of this product are described, with reference to illustrative examples that have used CryoSat-2 altimetry data.

2.5.1.1 Digital Elevation Models

Cryo-TEMPO land ice elevation measurements can be used to generate DEM's of the ice sheet surface, as shown in Figure 2. Ice Sheet DEM's have a wide range of applications, encompassing fieldwork planning, modelling and satellite Earth Observation (EO). In particular, topographic information serves as an important boundary condition for regional climate models and dynamical ice sheet models, both of which are an essential component of climate projections and forecasts of future sea level rise.

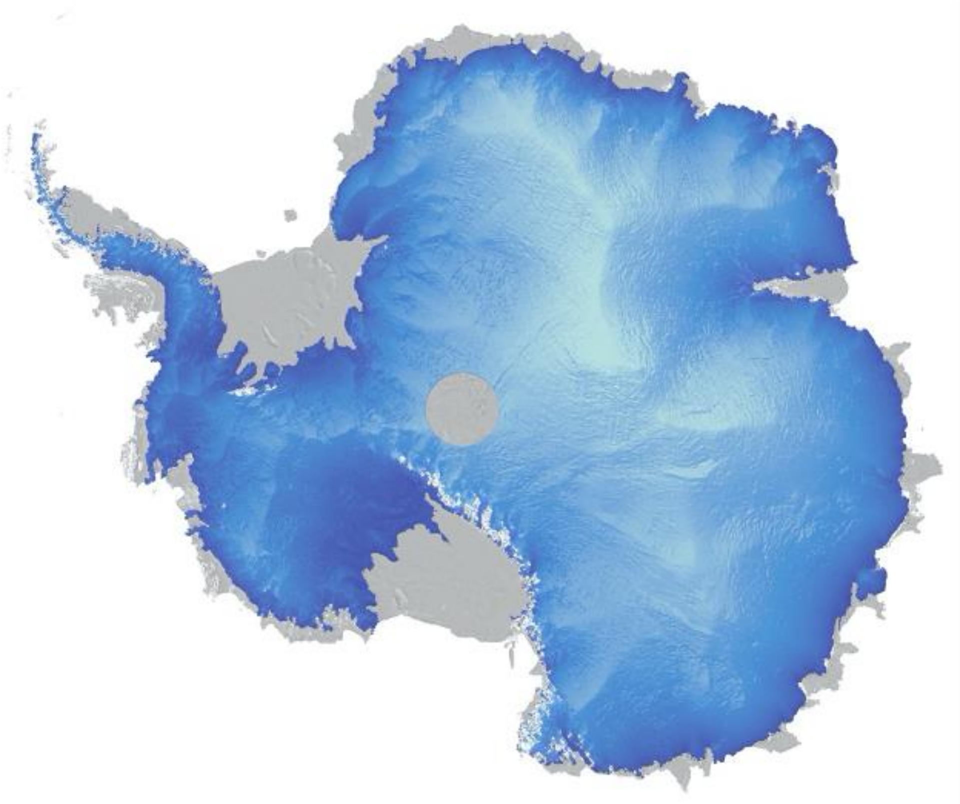


Figure 2. A Digital Elevation Model of the Antarctic Ice Sheet derived from CryoSat-2 measurements [*credit: McMillan / CPOM*].

2.5.1.2 Surface Slope Models

Cryo-TEMPO land ice elevation measurements can also be used to generate maps of surface slope (Figure 3), which provides information relating to the position and migration of glacier grounding lines, and the locations of ice divides and subglacial lakes.

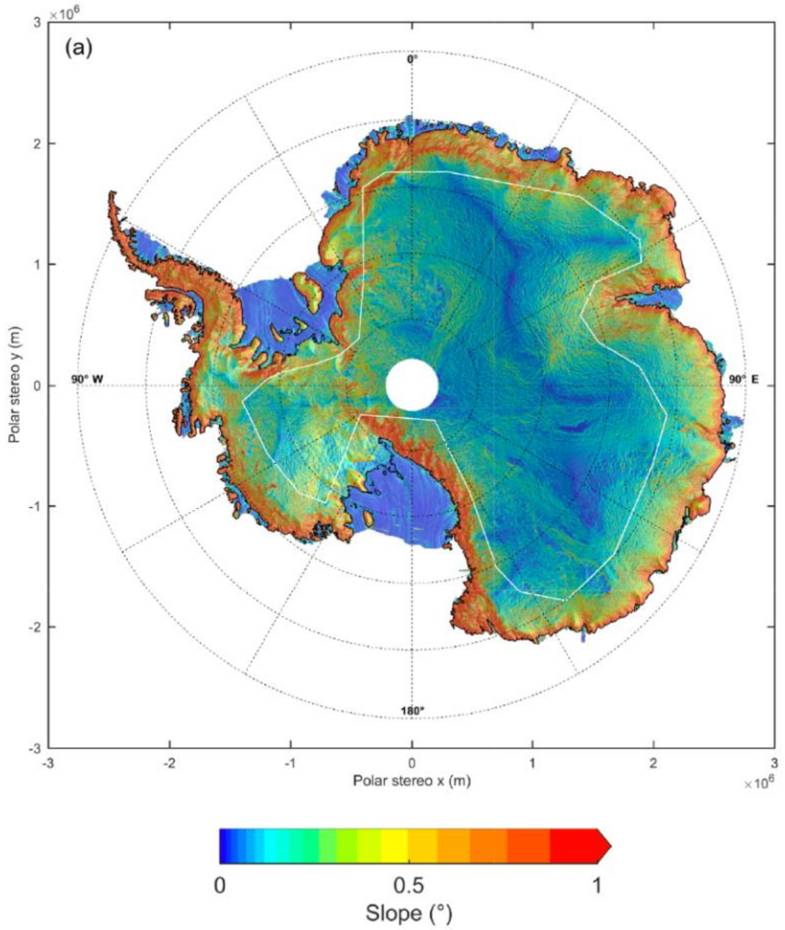


Figure 3. Surface slope of the Antarctic Ice Sheet derived from CryoSat-2 measurements (Slater et al., 2018).

2.5.1.3 Surface Elevation Change

The continuous 10-year record of Cryo-TEMPO land ice elevation measurements can be used to generate estimates of ice sheet surface elevation change (Figure 4). Such datasets have a wide range of applications including the determination of ice sheet mass balance, estimation of ice sheet's sea level contribution, detection of ice sheet grounding line retreat, measurement of ice shelf thinning, and the evaluation of ice sheet models.

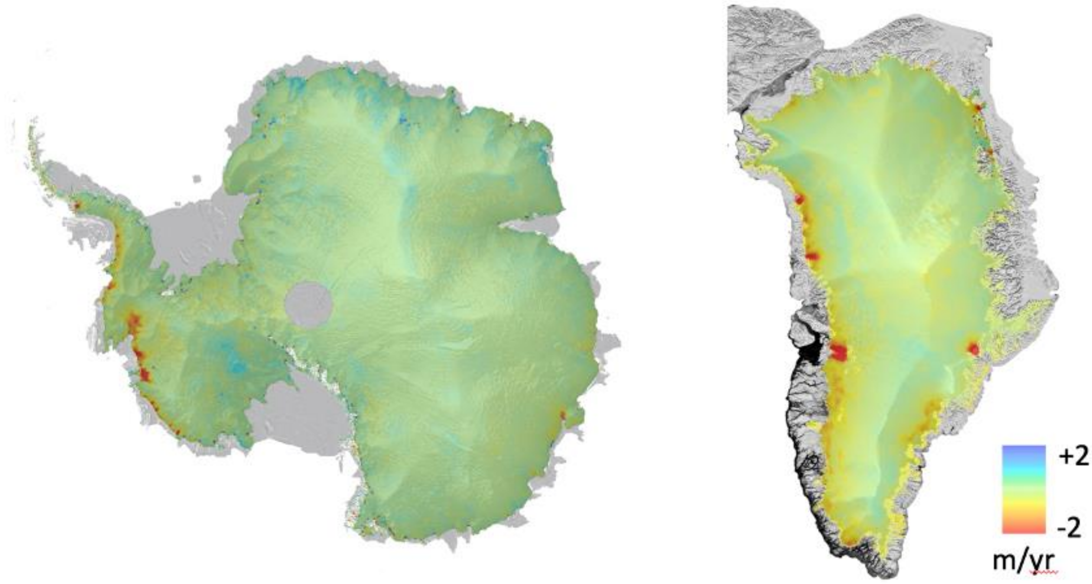


Figure 4. Surface elevation change of the Antarctic and Greenland and ice sheets derived from CryoSat-2 measurements (McMillan et al., 2014; McMillan et al., 2016).

2.5.1.4 Subglacial Lake Activity

Cryo-TEMPO land ice elevation measurements can be used to monitor subglacial lake activity beneath the Antarctic Ice Sheet, by resolving the surface imprint of lakes filling and draining (Figure 5). Such information can, in turn, be used to derive information about the elusive subglacial environment such as geothermal heat flux and hydrological pathways.

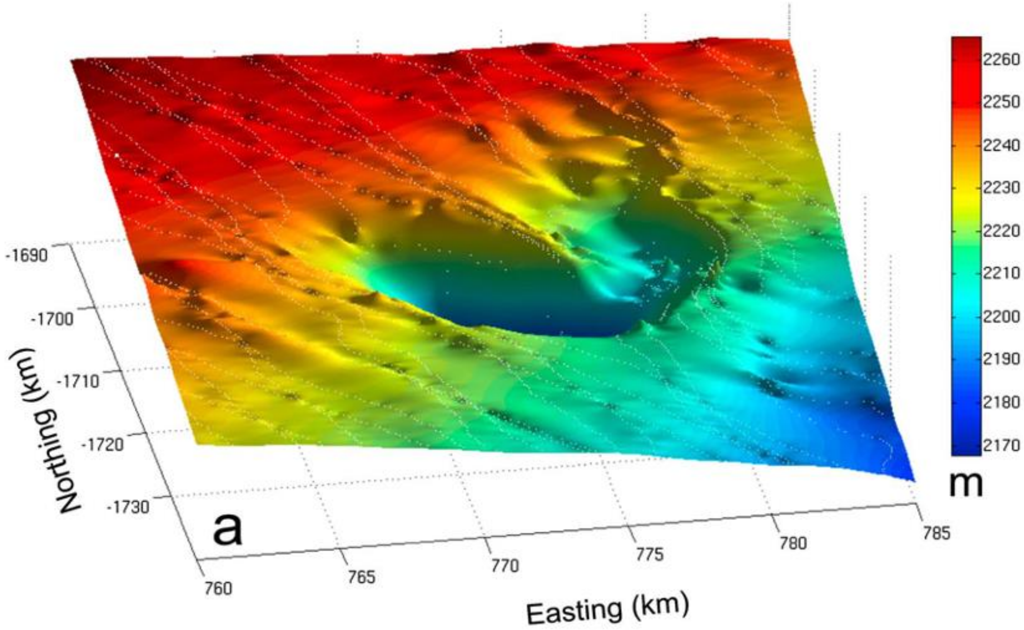


Figure 5. The ice surface topography above the Cook E2 subglacial lake in East Antarctica, showing a vast crater in the ice sheet surface which formed when an underlying subglacial lake drained (McMillan et al., 2013).

2.5.1.4 Bayesian Calibration of Ice Sheet Model Ensembles

Ensembles of ice sheet model simulations can be used to explore the sensitivity of model projections to parameter perturbations and other model inputs. Such ensembles can provide a wide distribution of sea level contributions over the next century and therefore observations can be used as reference, as part of a process to constrain uncertainty via calibration. To illustrate this, an example of a comparison between observed rates of surface elevation change – derived from Cryo-TEMPO baseline A data in the Amundsen Sea sector of West Antarctica – and a subset of a 284-member ensemble of the BISICLES model is shown in Figure 6 below.

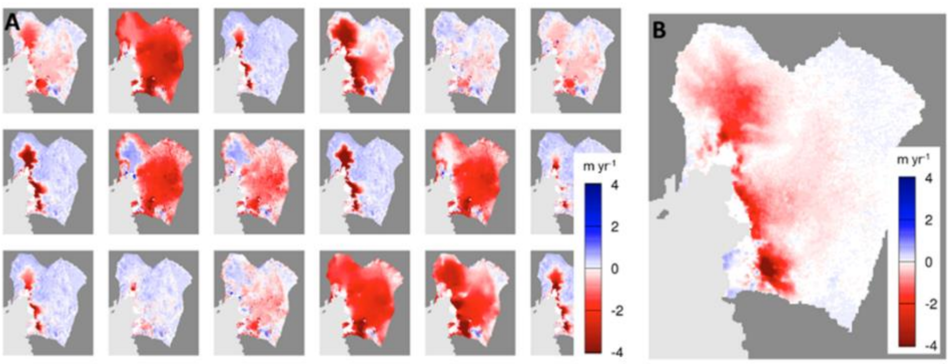


Figure 66. Rates of surface elevation change in the Amundsen Sea Sector of West Antarctica for a subset of a 284-member ensemble of BISICLE model simulations (A, adapted from Nias et al., 2016) and the Cryo-TEMPO TDP 2011-2021 mean (B).

2.5.2 Sea Ice

The Cryo-TEMPO Sea Ice product provides a 12-year, quality controlled, data record of radar freeboard, sea-ice freeboard with associated uncertainties and state-of-the-art snow on sea ice information. The data are available for the Arctic, covering the winter months between October through to April. The data are provided at full resolution and with low-level freeboard information to allow a wide range of customizable applications, targeted primarily for the expert user in polar remote sensing and numerical modelling, or for operational centres that use the CryoSat-2 freeboard data as input to downstream services. A selected list of use cases is given below.

2.5.2.1 Gridded sea-ice freeboard for customizable grids and periods

Trajectory-based sea-ice freeboard information can be used to create gridded fields with customizable projections as well as spatial and temporal coverage. This is especially important for applications that require uncertainty estimations, since freeboard uncertainty on a grid level depends on the number of aggregated trajectory-based observation in the grid cell and this information cannot directly be transformed from grid to another by reprojection. Likewise, the trajectory-based data dissemination provided by the Cryo-TEMPO sea ice product allows flexibility with respect to the temporal coverage of grids, especially for applications that require higher temporal resolution than the often-used monthly periods. An example is shown in Figure 7 with a gridded weekly period at a resolution of 12.5 km.

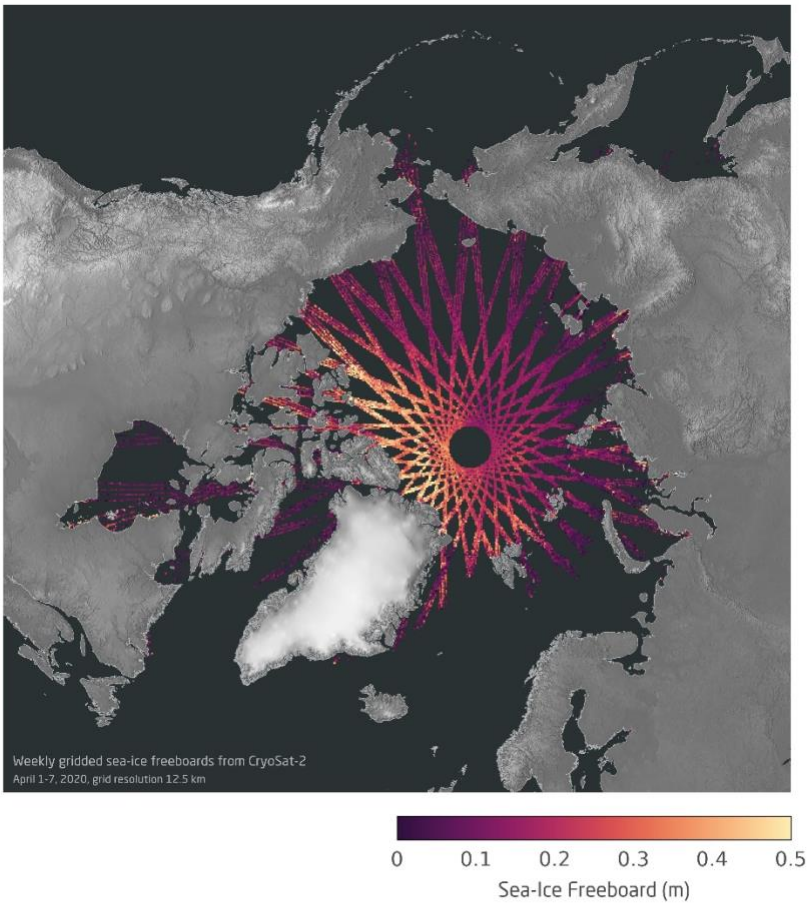


Figure 7. Sea-ice freeboard with observations from 7 days (April 1-7, 2020) gridded to custom grid with a grid resolution of 12.5 km.

2.5.2.2 Sea-ice freeboard evolution along drifting sea ice

Trajectory based sea-ice information from radar altimetry is also uniquely suited to analysing the sea-ice evolution along its drift path. Figure 8 shows an example of sea-ice freeboard measurements recorded within a 50 km radius around the ice drift of the research icebreaker *Polarstern*, from October 2019 until April 2020. Such data are very important for charting the evolution of the sea-ice freeboard along the drift path of the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC) study (Mosaic-expedition.org).

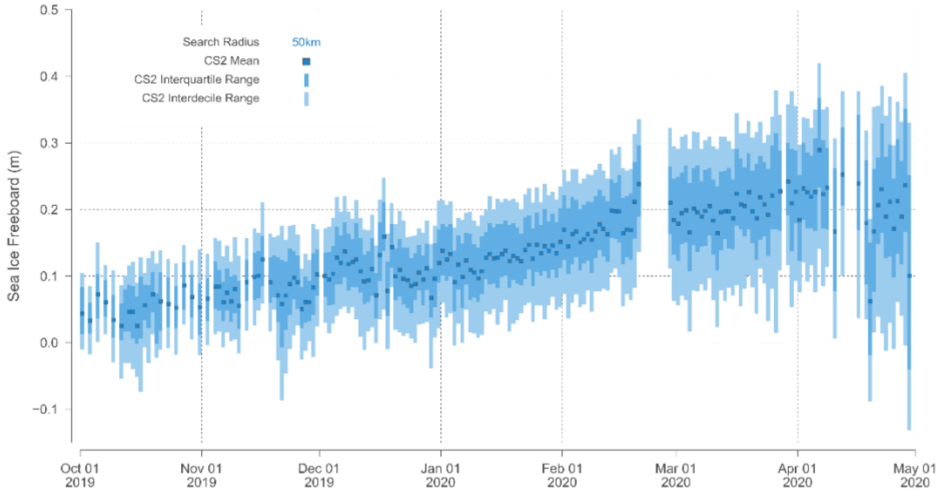


Figure 8. Sea-ice freeboard distribution extracted along the drift path of the research icebreaker Polarstern during the Multidisciplinary drifting Observatory for the Study of Arctic Climate (MOSAiC), within a search radius of 50 km (adapted from Krumpen et al., 2021).

2.5.2.3 Use of freeboard as a low-level assimilation parameter in numerical models

The 10-year data record of sea ice variables from CryoSat-2 represents a valuable source for assimilation into numerical sea ice models (e.g., Kaminski et al., 2018). Lower-level parameters such as radar freeboard have the advantage of being close to the actual observation of the satellite with a few assumptions and input by auxiliary data required. As such, they can therefore function effectively as an observational operator for sea-ice thickness remote sensing data.

2.5.2.3 Custom sea-ice thickness time series

Combining all the use cases above, the Cryo-TEMPO Sea Ice product can be used to explore novel strategies for the sea-ice freeboard to thickness conversions, e.g., Mallett et al., 2020. The objective of these custom time series may range from using improved auxiliary datasets, to establishing consistency with other methods and altimeter platforms.

2.5.3 Polar Ocean

The Cryo-TEMPO Polar Ocean product provides a 10-year, quality-controlled record of sea level anomalies and dynamic ocean topography of the Arctic Ocean. As such it has a wide range of potential uses for both the specialist and non-specialist user, including the production of time series of sea level rise, regional trend maps, ocean circulation, freshwater fractions, and sea level budget. In turn these data can be used to study a diverse range of climatological and oceanographic processes. Below, several potential use cases of this product are described, with reference to illustrative past examples which have used CryoSat-2 data.

2.5.3.1 Regional Sea Level Rise

The continuous 10-year record of Cryo-TEMPO Polar Ocean sea level anomaly measurements can be used to generate time series and regional trend maps of Polar Ocean sea level rise (Figure 9). This product has many applications, including the understanding of Polar Ocean dynamics, ocean-ice interactions, studying the regional and global sea level, and as input to coupled climate models.

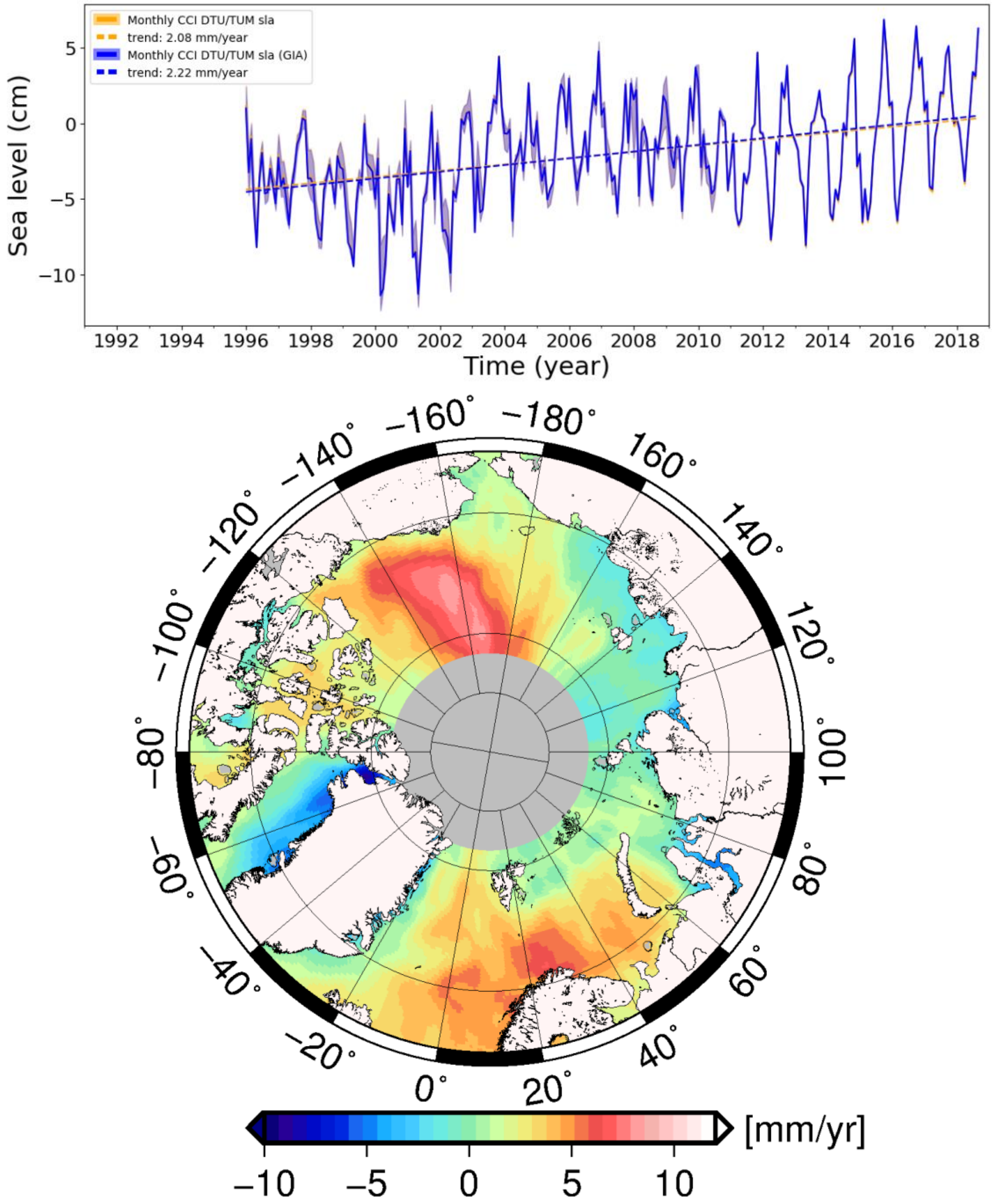


Figure 9. Top: Sea level trends and monthly averaged sea level anomalies of the Pan-Arctic. Bottom: Spatial sea level trends (Rose et.al. 2019)

2.5.3.2 Ocean Circulation

The Cryo-TEMPO Polar Ocean absolute dynamic topography (ADT) can be used to derive surface geostrophic currents (Figure 10). These currents have multiple applications such as studying the general large-scale patterns of ice drift, and major surface circulation features such as the Beaufort Gyre, the Transpolar Drift and the Nordic Seas circulation (e.g., Raj et al., 2018).

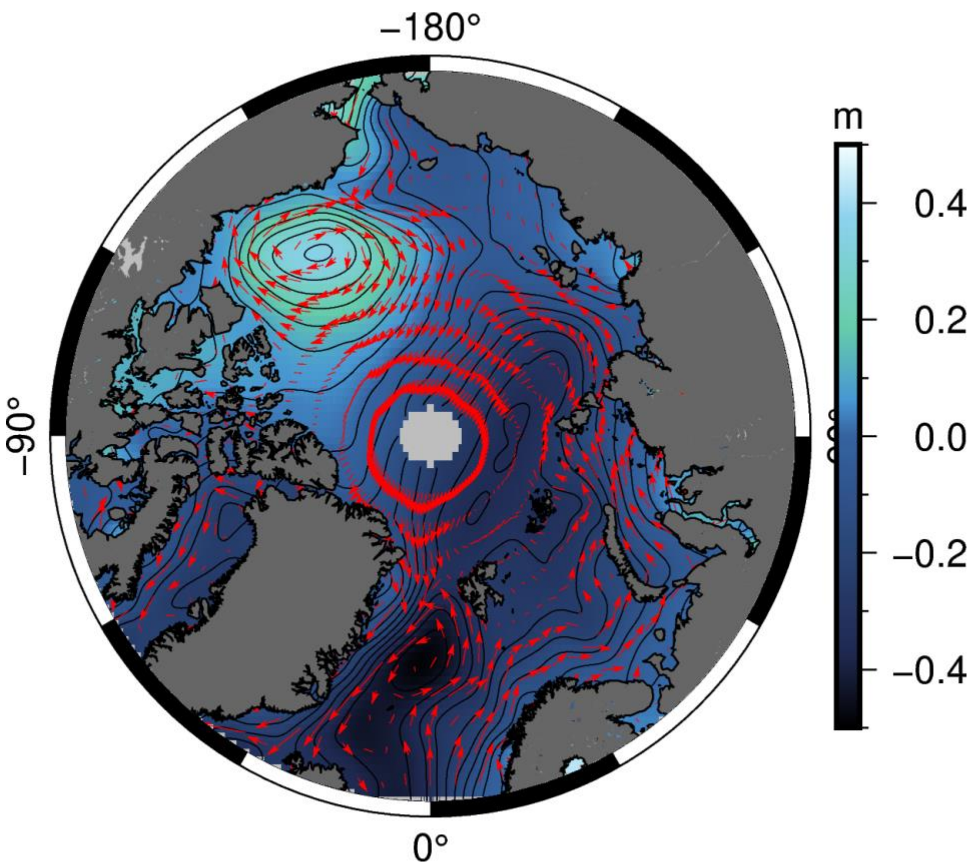


Figure 10. Mean Dynamic Ocean Topography (DOT) derived from averaging Cryosat-2 ADT from 2010-2020 overlayed with geostrophic currents calculated from CryoSat-2.

2.5.3.3 Fresh Water Content

All fresh water from melting glaciers and river outflows ends up in the Polar Oceans. Cryo-TEMPO polar ocean products can be used to examine the amount and the origin of this water. For example, to undertake dedicated study of these processes in the Beaufort Gyre region, which is the largest reservoir of freshwater in the Arctic Ocean (Figure 10). See also Figure 3 in Solomon et al. (2021).

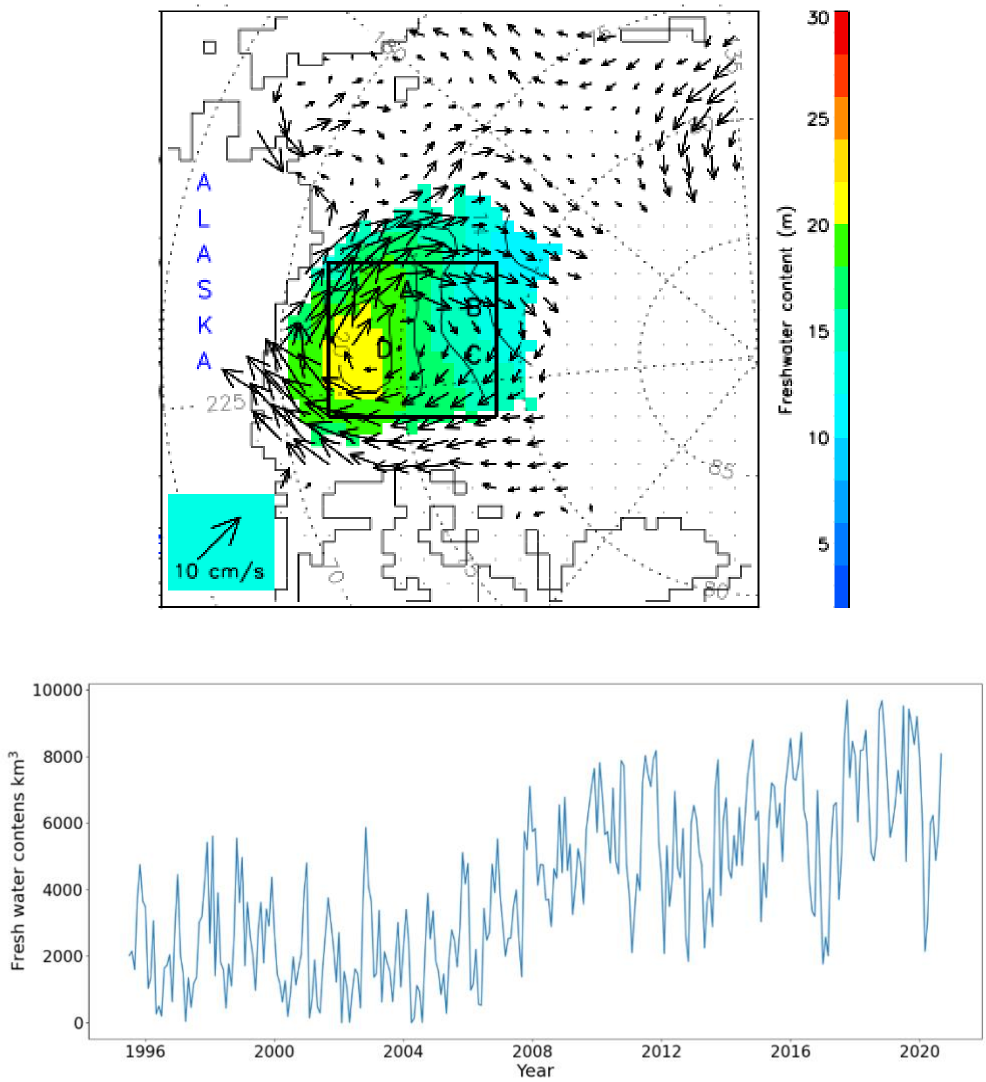


Figure 11. Spatial and temporal variability in freshwater content in the Beaufort Gyre from 1995-2020 derived from altimetric DOT (Proshutisky et al., 2019).

2.5.3.4 Sea Level Budget

The Cryo-TEMPO Polar Ocean product can aid in improving the Arctic sea level budget, by using the absolute sea level from altimetry to compare to the steric and ocean mass contributions (Figure 12).

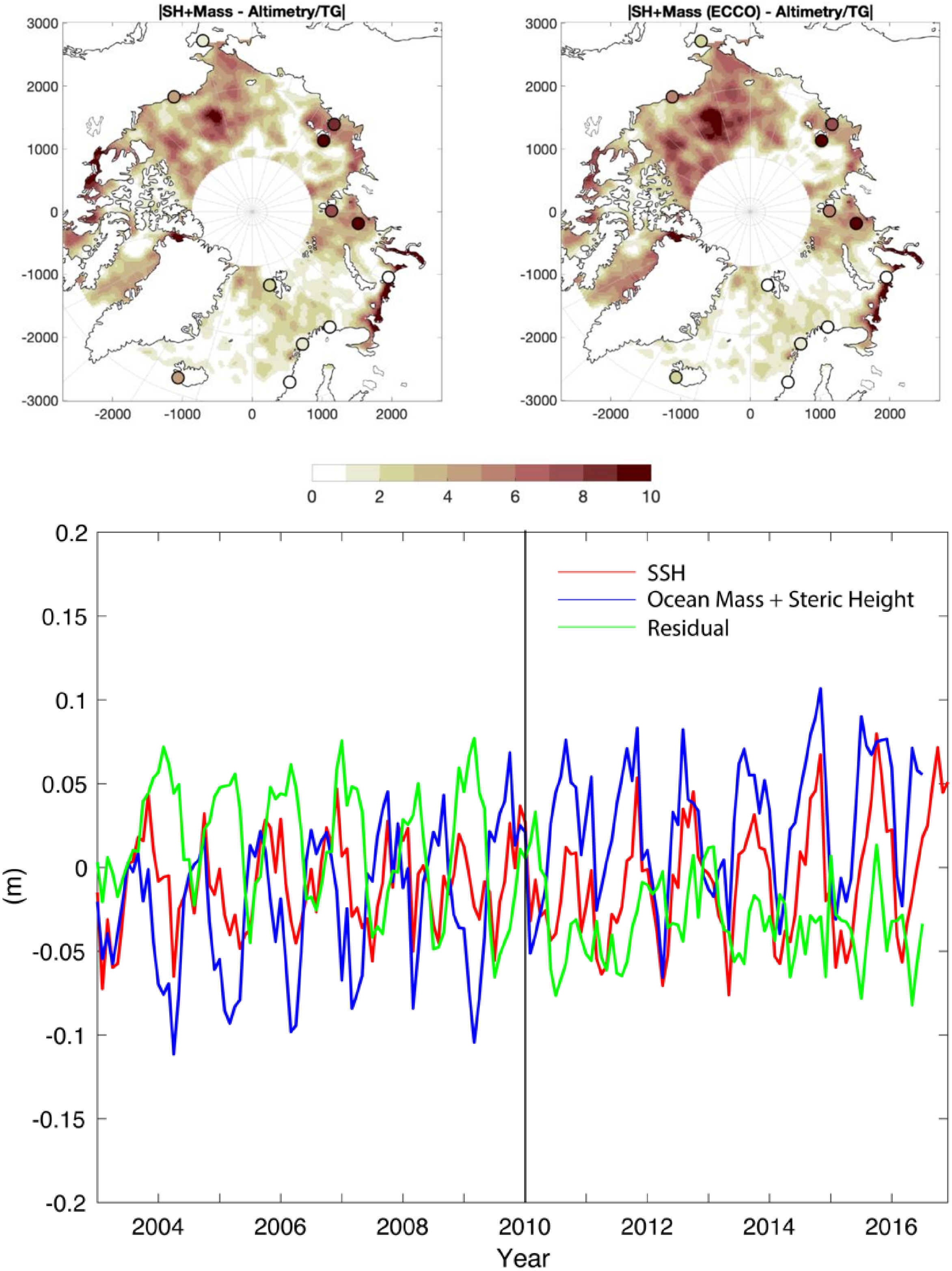


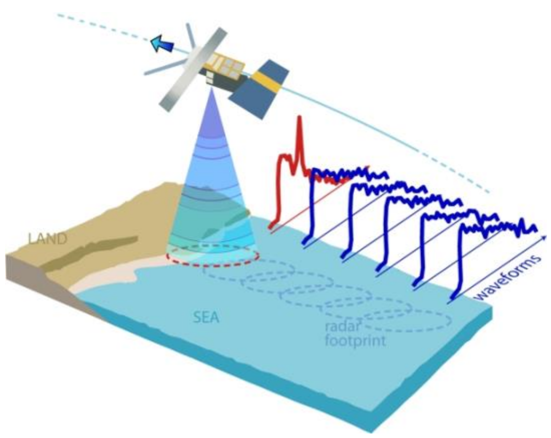
Figure 12. Sea level budget. Top: Spatial variability (from Ludwigsen et al., 2021). Bottom: temporal variability (from Raj et al., 2020).

2.5.4 Coastal Ocean

The Cryo-TEMPO Coastal Ocean product provides a quality-controlled record of along-track sea level anomalies (SLA) and absolute dynamic topography (ADT) over the Mediterranean basin for the whole duration of the CryoSat-2 mission. Due to the combination of CryoSat-2 SAR technology (described in section 2.5.4.1) and the regional-specific tuning of parameters of the Cryo-TEMPO processing chain, this dataset is characterized by the highest accuracy and resolution for coastal applications. Such applications include among others: analysis of sea level rise, assimilation into operational numerical simulations, and integration with other altimetry observations to generate level-4 multi-sensor gridded products (described in Section 2.5.4.2).

2.5.4.1. Improved accuracy approaching the coast

Due to their smaller footprint, higher spatial resolution and reduced noise (Figure 12), SAR observations have demonstrated improved accuracy near the coast, advancing our capability to monitor sea level and small-scale ocean dynamics in those socio-economically important regions. The Cryo-TEMPO products further enhance this improved accuracy for the Mediterranean coastal regions, through the implementation of a regional and dynamic-specific optimization of some of the processing and post-processing parameters used to retrieve SLA from SAR altimetry observations.



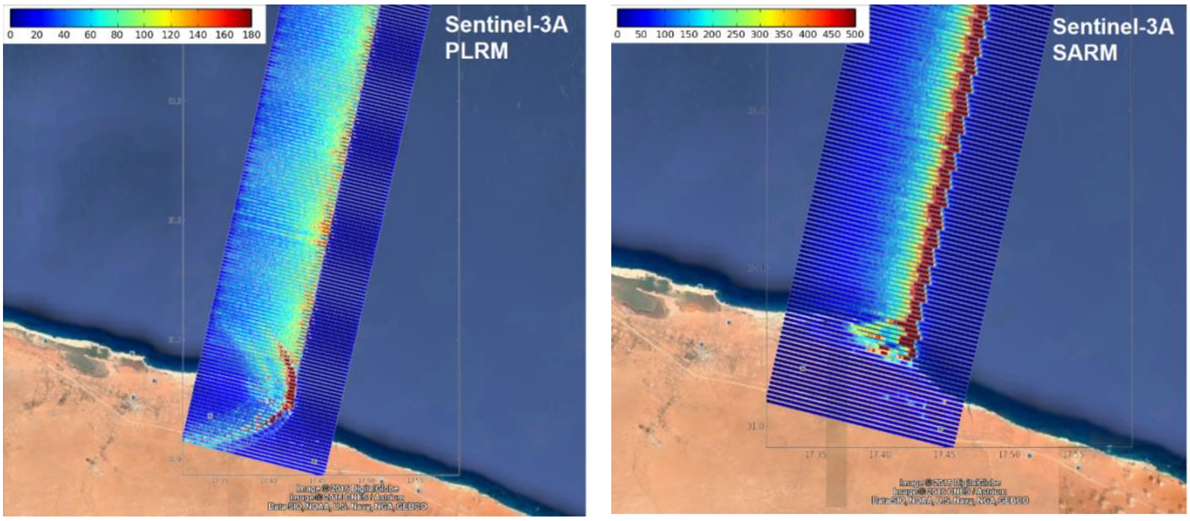


Figure 13. Schematics of radar altimetry characteristics approaching the coast; when the satellite footprint reaches the shore, spurious reflection from land target contaminate the recorded waveform and negatively impact the altimetry-derived geophysical parameters [Credit: COASTALT]. (Top left) Example of along-track LRM observations from Sentinel-3A approaching the Algerian coast (each stripe represents a recorded 1Hz waveform). Artifacts due to land reflection (red parabola-like feature) start to contaminate the altimetry waveforms from some 10s of km from the coastline. (Top right) The same Sentinel-3A track but showing SAR mode observations. Due to the smaller footprint of SAR observations, land contamination affects only a few SAR waveforms very close to the coast. The Sentinel-3 SAR altimeter was built on the heritage of CryoSat-2 SIRAL instrument which provided the first spaceborne demonstration of delay-Doppler technology.

2.5.4.2 Mediterranean surface circulation

Cryo-TEMPO Coastal Ocean observations can be integrated with other altimetry observations to reconstruct 2-dimensional fields of absolute dynamic topography and, in turn, the surface geostrophic velocities, which are used to investigate ocean dynamics (e.g. eddy characteristics) and surface ocean dispersion (Figure 13). More accurate and spatially resolved observations of SLA near to the coastline will enhance our capability to correctly observe, reconstruct and analyse small scale ocean processes, especially near to the shore.

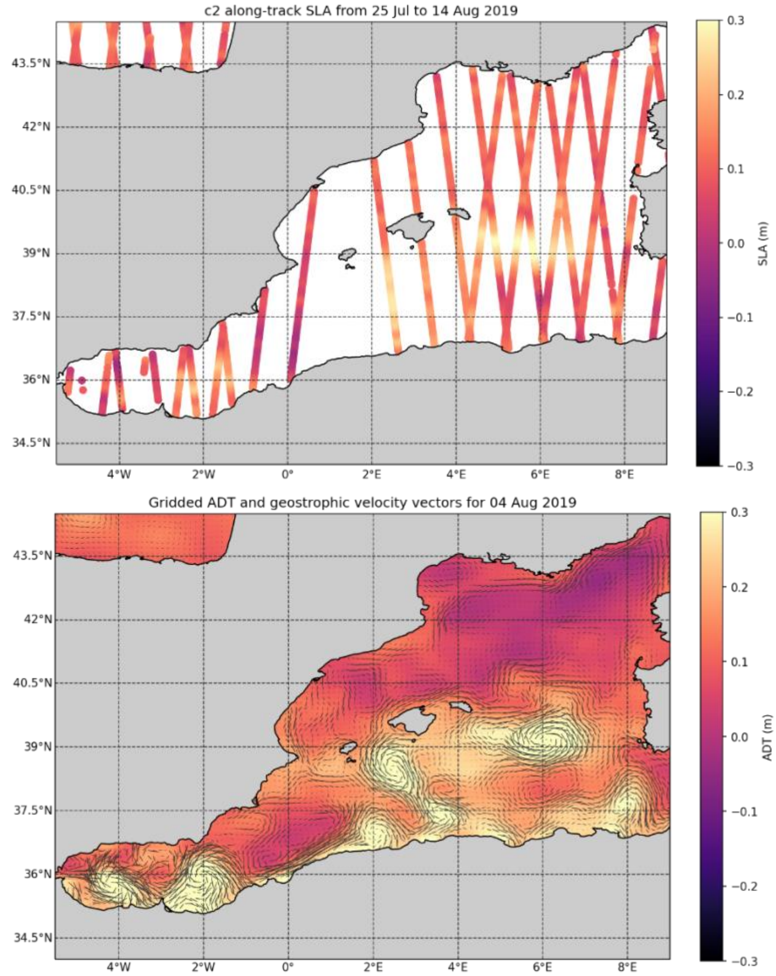


Figure 14. (Top) Example of observed along-track sea level anomaly (SLA) from CryoSat-2 from 25 July to 14 August 2019. (Bottom) Result of merging along-track observations from the multiple active altimeters (e.g. Jason-3, Sentinel-3, SARAL\ALtiKa etc.) to create daily level-4 maps of absolute dynamic topography (ADT; colour scale), which are in turn used to derive surface geostrophic velocities (vectors). More information on the generation and application of these products can be found in Taburet et al., 2019.

2.5.5 Inland water

Cryo-TEMPO inland water measurements can be used to estimate water surface elevations of rivers and lakes. The along track resolution of ~ 340 m in SAR and SARIn modes allows accurate measurement of a higher number of targets compared with the previous satellite missions, which have all operated in LRM mode. For specific examples, the reader is referred to Nielsen et al. (2017) and Jiang et al. (2017).

Measurement of accurate river profiles and slopes is beneficial for hydrological and hydraulic applications, as well as for river discharge estimation, and provides useful information for hydraulic risk assessments, water resource management and for determining local climate change (Figure 15). Although the 369-day repetition cycle of Cryosat-2 challenges many common methods of processing satellite altimetry data over rivers, it represents an unprecedented information resource due to its spatio-temporal sampling scheme. The small across-track distance of CryoSat-2 tracks enables observations that are distributed almost continuously along the river, providing added value to the definition of hydrodynamic modelling parameters (e.g. calibration of the roughness coefficient). This is even the case for widely monitored rivers, where ground stations are still typically located at distances that exceed the CryoSat-2 across-track spacing (e.g. for the Po River ground stations are located every 40 km vs 9 km for Cryosat-2). Indeed, high spatial resolution is more important than temporal resolution for calibrating parameters of large-scale river models. Satellite altimetry data can also be used to update the states of a hydrodynamic model of a river, i.e. its water levels through data assimilation, contributing to improvements in the accuracy of model outcomes. Examples of CryoSat-2 based lake level times series for selected Canadian lakes are shown in Figure 16, together with Envisat based time series and in situ data.

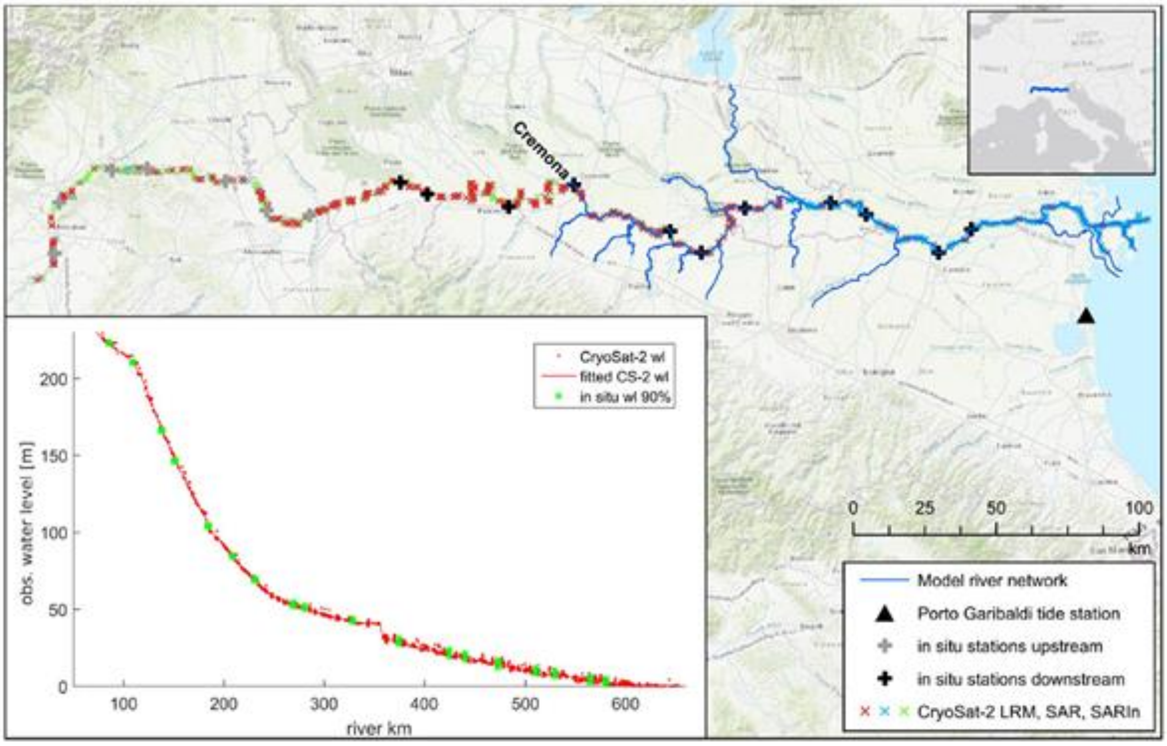


Figure 15. Map of the Po River, showing the filtered CryoSat-2 observations, in situ stations and the model river network. The inset shows the water levels of all CryoSat-2 observations along the river line as well as the mean and 90% quantiles of the in situ observations (Schneider et al., 2018).

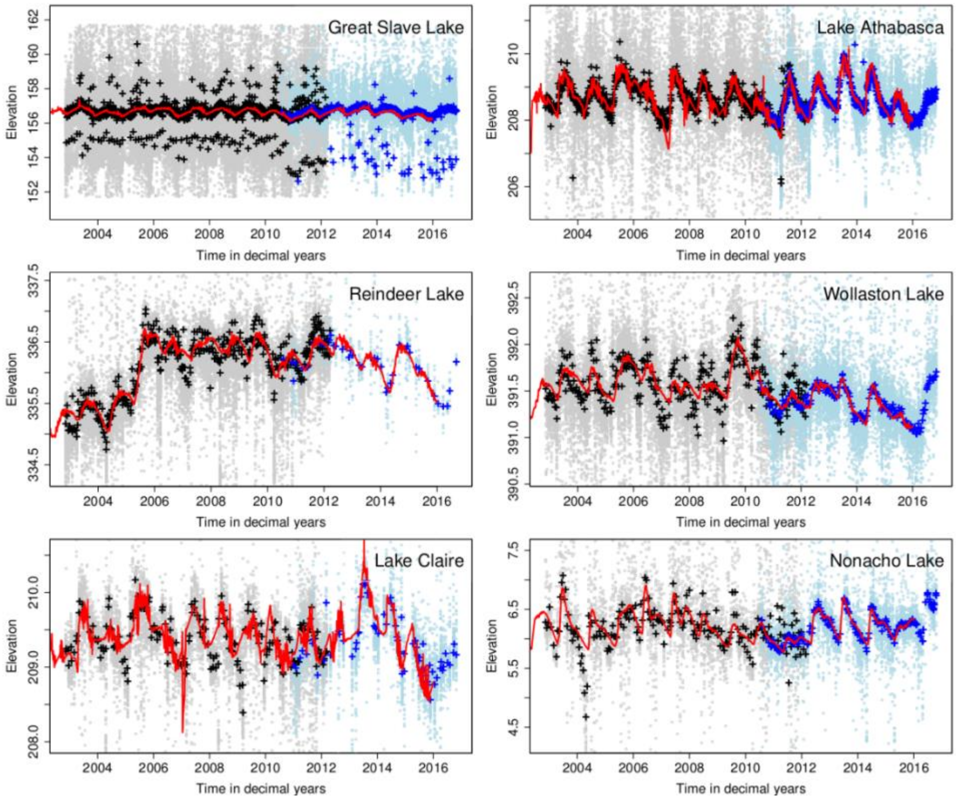


Figure 16. Water level time series of selected Canadian lakes based on Envisat (black) and CryoSat-2 (blue). The individual measurement of Envisat (gray) and CryoSat-2 (light blue) are shown with dots. For comparison in situ water levels (red) are also shown (Nielsen et al, 2017).

3 THEMATIC PRODUCT DESCRIPTION

Each TDP contains a number of standard parameters general to all themes and a number of special parameters specific to the individual theme. The standard parameters relate to the location and timing of the observations. The parameters specific to each theme are detailed below for each theme.

3.1 Land-Ice

The Cryo-TEMPO Land Ice Thematic Product comprises quality-controlled measurements of ice sheet surface elevation derived using dedicated processing algorithms for land ice surfaces. Alongside surface elevation measurements, within each product are a set of parameters that are designed to assist the user in the use and interpretation of the data. These parameters include an estimate of measurement uncertainty, backscatter coefficient, surface type, a reference elevation and the glaciological catchment from which the measurement was derived. The Cryo-TEMPO Land Ice product encompasses both grounded and floating parts of Greenland and Antarctica (i.e. inclusive of ice shelves and floating ice tongues) and covers the full duration of the CryoSat-2 mission operation (2010-present).

3.1.1 Surface height products

The core parameter within the Cryo-TEMPO Land Ice Product is a measurement of the ice sheet's surface elevation. Measurements are provided at approximately 340 meter intervals along the satellite track, according to the satellite's native sampling frequency. Surface elevation is computed based upon the measured range between the satellite and the surface, and land ice processing applies a range of corrections to account for the propagation of the radar signal through Earth's atmosphere, tidal forcing, and the surface slope of the ice sheet within the radar footprint. Precise elevation determination – via the process of *waveform retracking* – is also applied. For full details of the theory and practical implementation of these processing steps, please refer to the latest CryoSat-2 product handbook (https://earth.esa.int/eogateway/documents/20142/0/CryoSat-Product-Handbook-Baseline-E-draft.pdf/fc311af8-b926-cf59-5e3a-6b81942e262f).

3.1.2 Uncertainty estimates

Each measurement over land ice has with it an associated uncertainty estimate. These uncertainties are derived empirically, based upon the relationship between ice sheet surface slope and the height difference relative to co-located ICESat-2 laser altimeter measurements. This approach is based upon the knowledge that radar altimeter measurement accuracy degrades with surface slope. In practice, a look up table is created for each ice sheet, which relates the surface slope to the CryoSat-2-ICESat-2 height difference. For each Cryo-TEMPO record, the surface slope at the echoing point is then calculated and used to define the associated uncertainty value. This uncertainty value is then written as an output parameter within the product. More information can be found in the Cryo-TEMPO ATBD.

3.1.3 Auxiliary Parameters

Alongside the Cryo-TEMPO elevation measurement and its associated uncertainty, the user is provided with several auxiliary parameters dedicated to ice sheet surfaces, that are designed to aid usage and interpretation. These auxiliary parameters are (1) an estimate of the Backscatter Coefficient, (2) Surface Type, (3) a Reference Elevation, and (4) Glaciological Catchment. Each of these parameters is described in turn below.

3.1.3.1 Backscatter Coefficient

The radar backscatter coefficient (sigma-0) provides information related to the strength of the return pulse received by the altimeter and, in turn, the properties of the surface from which the pulse was scattered. Over ice sheet surfaces, temporal changes in backscatter have been related to changes in snowpack properties, and specifically the depth to which the radar wave penetrates into the near surface snowpack (Wingham et al., 1998; Zwally et al., 2005). In many approaches to processing altimetry data, it is therefore common to derive an empirical linear relationship between changes in surface elevation and backscatter, and to apply this as a correction when generating time series of ice sheet elevation change (Wingham et al., 1998; Zwally et al., 2005; McMillan et al., 2014; Shepherd et al., 2019). There are several ways of implementing this in practice, and so the reader is referred to the above texts for further information relating to the practical implementation of this step. The backscatter coefficient is therefore written as an auxiliary parameter within the product, to provide this information to users who wish to derive time series of elevation change using this approach.

3.1.3.2 Surface Type Indicator

Each Cryo-TEMPO elevation measurement has associated with it an indication of the surface type; i.e. whether the measurement has been acquired over grounded ice, floating ice, or exposed bedrock. In accordance with the philosophy of Cryo-TEMPO, which is to generate bespoke thematic datasets that are optimised for specific surfaces, these surface type masks are based upon state-of-the-art, ice sheet specific products.

For Greenland, surface type information from BedMachine Greenland version 3 (Morlighem *et al.*, 2017) is used. The mask is freely available and can be accessed directly via the NASA National Snow and Ice Data Center, at https://nsidc.org/data/idbmg4. The BedMachine Greenland version 3 mask is based upon the MEaSUREs Greenland Ice Mapping Project (GIMP) Land Ice and Ocean Classification Mask, Version 1, supplemented with grounding line information (the boundary between grounded ice and floating ice tongues) based upon unpublished InSAR data (courtesy of E. Rignot and J. Mouginot). The surface type mask is shown in Figure 17.

For Antarctica, surface type information from BedMachine Antarctica version 2 (Morlighem, 2020) is used. The mask is freely available and can be accessed directly via the NASA National Snow and Ice Data Center, at https://nsidc.org/data/nsidc-0756/versions/2. The BedMachine Antarctica version 2 mask uses Grounding Lines derived using interferometric SAR data (Rignot *et al.*, 2011). The surface type mask is shown in Figure 17.

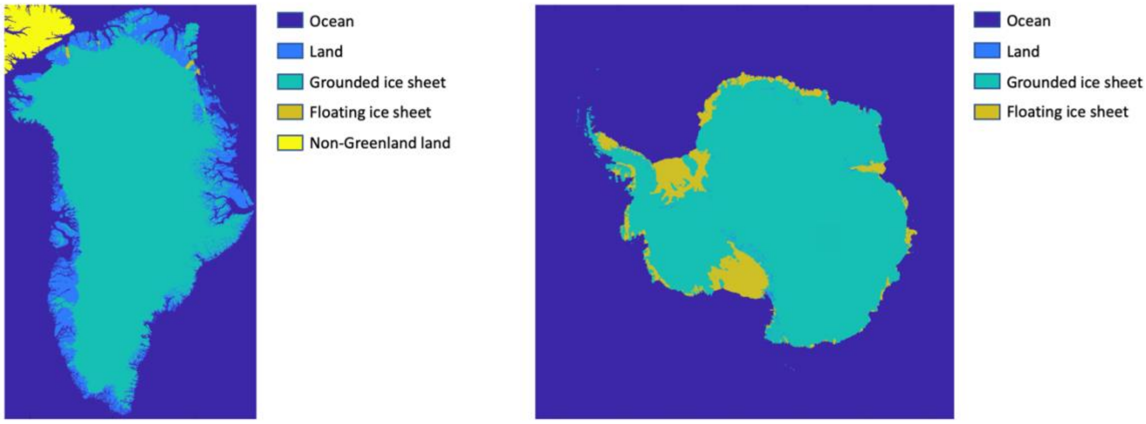


Figure 17. Cryo-TEMPO surface discrimination masks, based upon the BedMachine Greenland version 3 (Morlighem *et al.*, 2017) and BedMachine Antarctica version 2 (Morlighem, 2020) datasets.

3.1.3.3 Reference Elevation

Each Cryo-TEMPO elevation measurement has associated with it a static reference surface elevation, derived from a high-resolution Digital Elevation Model (DEM). For Greenland, the reference elevation is taken from a 1km posting version of ArcticDEM (Porter *et al.*, 2018). This DEM was developed by the Polar Geospatial Center under NSF-OPP awards 1043681, 1559691, and 1542736 and can be accessed directly at http://data.pgc.umn.edu/elev/dem/setsm/ArcticDEM/mosaic/v3.0/1km/.

For Antarctica, the reference elevation is taken from a 1km posting version of REMA (Howat *et al.*, 2019). This DEM was produced by the Byrd Polar and Climate Research Center and the Polar Geospatial Center using data from DigitalGlobe Inc., under NSF-OPP awards 1543501, 1810976, 1542736, 1559691, 1043681, 1541332, 0753663, 1548562, 1238993 and NASA award NNX10AN61G, with computer time provided through a Blue Waters Innovation Initiative. The DEMs can be accessed directly at http://data.pgc.umn.edu/elev/dem/setsm/REMA/mosaic/v1.1/1km/.

3.1.3.4 Glaciological Catchment

Each Cryo-TEMPO elevation measurement has associated with it glaciological catchment identifiers, the purpose of which is to allow the user to easily filter by – and extract data from – a specific basin or catchment of interest. For both Greenland and Antarctica, the glaciological catchments written in the Cryo-TEMPO product are the same as have been used in the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE; http://imbie.org/), thereby allowing the user to easily extract data over a consistent region to the IMBIE datasets. Following IMBIE, two catchment identifiers are provided for each record within the Cryo-TEMPO baseline B product, using the *Zwally* and *Rignot* definitions (http://imbie.org/imbie-3/drainage-basins/). For Antarctica, the ice sheet is split into 27 and 18 distinct basins, for the Zwally and Rignot definitions, respectively. For Greenland, the Zwally definition splits the ice sheet into 19 distinct basins, which in turn are grouped into 8 larger regions, whereas the Rignot definition consists of 6 basins. An example of the Zwally basins for Greenland and Antarctica is shown in Figure 17.

Figure 18Figure 18

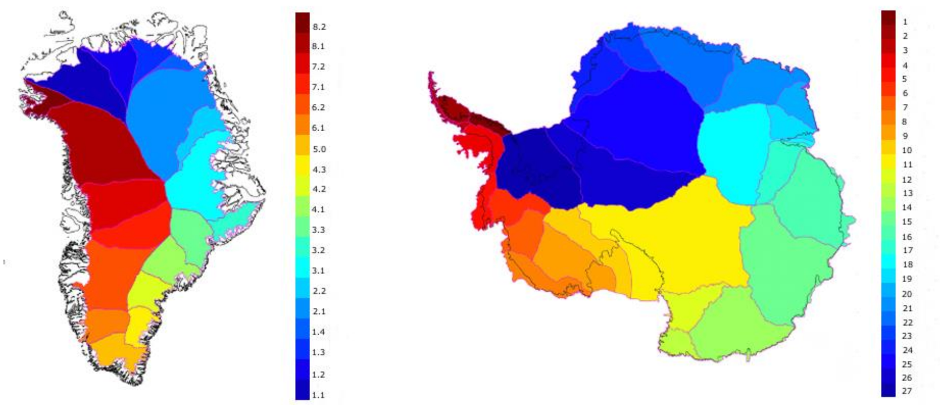


Figure 18. Cryo-TEMPO glaciological catchment masks, based upon the Zwally *et al.* (2012) definition. The 19 basins in Greenland are grouped into eight separate regions (1=North, 2=North-East, 3=East, 4=South-East, 5=South, 6=South-West, 7=West, 8=North-West).

3.2 Sea Ice

The Cryo-TEMPO product provides radar freeboard and sea ice freeboard for both the northern and (in Phase 2 of the project) the southern Polar Oceans. The Arctic Polar Ocean is bounded to the south by the 67° N parallel. The Antarctic Polar Ocean is bounded to the north by the 58° S parallel.

3.2.1 Surface height products

The main parameters in the Cryo-TEMPO Sea Ice product are radar freeboard and sea-ice freeboard. Freeboard is generally defined as the elevation of the sea ice surface above the local sea surface and represented by the variable sea ice freeboard in the product. Radar freeboard is similar to sea-ice freeboard with the exception of a geometric correction that depends on snow depth and density. Both freeboard values are distributed at the full resolution of the CryoSat-2 radar altimeter along the ground track for each polar orbit segment.

In addition to the freeboard values, snow depth on sea ice is included in the product files, however this parameter is based on a climatology and not on observations of the same spatial and temporal resolution as the freeboard data.

The freeboard retrieval process can be summarized as follows:

1. Surface type classification of each radar altimeter waveform (sea-ice surface; open water at sea ice fractures; ambiguous).
2. Estimation of radar range (retracking) between satellite and surface for each waveform corresponding to the different surface types.
3. Application of range corrections due to the varying radar wave propagation speed in the ionosphere and troposphere.
4. Removal of the effect of tides on the along-track elevations.
5. Along-track interpolation of the sea-level anomaly from the discrete observations of sea surface height within the ice-covered region (radar freeboard).
6. Range correction over snow covered sea ice due to the lower wave propagation speed within the snow layer (sea ice freeboard).

3.2.3 Uncertainty estimates

Uncertainties are available for all product parameters and are generated using error propagation through the full retrieval process. Because the sea ice product is distributed at full sensor resolution, the resulting freeboards are expected to be noisy and uncertainties to be of the same order as freeboard values. For more information, the reader is referred to the Cryo-TEMPO sea-ice ATBD.

3.2.4 Surface type indicator

All geophysical variables (radar freeboard, sea-ice freeboard and snow depth) are to be interpreted as mean values for the sea-ice covered area in a CryoSat-2 radar altimeter footprint. The spatial extent of the Cryo-TEMPO Sea Ice product files is identical to the source L1B data files and therefore contains regions that are not covered by sea ice. The surface type indicator will not be provided as all geophysical variables will be set to not-a-number (NaN) for data over land, open ocean or leads (fractures) in the sea ice cover.

3.2.5 Arctic Sea Ice Regions

Each data point is associated with an identifier describing the region, respectively the sea defined by the International Hydrographic Office (IHO). The named seas cover all areas with known sea ice presence in the past and are meant to compute regional sea ice statistics. The region mask in the Cryo-TEMPO thematic sea ice product is based on the 2021 version of the regional mask for Arctic sea ice trends and climatologies generated by J. Scott Stewart and Walter N. Meier, NSIDC.

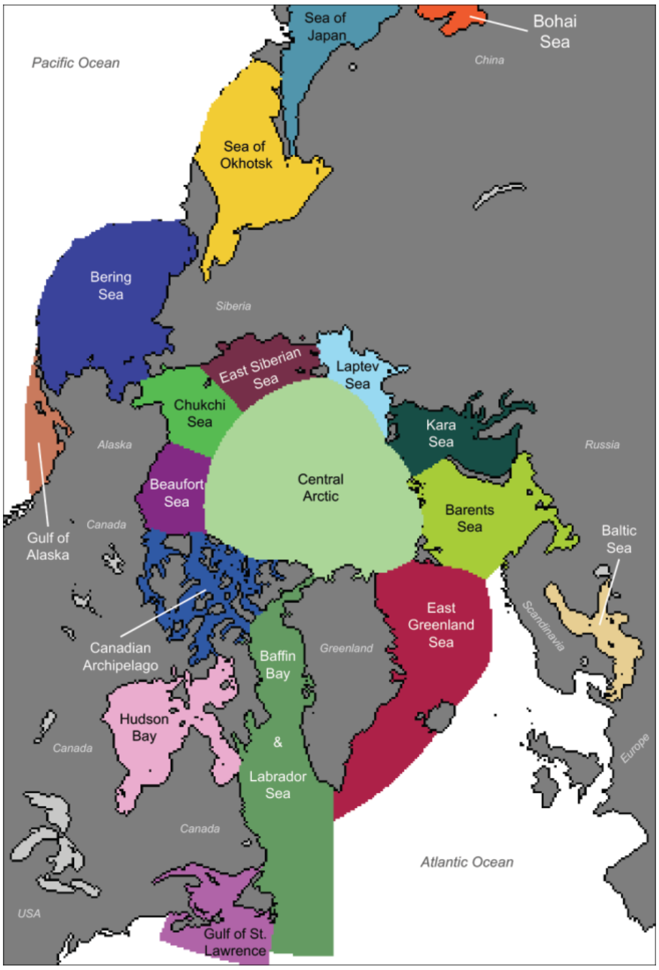


Figure 18: Cryo-TEMPO Arctic sea ice regions based on the 2021 NSDIC regional mask for Arctic sea ice trends and climatologies (credit: J. Scott Stewart and Walter N. Meier, NSIDC)

3.3 Polar Ocean

The Cryo-TEMPO Polar Ocean covers the northern and (in Phase 2 of the project) the southern Polar Oceans. The Arctic Polar Ocean is bounded to the south by the 67° N parallel. The Antarctic Polar Ocean is bounded to the north by the 58° S parallel.

3.3.1 Surface height products

The main parameters in the Polar Ocean Thematic Product are sea level anomaly and absolute dynamic topography. These products are obtained in the following way after processing and adding various standard range corrections as described in the Polar Ocean ATBD.

Sea Level Anomaly (SLA) is derived from observed sea surface height by subtracting the reference mean sea surface, via the following calculation:

Sea Level Anomaly = Sea Surface Height - Mean Sea Surface

Absolute Dynamic Topography (ADT) is then obtained by subtracting the geoid from the SSH rather than the Mean Sea Surface, via the following calculation:

Absolute Dynamic Topography = Sea surface height – Geoid

The ADT is related to the SLA in the following way:

Absolute Dynamic Topography = Sea level anomaly + Mean Dynamic Topography,

where the Mean Dynamic Topography used within Cryo-TEMPO is the DTU17 MDT (Knudsen et. al. 2019) computed from the DTU15MSS and the OGMOC geoid.

3.3.2 Uncertainty estimates

The Polar Ocean SLA and ADT have an associated uncertainty estimate included within the product. These uncertainty values have been generated using error propagation through the full retrieval process. The Polar Ocean product is distributed at full sensor resolution of 20 Hz corresponding to ~ 340 meters along-track. Hence, due to the high resolution, the sea level anomaly and absolute dynamic topography are expected to include a certain degree of noise.

3.3.3 Surface type indicator

Alongside the Cryo-TEMPO elevation measurement, and its associated uncertainty, the user is also provided with additional parameters or flags to aid the usage and interpretation of these datasets. The flags indicate the operating mode of CryoSat-2 (LRM, SAR or SARin) and the surface type of the retracker output. As the Polar Ocean and Sea Ice TDP's have been processed using an identical retracker, the output flags are similar for the two products and the user is referred to the flags found under the Sea Ice theme.

3.3.4 Polar Ocean Regions

Similar to the sea ice processing, each data point is associated with an identifier describing the region, respectively the sea defined by the International Hydrographic Office (IHO). The named seas cover all areas with known sea ice presence in the past and are meant to compute regional sea ice statistics. The region mask in the CryoTEMPO thematic sea ice product is based on the 2021 version of the regional mask for Arctic sea ice trends and climatologies generated by J. Scott Stewart and Walter N. Meier, NSIDC.

3.4 Coastal Ocean

The Cryo-TEMPO Coastal Ocean Thematic Product covers the whole Mediterranean and Black Sea basins ranging from 6.4° W to 42° E in longitude and from 30° N to 47.5° N in latitude, and spanning the whole duration of the CryoSat-2 mission.

3.4.1 Surface height products.

The main products in the Coastal Ocean TDP are sea level anomaly and absolute dynamic topography. These products are obtained through the following steps:

1. The CryoSat-2 waveforms are retracked to obtain the range estimates (i.e. the distance from the satellite to the observed surface).

2. The range is corrected for atmospheric effects, i.e. factors that impact the path delay of the altimeter impulse through the atmosphere. These include:
   a. A Dry Tropospheric Correction (DTC), which is a correction for refraction due to the dry gas component of the atmosphere, which generates a path delay in the radar return signal.
   b. A Wet Tropospheric Correction (WTC), which is a correction for the path delay in the altimetric return signal due to water vapor in the atmosphere.
   c. An ionospheric correction, which is a correction that compensates for the free electrons in Earth's ionosphere that slow the radar pulse.

3. Sea surface height (SSH; defined as the height of the sea surface above the reference ellipsoid) is then calculated by subtracting the corrected range from the satellite altitude (distance of the satellite from the reference ellipsoid) taking into account a series of geophysical corrections at the ocean surface (tides, atmospheric pressure, sea state). For this, the following calculation is performed:

   Sea Surface Height = Altitude - Corrected Range - Solid Earth Tide Height - Geocentric Ocean Tide Height - Pole Tide Height - Dynamic Atmospheric Correction - Sea State Bias - High-Frequency Adjustment

4. Sea Level Anomaly (SLA) is derived from SSH by subtracting the reference mean sea surface (MSS):

   Sea Level Anomaly = Sea Surface Height - Mean Sea Surface

5. Absolute Dynamic Topography (ADT) is then obtained by adding the SLA to the mean dynamic topography (MDT):

   Absolute Dynamic Topography = Sea Level Anomaly + Mean Dynamic Topography

For a more detailed description of the corrections applied, please refer to the CryoSat-2 GOP Product handbook (https://earth.esa.int/documents/10174/125272/CryoSat-Baseline-C-Ocean-Product-Handbook) as well as the Cryo-TEMPO Coastal Ocean ATBD.

In Cryo-TEMPO, SLA and ADT are then filtered using a Lanczos-2 filter (i.e. a two-lobe filter kernel) with a cutoff wavelength (which in the case of the two-lobe kernel is the same as the filter half-window width) of ~ 43 km (i.e. 127 observations). This post-processing step is designed to provide an additional smoother field, which can easily be used and analysed directly by non-expert altimetry users. For more details on the filtering technique applied please refer to the Cryo-TEMPO ATBD. Both filtered and un-filtered SLA and ADT are included in the Cryo-TEMPO product.

Additional parameters included within the Cryo-TEMPO Coastal Ocean product are:

- A flag for valid/invalid altimetry measurements. These are based on a Cryo-TEMPO specific iterative editing scheme (see the Cryo-TEMPO Coastal Ocean ATBD for more details).
- A flag to identify the CryoSat-2 operating mode, namely to distinguish whether the observations were acquired in SAR or LRM mode.
- Distance of each observation from the closest coastline point. The distance is computed based on the GSHHG database (https://www.soest.hawaii.edu/pwessel/gshhg/)

3.4.2 Uncertainty estimates.

Within the TDP, uncertainties on SLA and ADT are also provided for each observation. For individual SLA observations these are estimated as the sum of a location dependent large-wavelength error and a short-wavelength error which varies as a function of SWH and distance from the coast, and is directly computed from the CP TDP. For individual ADT observations this error is combined with the error associated with MDT estimates. Finally, errors from individual observations are propagated together to estimate the errors of the resulting filtered SLA and ADT. An exhaustive description of the methodology used to estimate the uncertainties can be found in the the Cryo-TEMPO Coastal Ocean ATBD.

3.5 Inland Water

The Cryo-TEMPO Inland Water Thematic Product includes the water surface height over a set of land water bodies. The algorithm for estimating this water level considers the signal reflected by inland waters as well as multiple geophysical corrections. Additionally, the uncertainty value and a quality flag associated to each measurement are included in the product, so as to provide the user with information relating to the reliability of the measurement. Finally, information on the type of surface (based on the GLWD3 dataset; https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database) and the occurrence of water (based on GSWE; https://global-surface-water.appspot.com) give additional, domain-specific information useful for the analysis of the thematic product.

3.5.1 Surface height products

The main parameter in the Inland Water TDP is the water level relative to the ellipsoid. Altimeters send an electromagnetic pulse and record the propagation time between the emission and the return of the echo from the surface, which gives the range between the satellite and the surface. This range needs to be corrected because the propagation is modified by atmospheric conditions. In addition, geophysical corrections, linked to the vertical movements of the earth surface (tides for example) must also be applied. The Cryo-TEMPO Inland Water ATBD contains the full description of the algorithms used to derive the Inland Water Thematic Product.

3.5.2 Uncertainty estimates

The uncertainty associated with each Cryo-TEMPO water surface height estimate is provided in the product. This uncertainty is calculated based on a bottom-up approach, considering the uncertainties of the different components in the estimation of the water level by surface type and waveform classification. Further details of the method used can be found within the Inland Water ATBD.

3.5.3 Auxiliary parameters

Alongside the Cryo-TEMPO elevation measurement and its associated uncertainty, the user is provided with two auxiliary parameters dedicated to inland water surfaces. These parameters are included to facilitate the use and interpretation of the products, and are (1) Surface Type, (2) Water Occurrence. These are described in turn below.

3.5.3.1 Surface Type

Each Cryo-TEMPO water height estimation has associated with it an indication of the surface type following the Global Lakes and Wetlands Database Grid – Level 3 (GLWD3). This database comprises lakes, reservoirs, rivers and different wetland types.

3.5.3.2 Water Occurrence

Another useful source of information, which will also be included in the Cryo-TEMPO Inland Water product, is that of the water occurrence from the Global Surface Water Explorer (GSWE). This dataset provides statistics on the location, distribution, extent and changes over time of the world's surface waters from 1984 to 2016.

4 TECHNICAL DESCRIPTION

This section of the Cryo-TEMPO Product Handbook details the technical specification, format and parameters contain within each Thematic Product.

4.1 Cryo-TEMPO Product Format

The Cryo-TEMPO products are designed to follow EO data principles. Product files are provided in NetCDF v4 classic format. This format is flexible, self-describing and can be read by all system platforms using different software. The NetCDF file contains dimensions, variables and attributes following the Climate and Forecast NetCDF conventions CF-1.8. Each Cryo-TEMPO TDP product file contains along-track measurements from a CryoSat-2 orbit segment that crosses the thematic domain.

4.1.1 Cryo-TEMPO File Naming Convention

The file naming convention is designed to provide fixed length filenames across all themes:

CS_OFFL_SIR_TDP_<THEME>**_** <AREA>_<STARTTIME>**_**<ENDTIME>**_**<CC>**_**<OOOOO>**_**<BVVV>**.nc**

Where:

- <THEME> = 2 characters identifying the theme, as follows:

Theme Name	<THEME>
Land Ice	LI
Sea Ice	SI
Polar Ocean	PO
Coastal Ocean	CO
Inland Water	IW

- <AREA> = 6 characters, defining the specific area domain within each theme. Currently, area names are selectable from one of the following, although additional areas may be added in future phases of the project:

Area Name	<AREA>
Arctic	ARCTIC
Antarctic	ANTARC
Greenland	GREENL
Mediterranean Sea	MEDSEA
Italian basins	ITBASI
Canadian Lakes	CALAKE
US lakes	USLAKE
Swedish lakes	SWLAKE

- < STARTTIME>_<ENDTIME > = the start and end acquisition times of the data included within the file. Both STARTTIME and ENDTIME are fixed at 15 characters, following the convention yyyymmddThhmmss, with (each letter corresponding to a character):
    - yyyy = year
    - mm = month
    - dd = day
    - hh = hours (24 hour format)
    - mm = minutes
    - ss = seconds

- <CC> = 2 characters, indicating the CryoSat-2 cycle number (as provided in the L1b files). Note that this is the cycle with period ~369 days (dependent on the CryoSat-2 phase), and not a ~30-day sub-cycle number.

- <OOOOO> = 5 characters, indicating the CryoSat-2 relative orbit number within the cycle (as provided in the L1b files).

- <BVVV> = 4 characters; B = Cryo-TEMPO baseline (not the L1b baseline), and is a letter 'A', 'B', …) indicating major product releases; VVV = minor release version number within the current Cryo-TEMPO baseline (3 numeric digits; '001', '002', …).

4.1.2 Cryo-TEMPO File Directory Structure

Cryo-TEMPO product files are distributed by ftp from the ESA's CryoSat-2 Science Server:

ftp://science-pds.cryosat.esa.int

Each Thematic Product is stored using the following directory structure:

Land Ice:

TEMPO_POCA_LI/<YYYY>/<MM>/[ANTARC,GREENL]/

Sea Ice:

TEMPO_POCA_SI/<YYYY>/<MM>/ARCTIC/

Polar Oceans:

TEMPO_POCA_PO/<YYYY>/<MM>/ARCTIC/

Coastal Oceans:

TEMPO_POCA_CO/<YYYY>/<MM>/MEDSEA/

Inland Waters:

TEMPO_POCA_IW/<YYYY>/<MM>/[CALAKE,USLAKE,SWLAKE,ITBASI]/

Where <YYYY> is the year, and <MM> is the month (0-padded) of data acquisition. More specifically, files are stored in the appropriate directory based on the year and month of their start time.

The following sections provide theme-specific information relating to the structure and content of Cryo-TEMPO data files.

4.2 Land Ice

4.2.1 Structure

The following list outlines all the variables included within each Cryo-TEMPO Land Ice NetCDF file.

4.2.1.1 Coordinates and time

The primary coordinate in the netCDF file is 'time'. The spatial coordinates of the measurements are provided by longitude and latitude.

double time (time)	
standard_name	time
long_name	time in UTC: seconds since 1 Jan 2000
calendar	Gregorian
units	seconds
comments	UTC time counted in seconds since 2000-01-01 00:00:00. Note that Cryo-TEMPO adjusts the TAI time found in CryoSat L1b products for leap seconds to produce UTC time.
double latitude (time)	
standard_name	latitude
long_name	Latitude coordinate
units	degrees_north
valid_min	-90
valid_max	90
coordinates	time
comments	Latitude of measurement in decimal degrees; a positive latitude indicates Northern hemisphere, a negative latitude indicates Southern hemisphere. If the point of closest approach (POCA) cannot be calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir latitude is provided.
double longitude (time)	
standard_name	longitude
long_name	Longitude coordinate
units	degrees east
valid_min	-180
valid_max	180

coordinates	time
comments	Longitude of measurement in decimal degrees east relative to the Greenwich meridian. If the point of closest approach (POCA) cannot be calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir longitude is provided.

4.2.1.2 Variables

double elevation (time)	
long_name	ice sheet elevation
standard_name	height_above_reference_ellipsoid
units	metres
coordinates	time
comments	Elevation of the ice surface above the reference ellipsoid (WGS84) at the measurement location [longitude] [latitude]. All instrumental and appropriate geophysical corrections included. Corrected for surface slope via a slope model in LRM mode. Corrected for surface slope via phase information in SARin mode. Where elevation cannot be calculated, the value is set to NaN.
double uncertainty (time)	
long_name	Uncertainty of ice sheet elevation
standard_name	elevation_uncertainty
units	metres
coordinates	time
comments	Uncertainty associated with the ice sheet elevation measurement; defined as the precision measured at orbital cross-overs per 0.1 degree band of slope.
double backscatter (time)	
long_name	backscatter coefficient
standard_name	surface_backscattering_coefficient_of_radar_wave
units	dB
coordinates	time
comments	The measured backscatter coefficient from the surface, corrected for instrument effects, and including a system bias that calibrates the results against previous missions. The backscatter is computed from the amplitude of the waveform in Watts, as measured by the retracker. The measured power is used to solve the radar equation to recover the value for backscatter.
byte surface_type (time)	

_FillValue	-128b
long_name	surface type identifier
standard_name	surface_type
flag_values	0b,1b,2b,3b,4b
flag_meanings	Ocean, grounded_ice, floating_ice, ice_free_land, non_greenland_land (used for tracks over Greenland only)
coordinates	time
comments	Surface type identifier, for use in discriminating different surface types within the Land Ice TDP domain; derived from the BedMachine Greenland version 3 (Morlighem *et al.*, 2017) and BedMachine Antarctica version 2 (Morlighem, 2020) datasets.
source	https://nsidc.org/data/nsidc-0756/versions/2 (Antarctic products) https://nsidc.org/data/idbmg4 (Greenland products)
byte instrument_mode (time)	
_FillValue	-128b
long_name	SIRAL instrument measurement mode
standard_name	cryosat_measurement_mode
flag_values	1b, 2b, 3b
flag_meanings	lrm, sar, sarin
coordinates	time
comments	Identifier used to indicate which mode the SIRAL instrument was operating in at each measurement; either LRM, SAR or SARIn.
double reference_dem (time)	
long_name	Reference elevation from external Digital Elevation Model
standard_name	reference_dem_elevation
units	metres
coordinates	time
comment	Reference elevation values at each measurement location, extracted from an auxiliary Digital Elevation Model (DEM). The 1km REMA v1.1 mosaic is used for Antarctica and the 1 km ArcticDEM v3 mosaic is used for Greenland.
byte basin_id(time)	
_FillValue	-128b
long_name	Glacialogical basin identification number
standard_name	basin_identifier
coordinates	time
comment	Glaciological catchment identifier, which have been taken from the Zwally et al., 2012 definitions, as used in the Ice Sheet Mass Balance Intercomparison Exercise (IMBIE; http://imbie.org/).

byte basin_id2(time)	
_FillValue	-128b
long_name	Glacialogical basin identification number
standard_name	basin_identifier
coordinates	time
comment	IMBIE glacialogical basin id number (Rignot et al., 2016) associated with each measurement. Values are : 0 (unclassified), 1:Islands, 2: West H-Hp, 3:West F-G, 4:East E-Ep, 5: East D-Dp, 6: East Cp-D, 7: East B-C, 8: East A-Ap, 9: East Jpp-K, 10: West G-H, 11: East Dp-E, 12: East Ap-B, 13: East C-Cp, 14: East K-A, 15: West J-Jpp, 16: Peninsula Ipp-J, 17: Peninsula I-Ipp, 18: Peninsula Hp-I, 19: West Ep-F" Source: http://imbie.org/imbie-2016/drainage-basins

4.2.2 Global Attributes

Global Attribute	Description
title	Cryo-TEMPO Land Ice Thematic Product
project	ESA Cryo-TEMPO
creator_name	ESA Cryo-TEMPO Project
creator_url	http://cryosat.mssl.ucl.ac.uk/tempo
date_created	Date and time product created in format DD-MM-YYYY HH:MM:SS
platform	CryoSat-2
sensor	SIRAL
instrument_mode	LRM or SARin
src_esa_l1b_file	File name of ESA L1b file used as primary input to the Cryo-TEMPO processor to produce this file. Example: CS_OFFL_SIR_LRM_1B_20221030T205359_20221030T205615_E001.nc
ascending_start_record	Record number (from 0) of the first measurement where the nadir orbit is ascending. If no ascending records, contains the string "None"
descending_start_record	Record number (from 0) of the first measurement where the nadir orbit is descending. If not descending records, contains the string "None"
geospatial_lat_min	Minimum latitude value in product (degrees N)
geospatial_lat_max	Maximum latitude value in product (degrees N)
geospatial_lon_min	Minimum longitude value in product (degrees E, -180,180)
geospatial_lon_max	Maximum longitude value in product (degrees E, -180,180)
geospatial_vertical_min	Minimum elevation value in product (m)

geospatial_vertical_max	Maximum elevation value in product (m)
time_coverage_start	UTC time of first measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
time_coverage_end	UTC time of last measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
cycle_number	Cycle number used in corresponding ESA L1b products. Each cycle is approximately 369 days long depending upon the phase of the mission.
rel_orbit_number	Relative orbit number within the cycle as used in corresponding ESA L1b products
abs_orbit_number	Absolute orbit number as used in ESA L1b products
cnes_subcycle	CryoSat sub-cycle number defined by CNES. Each sub-cycle is 28.94 days long.
cnes_track	Track number within CNES sub-cycle.
product_baseline	Cryo-TEMPO product baseline (major product release) identifier. First baseline is 'A', second baseline will be 'B', etc.
product_version	Cryo-TEMPO product version number within baseline. Version numbers start at 1.
sw_version	Cryo-TEMPO unique software version used to process the product.
Conventions	CF-1.8. NetCDF climate variable convention standard used in this product as defined by https://cfconventions.org/
zone	Area of product coverage. Either 'Antarctica' or 'Greenland'.
doi	Digital Object identifier: "10.5270/CR2-3205d1e"

4.3 Sea-Ice

4.3.1 Structure

Each NetCDF file contains an orbit segment over polar marine areas only, with the exception of short segments over land.

4.3.1.1 Coordinates and time

The primary coordinate in the netCDF file is 'time'. The spatial coordinates of the measurements are provided by longitude and latitude.

double time (time)	
standard_name	time
long_name	time in UTC: seconds since 1 Jan 2000
calendar	Gregorian
units	seconds
comments	UTC time counted in seconds since 2000-01-01 00:00:00.
double latitude (time)	
standard_name	latitude
long_name	latitude of satellite nadir measurement point
units	degrees_north
valid_min	-90
valid_max	90
coordinates	time
comments	Latitude of measurement in decimal degrees; a positive latitude indicates Northern hemisphere, a negative latitude indicates Southern hemisphere.
double longitude (time)	
standard_name	longitude
long_name	longitude of satellite nadir measurement point
units	degrees_east
valid_min	-180
valid_max	180
coordinates	time
comments	Longitude of measurement in decimal degrees relative to the Greenwich meridian.

4.3.1.2 Variables

float radar_freeboard (time)	
long_name	radar freeboard
units	metres
coordinates	Longitude latitude
ancillary_variables	radar_freeboard_uncertainty
comment	Radar freeboard is defined as the elevation based on the assumption of vacuum light speed without a snow propagation or range penetration correction.
float radar_freeboard_uncertainty (time)	
long_name	radar freeboard uncertainty
units	metres
coordinates	Longitude latitude
comment	Algorithm uncertainty (error propagation) of the radar freeboard retrieval.

float sea_ice_freeboard (time)	
long_name	sea ice freeboard
standard_name	sea_ice_freeboard
units	m (metres)
comment	Sea-ice freeboard is defined as the elevation of the sea-ice surface above local sea level. The parameter is derived from radar freeboard by applying a range correction dependent on snow depth and density for variable radar wave propagation speed in the snow layer.
ancillary_variables	Sea_ice_freeboard_uncertainty
coordinates	Longitude latitude
float sea_ice_freeboard_uncertainty (time)	
long_name	sea ice freeboard uncertainty
units	m (metres)
coordinates	Longitude latitude
comment	algorithm uncertainty (error propagation) of the radar freeboard retrieval.
float sea_ice_freeboard_filtered (time)	
long_name	smoothed freeboard of the sea ice layer
standard_name	sea_ice_freeboard
units	m (metres)
coordinates	Longitude latitude
comment	Sea-ice freeboard filtered with a 25km locally weighted regression (loess) filter.
float snow_depth (time)	
long_name	Snow depth
standard_name	surface_snow_thickness
units	m (metres)
coordinates	Longitude latitude
comment	Snow depth interpolated from climatology based Warren99 climatology data in the central Arctic Basin and passive microwave data from AMSR-2 of snow on first-year sea ice outside the central Arctic basin.
float snow_depth_uncertainty (time)	
long_name	Snow depth uncertainty
units	m (meters)
coordinates	Longitude latitude
comment	Uncertainty of the snow depth.

4.3.1.3 Flags

byte instrument_mode (time)	
long_name	radar mode flag
flag_values	1, 2, 3

flag_meanings	1: pulse limited (LRM), 2: doppler delay (SAR), 3: doppler delay interferometric (SARin)
valid_min	1
valid_max	3
units	1
coordinates	Longitude latitude
comment	The mode that the SIRAL instrument was in at each measurement. Either LRM, SAR or SARin.

byte (time)	
long_name	Region code flag
flag_values	0, 1, 2, 3, 4, 5, 6, 7, 8 9 10 11 12 13 14 15 16 17 18
flag_meanings	0: Undefined Region 1: Central Arctic 2: Beaufort Sea 3: Chukchi Sea 4: East Siberian Sea 5: Laptev Sea 6: Kara Sea 7: Barents Sea 8: East Greenland Sea 9: Baffin Bay & Labrador Sea 10: Gulf of St. Lawrence 11: Hudson Bay 12: Canadian Archipelago 13: Bering Sea 14: Sea of Okhotsk 15: Sea of Japan 16: Bohai Sea 17: Baltic Sea 18: Gulf of Alaska
valid_min	0
valid_max	18
units	1
coordinates	Longitude latitude
comment	Adapted from "A new regional mask for Arctic sea ice trends and climatologies (J. Scott Stewart and Walter N. Meier, NSIDC)

4.3.2 Global Attributes

Global Attribute	Description
title	Cryo-TEMPO Sea Ice Thematic Product
project	ESA Cryo-TEMPO
creator_name	ESA Cryo-TEMPO Project

creator_url	http://cryosat.mssl.ucl.ac.uk/tempo
date_created	Date and time product created in format DD-MM-YYYY HH:MM:SS
platform	CryoSat-2
sensor	SIRAL
geospatial_lat_min	Minimum latitude value in product (degrees N)
geospatial_lat_max	Maximum latitude value in product (degrees N)
geospatial_lon_min	Minimum longitude value in product (degrees E, -180,180)
geospatial_lon_max	Maximum longitude value in product (degrees E, -180,180)
geospatial_vertical_min	Minimum elevation value in product (m)
geospatial_vertical_max	Maximum elevation value in product (m)
time_coverage_start	UTC time of first measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
time_coverage_end	UTC time of last measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
cycle_number	Cycle number used in corresponding ESA L1b products. Each cycle is approximately 369 days long depending upon the phase of the mission.
rel_orbit_number	Relative orbit number within the cycle as used in corresponding ESA L1b products
abs_orbit_number	Absolute orbit number as used in ESA L1b products
cnes_subcycle	CryoSat sub-cycle number defined by CNES. Each sub-cycle is 28.94 days long.
cnes_track	Track number within CNES sub-cycle.
product_baseline	Cryo-TEMPO product baseline (major product release) identifier. First baseline is ‘A’, second baseline will be ‘B’, etc.
product_version	Cryo-TEMPO product version number within baseline. Version numbers start at 1.
sw_version	Cryo-TEMPO unique software version used to process the product.
Conventions	CF-1.8. NetCDF climate variable convention standard used in this product as defined by https://cfconventions.org/.
zone	Area of product coverage. Either Northern Hemisphere or Southern Hemisphere (Antarctic Ocean).
doi	Digital Object identifier: "10.5270/CR2-e2dd631"

4.4 Polar Ocean

4.4.1 Structure

One netCDF file per cycle and pass number are generated.

4.4.1.1 Coordinates and time

The primary coordinate in the netCDF file is 'time'. The coordinates of the measurements are provided by longitude and latitude.

double time (time)	
standard_name	time
long_name	time in UTC: seconds since 1 Jan 2000
calendar	Gregorian
units	seconds
comments	UTC time counted in seconds since 2000-01-01 00:00:00.
double latitude (time)	
standard_name	latitude
long_name	latitude of satellite nadir measurement point
units	degrees_north
valid_min	-90
valid_max	90
coordinates	time
comments	Latitude of measurement in decimal degrees; a positive latitude indicates Northern hemisphere, a negative latitude indicates Southern hemisphere.
double longitude (time)	
standard_name	longitude
long_name	longitude of satellite nadir measurement point
units	degrees_east
valid_min	-180
valid_max	180
coordinates	time
comments	Longitude of measurement in decimal degrees relative to the Greenwich meridian.

4.4.1.2 Variables

float Sea_level_anomaly (time)	
long_name	Sea level anomaly
Standard_name	sea_surface_height_above_mean_sea_level
units	metres

coordinates	Longitude latitude
comment	Sea level anomalies have been interpolated and smoothed across sea ice covered regions. The sea level anomaly is given relative to the DTU15MSS mean sea surface.
float sea_level_anomaly_uncertainty (time)	
long_name	Sea level anomaly uncertainty
units	metres
coordinates	Longitude latitude
comments	Algorithm uncertainty (error propagation) of the sea level anomaly.
float sea_level_anomaly_filtered (time)	
long_name	Filtered sea level anomaly
units	metres
coordinates	Longitude latitude
comment	The interpolated sea level anomalies are filtered with a Lowess 35-km along-track filter. The sea level anomaly is given relative to the DTU15MSS mean sea surface.
Float sea_level_anomaly_raw (time)	
Long_name	sea level anomaly (unsmoothed 20 Hz values)
Standard_name	sea_surface_height_above_mean_sea_level
Units	meters
coordinates	Longitude latitude
comment	Raw sea level anomalies without smoothing, filtering or interpolation applied. The sea level anomaly is given relative to the DTU15MSS mean sea surface.
float dynamic_ocean_topography (time)	
long_name	Dynamic ocean topography
Standard_name	sea_surface_height_above_geoid
units	metres
coordinates	Longitude latitude
comment	Sea surface height relative to the OGMOC geoid. Derived from the level anomaly by adding the mean dynamic topography from the DTU17MDT model. Filtering and smoothing similar to the SLA above.
float dynamic_ocean_topography_uncertainty (time)	
Long_name	Dynamic ocean topography uncertainty
units	meters
coordinates	Longitude latitude
comment	Algorithm uncertainty (error propagation) of the dynamic ocean topography.
float dynamic_ocean_topography_filtered (time)	
long_name	Filtered dynamic ocean topography
Standard_name	sea_surface_height_above_geoid
units	metres
coordinates	Longitude latitude
comment	Dynamic ocean topography filtered with a Lowess along-track filter.

4.4.1.3 Flags

byte instrument_mode (time)	
long_name	radar mode flag
flag_values	1, 2, 3
flag_meaning	1: low resolution (LRM), 2: high resolution (SAR), 3: doppler delay interferometric (SARin)
valid_min	1
valid_max	3
units	1
coordinates	Longitude latitude
comment	The observation mode of Cryosat-2. Either LRM, SAR or SARin.

byte (time)	
long_name	Region code flag
flag_values	0, 1, 2, 3, 4, 5, 6, 7, 8 9 10 11 12 13 14 15 16 17 18
flag_meanings	0: Undefined Region 1: Central Arctic 2: Beaufort Sea 3: Chukchi Sea 4: East Siberian Sea 5: Laptev Sea 6: Kara Sea 7: Barents Sea 8: East Greenland Sea 9: Baffin Bay & Labrador Sea 10: Gulf of St. Lawrence 11: Hudson Bay 12: Canadian Archipelago 13: Bering Sea 14: Sea of Okhotsk 15: Sea of Japan 16: Bohai Sea 17: Baltic Sea 18: Gulf of Alaska
valid_min	0
valid_max	18
units	1
coordinates	Longitude latitude
comment	Adapted from "A new regional mask for Arctic sea ice trends and climatologies (J. Scott Stewart and Walter N. Meier, NSIDC)

4.4.2 Global Attributes

Global Attribute	Description
title	Cryo-TEMPO Polar Ocean Thematic Product
project	ESA Cryo-TEMPO
creator_name	ESA Cryo-TEMPO Project
creator_url	http://cryosat.mssl.ucl.ac.uk/tempo
date_created	Date and time product created in format DD-MM-YYYY HH:MM:SS
platform	CryoSat-2
sensor	SIRAL
geospatial_lat_min	Minimum latitude value in product (degrees N)
geospatial_lat_max	Maximum latitude value in product (degrees N)
geospatial_lon_min	Minimum longitude value in product (degrees E, -180,180)
geospatial_lon_max	Maximum longitude value in product (degrees E, -180,180)
geospatial_vertical_min	Minimum elevation value in product (m)
geospatial_vertical_max	Maximum elevation value in product (m)
time_coverage_start	UTC time of first measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
time_coverage_end	UTC time of last measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
cycle_number	Cycle number used in corresponding ESA L1b products. Each cycle is approximately 369 days long depending upon the phase of the mission.
rel_orbit_number	Relative orbit number within the cycle as used in corresponding ESA L1b products
abs_orbit_number	Absolute orbit number as used in ESA L1b products
cnes_subcycle	CryoSat sub-cycle number defined by CNES. Each sub-cycle is 28.94 days long.
cnes_track	Track number within CNES sub-cycle.
product_baseline	Cryo-TEMPO product baseline (major product release) identifier. First baseline is ‘A’, second baseline will be ‘B’, etc.
product_version	Cryo-TEMPO product version number within baseline. Version numbers start at 1.
sw_version	Cryo-TEMPO unique software version used to process the product.
Conventions	CF-1.8. NetCDF climate variable convention standard used in this product as defined by https://cfconventions.org/.
zone	Area of product coverage. Either ‘Northern Hemisphere’ or ‘Antarctic Ocean’.
doi	Digital Object identifier: "10.5270/CR2-7ece675"

4.5 Coastal Ocean

4.5.1 Structure

One netCDF file per cycle and pass number is generated.

4.5.1.1 Time and coordinates

double time (time)	
standard_name	time
long_name	UTC time
calendar	gregorian
units	"seconds since 2000-01-01"
_FillValue	NaN
comment	UTC time counted in seconds since 2000-01-01 00:00:00. Note that Cryo-TEMPO adjusts the TAI time found in CryoSat L1b products for leap seconds to produce UTC time.
double latitude (time)	
standard_name	latitude
long_name	"Latitude coordinate "
units	degrees_north
valid_min	-90
valid_max	90
coordinates	time
_FillValue	NaN
comment	Latitude of measurement in decimal degrees; a positive latitude indicates Northern hemisphere, a negative latitude indicates Southern hemisphere. If the point of closest approach (POCA) cannot be calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir latitude is provided.
double longitude (time)	
standard_name	latitude
long_name	"Longitude coordinate"
units	degrees_east
valid_min	-180
valid_max	180
coordinates	time
_FillValue	NaN
comment	Longitude of measurement in decimal degrees east relative to the Greenwich meridian. If the point of closest approach (POCA) cannot be calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir longitude is provided.

4.5.1.2 Variables

double sla (time)	
long_name	Sea Level Anomaly
units	m
_FillValue	NaN
coordinates	longitude latitude
source	LRM: MLE4 retracking, SAR: SAMOSA+ retracking.
comment	The sea level anomaly is given relative to the mean sea surface (composite of CNES-CLS2015, DTU and SCRIPPS models).
double adt (time)	
long_name	Absolute Dynamic Topography
units	m
_FillValue	NaN
coordinates	longitude latitude
source	LRM: MLE4 retracking, SAR: SAMOSA+ retracking.
comment	The absolute dynamic topography is the height relative to the geoid. It is derived from the level anomaly by adding the mean dynamic topography from the new CMEMS model (which includes merged Mediterranean MDT).
double sla_uncertainty (time)	
long_name	Sea Level Anomaly Uncertainty
units	m
_FillValue	NaN
coordinates	longitude latitude
comment	Estimated as the sum of a location dependent large-wavelength error and a short-wavelength error which varies as a function of SWH and distance from the coast and is directly computed from the CO TDP
double adt_uncertainty (time)	
long_name	Absolute Dynamic Topography Uncertainty
units	m
_FillValue	NaN
coordinates	longitude latitude
comment	Estimated as a combination of the SLA uncertainty and the uncertainty associated with MDT estimates
double sla_filtered (time)	
long_name	Filtered Sea Level Anomaly
units	m
_FillValue	NaN
coordinates	longitude latitude
source	LRM: MLE4 retracking, SAR: SAMOSA+ retracking.

comment	Sea level anomalies filtered with a Lanczos along-track filter.
double adt_filtered (time)	
long_name	Filtered Absolute Dynamic Topography
units	m
_FillValue	NaN
coordinates	longitude latitude
source	LRM: MLE4 retracking, SAR: SAMOSA+ retracking.
comment	Absolute dynamic topography filtered with a Lanczos along-track filter.
double sla_filtered_uncertainy (time)	
long_name	Sea Level Anomaly Uncertainty
units	m
_FillValue	NaN
coordinates	longitude latitude
comment	Estimated via error propagation of the individual SLA uncertainties.
double adt_filtered_uncertainty (time)	
long_name	Absolute Dynamic Topography Uncertainty
units	m
_FillValue	NaN
coordinates	longitude latitude
comment	Estimated via error propagation of the individual ADT uncertainties.
Double dist_coast (time)	
long_name	Distance from the coast
units	m
_FillValue	NaN
coordinates	longitude latitude
comment	Closest coastline points identified based on the full resolution Global Self-consistent, Hierarchical, High-resolution Geography (GSHHG) Database

4.5.1.3 Flags

byte flag_valid (time)	
long_name	Measurement validity flag
flag_values	0b, 1b,
flag_meaning	0b: valid 1b: invalid
_FillValue	-128b
coordinates	longitude latitude
byte instrument_mode (time)	
long_name	Instrument mode flag
flag_values	0b, 1b
flag_meaning	0b: SAR mode

	1b: LRM mode
_FillValue	-128b
coordinates	longitude latitude

4.5.2 Global Attributes

Attribute	Value
title	Cryo-TEMPO Coastal Ocean Thematic Product
project	ESA Cryo-TEMPO
creator_name	ESA Cryo-TEMPO Project
creator_url	http://cryosat.mssl.ucl.ac.uk/tempo
date_created	Date and time product created in format DD-MM-YYYY HH:MM:SS
platform	CryoSat-2
sensor	SIRAL
geospatial_lat_min	Minimum latitude value in product (degrees N)
geospatial_lat_max	Maximum latitude value in product (degrees N)
geospatial_lon_min	Minimum longitude value in product (degrees E, -180,180)
geospatial_lon_max	Maximum longitude value in product (degrees E, -180,180)
geospatial_vertical_min	Minimum elevation value in product (adt, m)
geospatial_vertical_max	Maximum elevation value in product (adt, m)
time_coverage_start	UTC time of first measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
time_coverage_end	UTC time of last measurement in product, format YYYY-MM-DD HH:MM:SS.MMMMMM
cycle_number	Cycle number used in corresponding ESA L1b products. Each cycle is approximately 369 days long depending upon the phase of the mission.
rel_orbit_number	Relative orbit number within the cycle as used in corresponding ESA L1b products.
abs_orbit_number	Absolute orbit number as used in ESA L1b products
cnes_subcycle	CryoSat sub-cycle number defined by CNES. Each sub-cycle is 28.94 days long.
cnes_track	Track number within CNES sub-cycle.
product_baseline	Cryo-TEMPO product baseline (major product release) identifier. First baseline is 'A', second baseline will be 'B', etc.
product_version	Cryo-TEMPO product version number within baseline. Version numbers start at 1.
sw_version	Cryo-TEMPO unique software version used to process the product.
Conventions	CF-1.8. NetCDF climate variable convention standard used in this product as defined by https://cfconventions.org/.
zone	Mediterranean Sea
doi	10.5270/CR2-65eeb1

4.6 Inland Water

4.6.1 Structure

One netCDF file per cycle and pass number is generated.

4.6.1.1 Time and Coordinates

double time (time)	
standard_name	time
long_name	time in UTC seconds since 1 Jan 2000
calendar	Gregorian
units	seconds
comments	UTC time counted in seconds since 2000-01-01 00:00:00. Note that Cryo-TEMPO adjusts the TAI time found in CryoSat L1b products for leap seconds to produce UTC time.
double latitude (time)	
standard_name	latitude
long_name	Latitude coordinate
units	degrees_north
valid_min	-90
valid_max	90
coordinates	time
comments	Latitude of measurement in decimal degrees; a positive latitude indicates Northern hemisphere, a negative latitude indicates Southern hemisphere. If the point of closest approach (POCA) cannot be calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir latitude is provided.
double longitude (time)	
standard_name	longitude
long_name	Longitude coordinate"longitude of satellite nadir measurement point"
units	degrees_east
valid_min	-180
valid_max	180
coordinates	time
comments	Longitude of measurement in decimal degrees east relative to the Greenwich meridian. If the point of closest approach (POCA) cannot be

	calculated by the SIRAL instrument in SARin mode or by LRM slope correction, then the nadir longitude is provided.

4.6.1.2 Variables

float wsh (time)	
standard_name	water_surface_height_above_ellipsoide
long_name	Water surface height above ellipsoide WGS84
units	m
valid_min	-250
valid_max	5000
_FillValue	NaN
comments	indicate retracker and geophysical corrections used
float geoid_correction_model (time)	
standard_name	geoid_height_above_reference_ellipsoid
long_name	Geoid height above reference ellipsoid
units	m
valid_min	-100
valid_max	100
_FillValue	NaN
comments	Earth Gravitational Model EGM 2008
float wsh_uncertainty (time)	
standard_name	water_surface_height_uncertainty
long_name	Water surface height uncertainty
units	cm
valid_min	0
valid_max	20
_FillValue	NaN
comments	short description on how it was estimated

4.6.1.3 Flags

byte wsh_quality_flag (time)	
standard_name	water_surface_height_quality_flag
long_name	Water surface height quality flag
flag_meaninngs	good_quality, bad_quality, no_data
flag_values	0b, 1b, 2b
comments	These are quality indicators and they are important to properly use the data.
byte instrument_mode (time)	
standard_name	instrument mode

long_name	SIRAL instrument measurement mode
flag_values	1b, 2b, 3b
flag_meanings	1b: low or LRM mode 2b : normal or SAR mode 3b : SARIn mode
byte surface_type (time)	
standard_name	surface_type
long_name	Surface type based on glwd3
units	1
valid_min	1
valid_max	12
_FillValue	-128
flag_values	1b, 2b, 3b, 4b, 5b, 6b, 7b, 8b, 9b, 10b, 11b, 12b
flag_meanings	lake reservoir river floodplain swamp_forest_and_flooded_forest coastal_wetland pan_brackish_saline_wetland bog_fen_mire_peatland intermitant_wetetland_Lake 50_100_wetland 25_50_wetland 0_25_wetland_compex
comments	Global lakes and Wetlands Database classification (https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database).
int land_water_occurrence (time)	
standard_name	land_water_occurrence
long_name	Statistical Water Occurrence based on GSWE
units	percent
valid_min	1
valid_max	100
comments	Statistical water occurrence is based on Global Surface Water Explorer.

4.6.2 Global Attributes

Attribute	Value
title	Cryo-TEMPO – Inland Water Thematic Product
project	ESA Cryo-TEMPO
creator_name	ESA Cryo-TEMPO Project
creator_url	http://cryosat.mssl.ucl.ac.uk/tempo
date_created	Date and time product created in format DD-MM-YYYY HH:MM:SS
platform	CryoSat-2
sensor	SIRAL
geospatial_lat_min	-90
geospatial_lat_max	90
geospatial_lon_min	-180
geospatial_lon_max	180
geospatial_vertical_min	-250

Attribute	Value
geospatial_vertical_max	5000
time_coverage_start	yyyy-mm-ddTHH:MM:SSZ (formats ISO)
time_coverage_end	yyyy-mm-ddTHH:MM:SSZ(formats ISO)
cycle_number	Cycle number used in corresponding ESA L1b products. Each cycle is approximately 369 days long depending upon the phase of the mission.
rel_orbit_number	Relative orbit number within the cycle as used in corresponding ESA L1b products
abs_orbit_number	Absolute orbit number as used in ESA L1b products
cnes_subcycle	CryoSat sub-cycle number defined by CNES. Each sub-cycle is 28.94 days long.
cnes_track	Track number within CNES sub-cycle.
product_baseline	Cryo-TEMPO product baseline (major product release) identifier. First baseline is ‘A’, second baseline will be ‘B’, etc.
product_version	Cryo-TEMPO product version number within baseline. Version numbers start at 1.
sw_version	Cryo-TEMPO unique software version used to process the product.
Conventions	CF-1.8
zone	POBASI/CALAKE/USLAKE
doi	10.5270/CR2-11aea35

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