



sea ice age
and drift

SAGE CCI
Product Validation Plan (PVP)

Reference : METNO-ESA-SAGE-CCI-PVP-001

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CLIMATE-SPACE - THEME I - B. ADDITIONAL ESSENTIAL CLIMATE VARIABLES (ECVS) - NEW ECV PRODUCTS

SAGE CCI


(Sea Ice Age and Drift)

Product Validation Plan (PVP)

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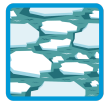
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Acronyms and Abbreviations


AARI	Arctic and Antarctic Research Institute (RUS)
ADP	Algorithm Development Plan
AMSR2	Advanced Microwave Scanning Radiometer 2
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
AR	Annual Review
ASCAT	Advanced Scatterometer
ATBD	Algorithm Theoretical Basis Document
AWI	Alfred-Wegener-Institute for Marine and Polar Research
BGEP	Beaufort Gyre Exploration Project
C3S	Copernicus Climate Change Service
CAR	Climate Assessment Report
CCI	ESA's Climate Change Initiative
CDR	Climate Data Records
CFOSAT	Chinese-French Oceanography Satellite
CMEMS	Copernicus Marine Service
CMIP	Coupled Model Intercomparison Project
CM SAF	The Climate Monitoring Satellite Application Facility
CMUG	Climate Modelling User Group
CP	Communication Package
CRDP	Climate Research Data Package
CRG	Climate Research Group
DAL	Distance Along the Line
DMI	Danish Meteorological Institute (DK)
DNN	Diffusion Neural Network
DOI	Digital Object Identifier
E3UB	End-to-End ECV Uncertainty Budget
ECV	GCOS Essential Climate Variable
ECCC	Environment and Climate Change Canada (CA)
ECMWF	European Center for Medium-Range Weather Forecasts
EO	Earth Observation
ERA5	ECMWF Reanalysis ver. 5
ERS	European Remote-Sensing Satellite
ES	Executive Summary
ESA	European Space Agency
EUMETSAT	European Organization for the Exploration of Meteorological Satellites
FCDR	Fundamental Climate Data Record
FM	Final Meeting
FP	Final Presentation
FR	Final Report
FYI	First-Year Ice
GCOS	WMO/ICO/UNEP Global Climate Observing System
HY-2	Haiyang-2
IABP	International Arctic Buoy Programme
ICESat-2	Ice, Cloud and land Elevation Satellite 2
ICDR	Interim Climate Data Record
IPCC	Intergovernmental Panel on Climate Change
IPS	Ice Profiling sonar
ITT	Invitations to Tender



JAMSTEC	Japan Agency for Marine-Earth Science and Technology (JP)
JAXA	Japan Aerospace Exploration Agency (JP)
KNMI	Royal Netherlands Meteorological Institute
KO	Kick Off
METNO or MET Norway	Norwegian Meteorological Institute
MIZ	Marginal Ice Zone
ML	Machine Learning
MPR	Monthly Progress Report
MS	MileStone
MYI	Multiyear Ice
NASA	National Aeronautics and Space Administration
NERSC	Nansen Environmental and Remote Sensing Center
NIC	National Ice Center
NorESM	Norwegian Earth System Model
NSIDC	National Snow and Ice Data Center (US)
Obs4MIPS	Observations for Model Intercomparison Projects
OSI SAF	The Ocean and Sea Ice Satellite Application Facility
PM	Progress Meeting, Project Manager
PMP	Project Management Plan
PMW	Passive Microwave
PSD	Product Specification Document
PSH	Project Scientific Highlights
PUG	Product User Guide
PVASR	Product Validation and Algorithm Selection Report
PVIR	Product Validation and Intercomparison Report
PVP	Product Validation Plan
QRS	Quarterly Status Reports
QuikSCAT	Quick Scatterometer Mission
RCM	Radarsat Constellation Mission
RID	Review Item Discrepancy
RMSD	Root Mean Square Difference
RMSE	Root Mean Square Error
RRDP	Round Robin Data Package
SAGE	Sea Ice Age and Drift
SAR	Synthetic Aperture Radar
SCAT	Scatterometer
SIC	Sea Ice Concentration
SID	Sea Ice Drift
SIMIP	Sea Ice Model Intercomparison Project
SMMR	Scanning Multichannel Microwave Radiometer
SRD	System Requirement Document
SoW	Statement of Work
SSD	System Specification Document
SSM/I,SSM/I	Special Sensor Microwave - Imager
SSMIS	Special Sensor Microwave - Imager/Sounder
SYI	Second-Year Ice
S&T	Science and Technology AS
T2m	2 Meter Temperature



TB	Brightness Temperature
UB	University of Bremen
UCLouvain	Université Catholique de Louvain
UH	University of Hamburg
ULS	Upward-Looking Sonar
UM	University of Manitoba
URD	User Requirement Document
UWR	User Workshop Report
WAI	Warm Air Intrusion
WBS	Work Breakdown Structure
WMO	World Meteorological Organization
WP	Work Package
WPD	Work Package Description
YI	Young Ice

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1. Introduction

1.1. Purpose and Scope

This document contains the 1st version of the Product Validation Plan (PVP) for the SAGE project for CLIMATE-SPACE - THEME I - B. ADDITIONAL ESSENTIAL CLIMATE VARIABLES (ECVS) - NEW ECV PRODUCTS, in accordance with the contract [AD1], SoW [AD2], and proposal [AD3-AD10].

The purpose of this document is to i) define the approach to the validation of the ECV data products and their associated uncertainties against - as far as it is possible - independent reference data, ideally from measurements, to ii) define the approach to the intercomparison activities of the ECV data products with other satellite and model data, and to iii) provide a comprehensive list of the measurements and data that will be used - including known limitations of use.

1.2. Document Overview


This document is structured as follows:

- Chapter 1 introduces this document.
- Chapter 2 provides information about the reference and inter-comparison data used.
- Chapter 3 describes the validation approaches
- Chapter 4 lists references
- Chapter 5 is an annex containing the buoy observations available (in general) for the sea-ice motion extension time period.

1.3. Applicable Documents

No	Doc. Id	Doc. Title	Date	Issue/ Revision/ Version
AD-1	4000147560/25/I-LR	ESA Contract No.	12/03/2025	NA
AD-2	ESA-EOP-SC-AMT-2024-36	Statement of Work and Annexes and Appendixes	31/07/2024	1.2
AD-3	METNO-ESA-SAGE-CL-001	SAGE Cover Letter	8/11/2024	1.0
AD-4	METNO-ESA-SAGE-TPROP-001	SAGE Technical Proposal	8/11/2024	1.0
AD-5	METNO-ESA-SAGE-IPROP-001	SAGE Implementation Proposal	8/11/2024	1.0
AD-6	METNO-ESA-SAGE-MPROP-001	SAGE Management Proposal	8/11/2024	1.0
AD-7	METNO-ESA-SAGE-FPROP-001	SAGE Financial Proposal	8/11/2024	1.0
AD-8	METNO-ESA-SAGE-CPROP-001	SAGE Contractual Proposal	8/11/2024	1.0
AD-9	METNO-ESA-SAGE-BF-001	SAGE Background and Facilities	8/11/2024	1.0
AD-10	METNO-ESA-SAGE-CV-001	SAGE Curricula Vitae	8/11/2024	1.0
RD-1	METNO-ESA-SAGE-CCI-PVASR-001	SAGE Product Validation and Algorithm Selection Report	1/04/2026	1.0

Note: If not provided, the reference applies to the latest released Issue/Revision/Version

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2. Reference and Inter-comparison data sets

This section provides information about the two different categories of data sets that will be used in WP400. The two different categories refer to reference data and inter-comparison data. Reference data are based on high-quality measurements of sea-ice motion and sea-ice type or age - preferably made in-situ, by buoys or by other ground-based devices, involving a minimum number (ideally none) of retrieval steps, geophysical models and assumptions. Buoy displacements at fine temporal resolution or ship-based observations by well-trained observers belong to this category. Inter-comparison data are based on observations of the above-mentioned sea ice ECV quantities - or other auxiliary variables - carried out by, e.g., air- and space-borne platforms and/or involving some form of retrieval, geophysical or numerical models, or assumptions. Sea-ice motion or sea-ice type/age data sets derived from independent (to this project) remote sensing data also belong to this category.

2.1. Data sets for sea-ice motion


This section contains the data sets that will be used to evaluate (primarily) the extension of the existing sea-ice motion product (Lavergne and Down, 2023) back into the past until 1979.

2.1.1. IABP and IPAB buoy observations

IABP and IPAB stand for “International Arctic Buoy Program” and “International Program for Antarctic Buoys”, which are the two main internationally coordinated initiatives that provide data from drifting buoy observations that will be used here. IAPB buoy data are available from here: <https://www.ncei.noaa.gov/products/international-arctic-buoy-program> (see also here: <https://arcticdata.io/catalog/view/doi:10.18739/A2RB6W32S>). IPAB buoy data are available from here: <https://www.ipab.aq/> (see also here: https://data.meereisportal.de/eisatlas/HTML/eisatlas_buoys.html). Data sets of buoy observations in both hemispheres for the time period spanning years 1991 through 2020 have already been accessed in the framework of the development of the sea-ice motion data set to be extended here (i.e. Lavergne and Down, 2023).

Additional data, i.e. for the time period spanning the years 1979 through 1992, have been accessed, quality checked and pre-processed at MET Norway within WP330. A first version of a list containing all these buoys has been created by MET Norway and is uploaded as a supplement to this report. For IABP buoys, data sets begin in February 1979; for IPAB buoys the first entry is from March 1985, i.e. substantially later than for the Arctic. The quality-checked list is shorter but not complete at the time of writing this document. There might also be more buoys to be added to the list in the supplement because not all buoy observations might have made it into the above-mentioned data bases.

Since these older buoy observations are also essential to fine-tune the sea-ice motion retrieval framework, we decided to share the available observations between WP330 and WP420. This is particularly important for the data sparse Southern Ocean. We will therefore split both data sets (for the Arctic and for the Southern Ocean) such that WP420 will use the data from every other week for the evaluation. The motivation for this split is to do the evaluation with a set of truly independent data.

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2.1.2. Drift stations


There exists a number of so-called North-Pole (NP) drifting stations initiated by Russia. We obtained the data sets of the drift of NP drifting stations 24 through 31, covering years 1978 through 1992 (http://wdc.aari.ru/datasets/d0016/NP_stations/, last access April 2 2026). NP-drift stations were installed on particularly solid multiyear sea ice floes, selected to withstand substantial melt and deformation processes and to therefore allow for long, uninterrupted observations of various meteorological variables. The files downloaded contain 6-hourly positions of the drift station in latitude/longitude coordinates, near surface air temperature, near surface air pressure, and near surface wind speed and direction. Also provided are the mean daily drift speed and direction of the drift station, as well as the cumulative distance travelled.

Table 2.1: North-Pole drift station number and time period covered.

Name	Start date [YYYY-MM-DD]	End date [YYYY-MM-DD]
NP-24	1978-05-04	1980-11-14
NP-25	1981-05-14	1984-04-18
NP-26	1983-07-01	1986-03-17
NP-27	1984-06-09	1987-05-18
NP-28	1986-05-18	1989-01-12
NP-29	1987-06-10	1988-08-08
NP-30	1987-10-04	1991-04-03
NP-31	1988-12-01	1991-04-05

2.1.3. NSIDC buoys sea-ice motion vectors (Arctic only)

The NSIDC sea-ice motion data set (Tschudi et al., 2020), see also <https://nsidc.org/data/nsidc-0116/versions/4/>, is composed of various input data sets. One of these is an independent (to our project) compilation of IABP buoy, i.e. Arctic, sea-ice motion vectors. These vectors are available as annual netCDF files and have been downloaded from <https://nsidc.org/data/nsidc-0116/versions/4/>, last accessed March 31, 2026, for the period 1979 through 2000. According to the NSIDC documentation about the sea-ice motion product, it is difficult to assign an error value to a buoy velocity. Their documentation reads: “The position accuracy of the buoys is about 0.5 km. The locations are interpolated to the 6-hour interval times. The accuracy is then dependent upon the initial position error and the interpolation error. It could be assumed that the overall error would be less than 1 cm/s for the average velocity over 24-hours.”

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2.1.4. NSIDC Advanced Very High Resolution Radiometer (AVHRR) sea-ice motion vectors

Clear-sky visible and infrared imagery obtained from satellites such as the Advanced Very High Resolution Radiometer (AVHRR) has been used to derive sea-ice motion from consecutive images already in the 1980s (e.g. Emery et al. 1991, 1995). The visible channel (here: 2) is useful during summer melt conditions when microwave and infrared data are unreliable. Thermal imagery (here: 4) is used throughout the year except during the summer melt season when surface ice and water have nearly the same temperature. For the NSIDC data set used, ice displacement was derived from four daily satellite passes (0000, 0600, 1200, and 1800 GMT) and matched with the corresponding passes of the next day; therefore, ice velocities from AVHRR data represent average velocities over 24 hours. These four orbits provide full coverage of the ice-covered areas at least once per day, and up to four times near the North Pole. Detection of ice displacement in AVHRR imagery was achieved with maximum cross correlation (MCC) techniques described in Emery et al. (1991, 1995). Between the images of two consecutive days, 10 x 10 pixel rectangular subsets of the same spatial locations were compared and the location with the best (highest) correlation coefficient. The change in location is considered the ice displacement, which allows ice motion to be calculated. This method applies to each of the channels for each of the four passes. All of the vector data for four passes and two channels are averaged together to create a set of daily vectors. For more information about the processing, we refer to: https://nsidc.org/sites/default/files/measureseaicemotion-0116-0748_0.pdf.


We downloaded these sea-ice motion vectors for the years 1981 through 2000 for both hemispheres from <https://nsidc.org/data/nsidc-0116/versions/4> [last accessed: April 22, 2026].

Note: This Section will be extended in v2 in case more drift data becomes known.

2.2. Data sets for sea-ice age and type

2.2.1. The RRDP data set

Within WP200, a Round Robin Data Package (RRDP) data set has been created (see PVASR [RD-1] for a description), comprising two “flavours”. One flavour is an ice-type and age data set based on trajectories of drifting buoys. While providing high spatio-temporal resolution information about colocated brightness temperature, ice-chart-based ice types and auxiliary information, such as from the ERA5 atmospheric reanalysis, this part of the RRDP has been momentarily considered as not being useful per se for the evaluation because of the high potential of the buoy’s ice age information being biased toward too young ice. The second flavour is a so-called “snapshot” RRDP data set. It contains maps of the location where two (or more) of the input snapshot maps - aka, e.g. ice charts - match with respect to the dominant ice type and a concentration $\geq 80\%$, and of the mean multiyear ice concentration if all involved datasets (of the multiyear concentration) agree within $\pm 20\%$. In addition to these two maps, the snapshot RRDP data set also contains the respective input data sets, e.g. ice charts, brightness temperature and other auxiliary information. The first version of this snapshot RRDP data set extends back to 2012, the year when the first AMSR2 brightness temperature observations became available.

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We will use a to-be-determined part of this data set also for our evaluation task. In contrast to the data set used for the evaluation of the backward extension of the sea-ice motion data set (see subsection 2.1), where the same kind of observations are also used to tune the sea-ice motion retrieval algorithm, it is less critical to pre-select and/or strictly separate the evaluation data already at this stage.

2.2.2. Sea-ice charts not covered in the RRDp data set

Historic sea-ice charts for the Northern Hemisphere are available via the NSIDC under, e.g., <https://noaadata.apps.nsidc.org/NOAA/G02176/>. This data set comprises digitised AARI sea ice charts of the years 1933 through 2006. Data are available in SIGRID code, as PNG images and as binary files on a 12.5 km grid-resolution EASE-grid. Given are partial concentrations of multiyear ice, first-year ice, new/young ice and land-fast sea ice. These are available for the entire data set, which, however, does *not cover* the entire Arctic Ocean but mainly the Northern Sea Route and adjacent seas. Typically, the respective maps are split between an eastern and a western part and will need to be merged in a pre-processing step. The data set has irregular temporal sampling with update intervals ranging from weekly to monthly.

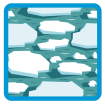
Another data set of historic sea-ice charts available via NSIDC is: <https://nsidc.org/data/g02172/versions/1>. This data set comprises digitised NIC sea ice charts of the years 1972 through 2006. Data are available in ArcGIS, as GIF images and as binary files on a 25 km grid-resolution EASE-grid. Partial concentrations of multiyear ice, first-year ice, new/young ice and land-fast sea ice are given from 1995 onwards. This data set covers the entire Arctic Ocean and comes at weekly sampling.

For the Southern Ocean, there is an archive of SIGRID-1 ice charts from both the NIC and the AARI available here: <http://wdc.aari.ru/datasets/d0001/south/>. The AARI part of this data set spans years 1971 through 1991, the NIC part spans years 1973 through 1994. These data are more difficult to work with because they are not gridded (unlike the two previously mentioned data sets) and, in addition, are stored in SIGRID-1 code. Nevertheless, these early ice charts could serve as a valuable data source for inter-comparison of the early parts of the to-be-built sea-ice age/type data sets.

Ice charts of the years before the first year covered in the RRDp (i.e. 2012) are available for both hemispheres in SIGRID-3 format here: <http://wdc.aari.ru/datasets/d0015/>.

2.2.3. ASPeCt/ASSIST-IceWatch ship-based observations

Manual visual ship-based observations carried out along the track of ships (mostly research vessels) traversing the sea ice cover are often the only direct source for ground-based information about the sea ice cover. Individual observers working from the ship's bridge assess the sea ice conditions following the so-called ASPeCt protocol (Southern Ocean) or the ASSIST / IceWatch manual (Arctic), recording the ice type, the floe size, and the height and fraction of ridges, among other information such as concentration and thickness of sea ice and its snow cover. This is done for up to three thickest sea-ice types within a radius of 1 kilometre / 1 nautical mile around the ship's position. Since the fraction of up to the three thickest sea-ice types is recorded in addition to the total sea-ice concentration, it is possible to derive fractions of new/young ice, first-year ice and multiyear ice should these exist. ASPeCt observations exist since the early 1980s and



have been used by Worby et al. (2008) to come up with a first climatology of the circum-Antarctic sea-ice thickness distribution. ASSIST/IceWatch observations seem to have been compiled routinely later (Hutchings et al., 2016; Hutchings and Faber, 2018) - at least in the sense of a homogeneous, community-agreed set of standard observations to be carried out similar to the ASPeCt protocol, which has been in place since the 1990s. For the Southern Ocean, we will use the original ASPeCt data set of Worby et al. (2008), which dates back to 1980, and the new compilation of Kern (2020), which contains data for the years 2002 through 2019. For the Arctic, we will use the compilation of Kern (2020) only.

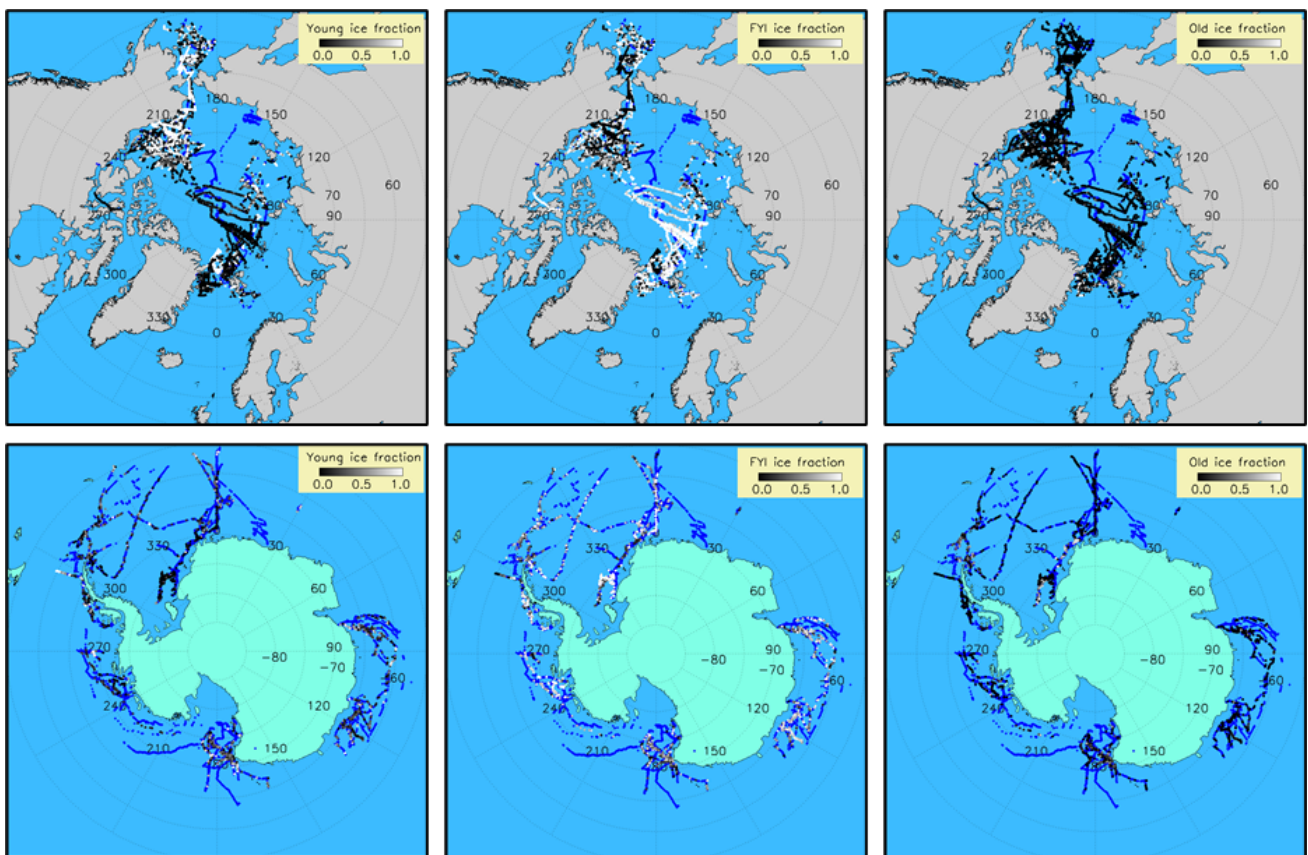



Figure 2.1: Maps of the distribution and actual fractions of new/young ice, first-year ice and multiyear ice for ASPeCt and ASSIST/IceWatch ship-based observations of the Kern 2020 data set for years 2002 through 2019. New/young ice is all ice that is not classified as first-year ice or multiyear ice; landfast ice is left out. Blue symbols denote that ship observations exist, but that no ice type information is available.

It is known that these observations are biased because ships traversing the sea ice in most cases follow leads and/or navigate in areas of comparably thin, level sea ice. It is hence not impossible that this data set predominantly contains observations of new/young ice and first-year ice. In addition, the quality of the visual classification into first-year ice or multiyear ice is unknown, and it is post-cruise almost impossible to assign a measure of uncertainty to these observations. Especially untrained observers might come up with a wrong classification. It has to be noted that, similar to all estimates of sea-ice age and type, visual observations only provide a categorical quantity. Any further information about the sea-ice age would need to be inferred from common knowledge about how various ice types, floe size and sea-ice thickness are interrelated.

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Nevertheless, this kind of data has proven to be very useful for evaluation activities (e.g. Kern et al., 2019; Fons et al., 2023). We note, however, that to our knowledge, it will be the first time that sea-ice type, floe size, and ridged ice information are used in a quantitative way.

2.2.4. North-Pole Drift Stations

There exists a number of so-called North Pole (NP) drifting stations initiated by Russia (see also subsection 2.12). We obtained the data sets of the drift of NP drifting stations 24 through 40, covering years 1978 through 2012 (http://wdc.aari.ru/datasets/d0016/NP_stations/, last accessed April 2 2026). NP-drift stations were installed on particularly solid multiyear sea ice floes, selected to withstand substantial melt and deformation processes and to therefore allow for long, uninterrupted observations of various meteorological variables. The files downloaded contain 6-hourly positions of the drift station in latitude/longitude coordinates, near surface air temperature, near surface air pressure, and near surface wind speed and direction. We can use the location of these drift stations as an indicator of the presence of multiyear ice. There is, however, no information about exactly how old the ice floe with the drift station is.

Table 2.2: North-Pole drift station number and time period covered; this is a continuation of Table 2.1

Name	Start date [YYYY-MM-DD]	End date [YYYY-MM-DD]
NP-32	2003.06.02	2004.03.03
NP-33	2004.09.10	2005.09.04
NP-34	2005.09.19	2006.05.25
NP-35	2007.09.21	2008.07.13
NP-36	2008-09-08	2009-08-24
NP-37	2009.09.07	2010.05.31
NP-38	2010-10-15	2011-09-20
NP-39	2011-10-02	2012-09-15
NP-40	2012-10-02	2012-11-01

2.2.5. Ice-type observations from old publications

A few older (pre 2000s) publications exist where authors were writing down and illustrating sea ice conditions while a research ship traversed the sea ice cover. This subsection gives a home to these publications, out of which we will digitise the information printed and use them for our evaluation purposes. This data might be the only source of sea-ice type information back in the past, especially in the Southern Ocean.


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Table 2.3: List of publications from which sea-ice type information can be digitized for further use.

Authors	Journal / Source	Hemisphere	Time
Massom, R., et al.	Remote Sensing of Environment, 68, 61-76, 1999	SH	1995
Jacka, T. H., et al.	Annals of Glaciology, 9, 1987	SH	1985
t.b.c.			

2.2.6. Ice-type estimates from Synthetic Aperture Radar (SAR)

Satellite SAR imagery allows for obtaining information about the sea-ice type distribution at a finer spatial resolution than is possible with passive microwave imagery or scatterometer data. Since the launch of the Sentinel-1 satellite coverage, with such SAR data has been improving substantially, allowing the use of these data in a routine manner for sea-ice type retrieval. One such data set is included in the snapshot RRDP database (see PVASR v1.0 [RD-1], Table 2.1: autoDMI and S1). Here we'd like to give home to other, less extensive data sets of this kind that are *not* included in the RRDP and are hence truly independent. These other SAR-based sea-ice type data sets are based on SAR sensors operating at C-Band (RADARSAT-1 and -2, Radarsat Constellation Mission (RCM), Envisat ASAR, Sentinel-1 SAR) but also at X-Band (TerraSAR-X, Tandem-X). Respective data sets could be obtained from Johannes Lohse (contacted & agreed), Wenkai Guo (contacted & agreed), and Xiao-Ming Li (contacted & agreed).

NOTE: This Section will be extended in v2 in case more ice-type and -age products will become available.

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3. Validation approaches

3.1. Community validation protocols or standards

3.1.1 Sea ice motion

The standard procedure to evaluate sea-ice motion products is to colocate the sea-ice motion vector with sea-ice motion vectors provided by drifting buoys. It is common to inter-compare the two motion components individually. Motion components either follow the notation of the cardinal directions: u (positive eastward) and v (positive northward), or the directions of the grid they are projected to: x (positive to the right) and y (positive up). We will follow the second concept - simply because it has been used by Lavergne and Down (2023), and will match the way and format the drift product will be extended


Another approach that is commonly used is to intercompare how different sea-ice motion products represent the drift of sea ice across a well-defined gate - for instance, through the Fram Strait or in the area of the transpolar drift. This is an approach particularly well-suited to investigate how well two products that overlap in time agree with each other or how well a product extension continues an already existing product. We will use this possibility as a means to check the consistency between the existing (Lavergne and Down, 2023) and the back-ward extended sea-ice motion product.

We refer to Section 3.3 for the statistical means that are going to be used.

3.1.2 Sea-ice type and age

For sea-ice type and age, there are several different validation approaches to choose from. One - and this is clearly the most important one - co-locates maps of sea-ice type and age of the (novel) product that needs to be evaluated with maps of other such products to subsequently quantify how well the different types and age classes are represented by the novel product. The metrics on how this can be done quantitatively are described in Section 3.2. Some pre-processing of the evaluation data might be needed in case they offer a much finer spatial resolution - e.g. SAR images classified into sea-ice types. We will utilise this form of evaluation as much as possible in order to reach a quantitative assessment.

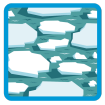
Another way to compare basin-scale products of the sea-ice type or age with each other is to compute time series of the total area or extent of the respective sea-ice types or age classes and compare these time series with each other (see e.g. Ye et al., 2023). To be useful, this approach has to advance beyond a pure intercomparison. It needs to take into account the typical seasonal development of a certain sea-ice type or age class. If, for instance, four out of five products consistently show an increase in the multiyear ice area in a region for which we know (from other sources) that the multiyear ice area typically decreases, and the 5th product exactly shows this decrease, then this 5th product will receive a higher "mark". We will employ this form of evaluation as well - mainly to illustrate the credibility of the novel product(s) with respect to the representation of the correct sea-ice type & age properties in space and time, and to discover any long-term

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trends that could potentially be caused by, e.g., retrieval assumptions that change over time, sensor drift or other external factors. Here we will employ statistical means as provided in Section 3.3.

Among our datasets for the evaluation of the sea-ice type and age products are individual, ground-based observations - available either as a buoy trajectory or as a ship trajectory. A buoy sits on an ice floe, drifts with that ice floe, and by that represents its characteristics, which - ideally - are also representing the sea-ice type and age of the sea ice around this ice floe. Unfortunately (see RD-1), it is not always known how old the ice floe with the buoy on it was. While one could try to figure this out by looking into high-resolution SAR images containing the ice floe the buoy is located on, it is unlikely that we will considerably increase the number of buoys with a more definite knowledge of the sea-ice type. Hence, the inter-comparison between buoy observations and our novel sea-ice type and age can only be of a qualitative nature and will focus on time-series of, for instance, time since buoy deployment versus retrieved sea-ice age, or on the detection of abrupt changes in sea-ice type (in the product) along the trajectory of the buoy.

A ship, in contrast, actively traverses the sea ice cover, encountering sea ice of various types and age classes. To our knowledge, there exists no approach yet about how to use ship-observation for the evaluation of sea-ice type or age products. Despite the uncertainties involved (see Section 2.2.3 and 3.4), we will follow the approach outlined for the sea-ice concentration in Beitsch et al. (2015) and work with daily along-ship track mean (or median) estimates of the reported sea-ice type, taking into account both ice type and floe size, and eventually also ridge height and ridged-ice fraction information, and thereby going beyond what is shown in Section 2.2.3. We will design a method to relate the ship-based information quantitatively to the sea-ice type products, building on preliminary work by Kern et al. (2011) and Ozsoy-Cicek et al. (2011). Whether this method will utilise elements of the metrics described in Section 3.2 or statistical means (see Section 3.3) remains to be seen.



3.2. Validation metrics

3.2.1 Confusion matrix

A confusion matrix is a specific table layout that allows visualisation of the performance of an algorithm, typically a supervised learning one. By definition, a confusion matrix C is such that C_{ij} is equal to the number of observations known to be in group i and predicted to be in group j (see Fig. 3.1).

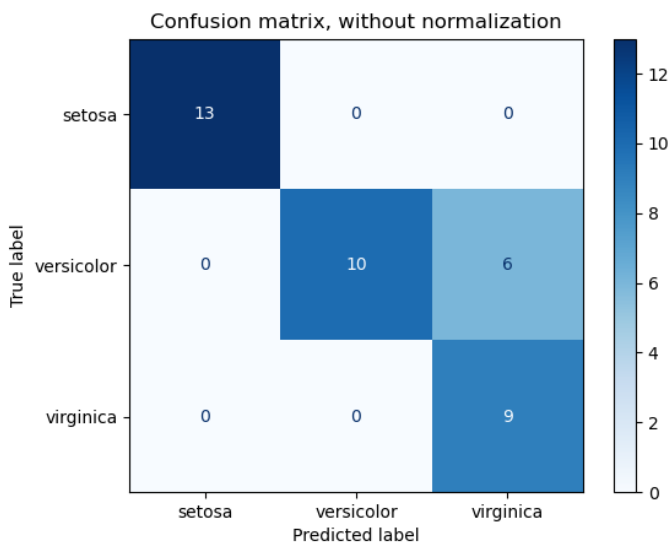


Figure 3.1: Example of a confusion matrix (from documentation of scikit-learn package).

3.2.2 Accuracy score

Accuracy (A) is computed as the ratio of correct predictions to the total number of samples:


$$A = True / Total \tag{1}$$

It ranges from 0 (worst) to 1 (best) and can be computed for binary or multiclass classification problems. It is simple to compute and common in use, but it can be biased in the case of an unbalanced dataset (i.e., significantly more samples that belong to one class than other classes).

3.2.3 Balanced accuracy score

The balanced accuracy (A_B) is computed as:

$$A_B = (TP / (TP + FN) + TN / (TN + FP)) / 2, \tag{2}$$

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where TP , TN , FP and FN denote true positive, true negative, false positive and false negative classifications, respectively. The balanced accuracy also ranges from 0 (worst) to 1 (best) and performs better than accuracy when the data samples are unbalanced.

3.2.4 Brier score loss

Brier loss is computed as follows:

$$BS(Y, \hat{P}) = \frac{1}{N} \sum_{i=0}^{N-1} \sum_{k=0}^{K-1} (y_{i,k} - \hat{p}_{i,k})^2 \tag{3}$$

where N is the number of samples, K is the number of classes, $y_{i,k}$ is the true label that belongs to a sample i and class k and can be either 0 or 1, $p_{i,k}$ is the predicted probability for sample i in the class k in the range $[0, 1]$.

For example, the true binary labels $y = [0, 1, 0, 0]$ can be presented by the following matrix Y :

$$Y_T = [[1, 0], [0, 1], [1, 0], [1, 0]]$$

And predictions can be presented by the following matrix of probabilities P :

$$P = [[0.9, 0.1], [0.1, 0.8], [0.8, 0.2], [0.7, 0.3]]$$

The Brier loss is used when the reference data or a classifier provides label probabilities. It can be used in binary, multiclass and multilabel classification problems. It ranges from 0 (best) to 2 (worst).

Figure 3.2 shows an example of comparing ice charts with averaged probabilities and the probabilistic prediction of sea-ice type by the NERSC sea-ice age algorithm.

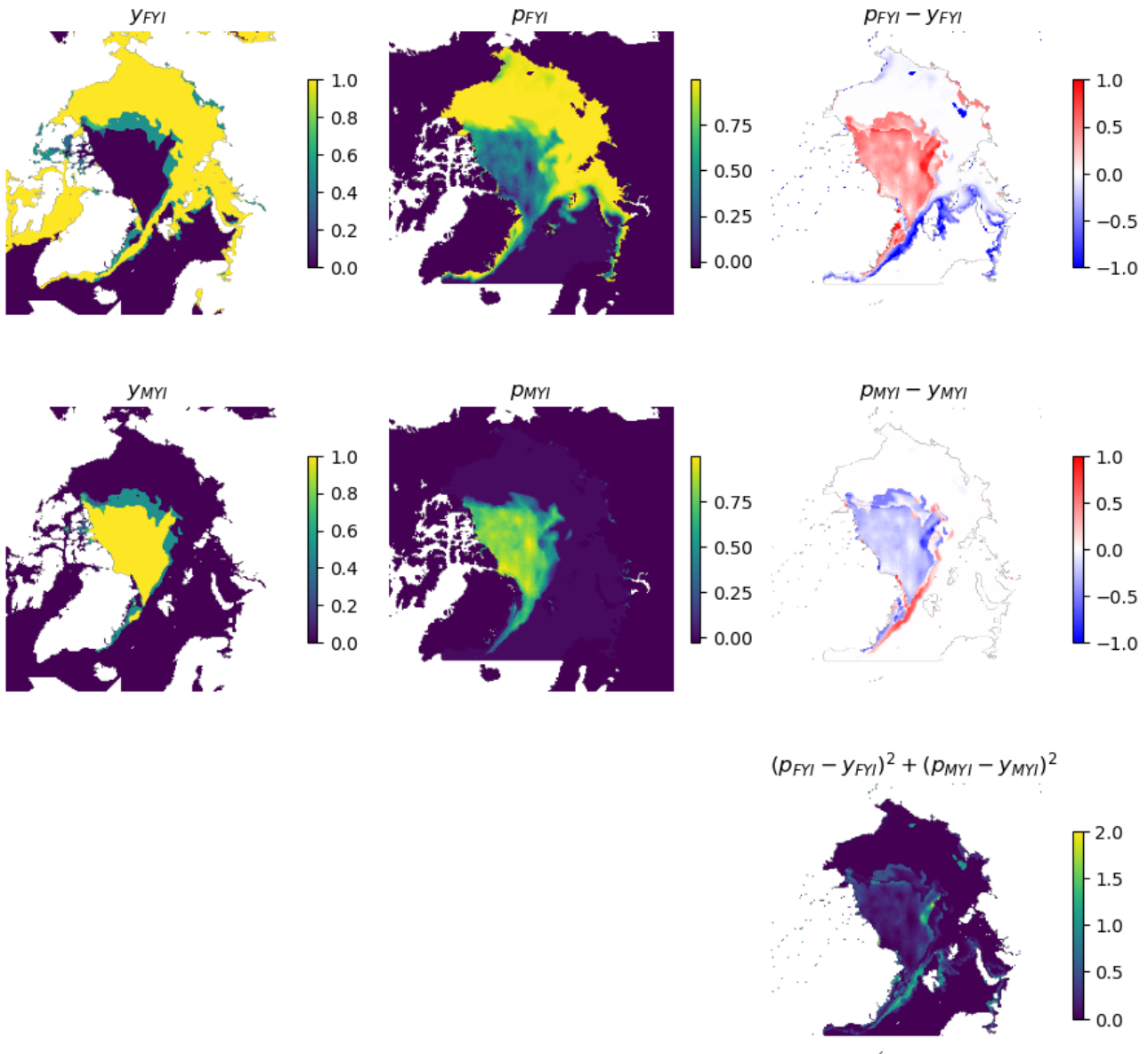
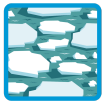



Figure 3.2 Example of comparison of probabilistic reference data and forecast. The left column shows the average probabilities (y) of first-year ice (FYI, upper row) and multiyear ice (MYI, second row) from the reference data. The second column shows the predicted probabilities of FYI and MYI by the NERSC ice age algorithm. The third column shows the difference between the FYI and MYI probabilities, as well as the geometric mean of these differences. The Brier score is computed as the average of the values in the lower right panel.

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3.2.5 Log-loss

The log-loss (L_{log}) is computed as follows:

$$L_{log}(y, \hat{p}) = -\log \Pr(y|\hat{p}) = -(y \log(\hat{p}) + (1 - y) \log(1 - \hat{p})) \quad (4)$$

where y is the true label, and p is the predicted probability. Although indices for y and p are omitted here, they are identical to $y_{i,k}$ and $p_{i,k}$ in Eq. 3.

Log-loss is used when a classifier provides label probabilities. It can be used in binary, multiclass and multilabel classification problems. It ranges from 0 (best) to 1 (worst).

3.3. Statistical means

As stated above, for the evaluation of the sea-ice drift product extension against buoys and NP-drift stations, we will follow the approach outlined in Lavergne and Down (2023). A matchup database will be created in which matchup data pairs of buoy (or NP-station) motion and retrieved motion will be generated. We will have to investigate whether we can use the same collocation strategy as outlined in Lavergne and Down (2023, section 3.6.2) or whether we have to relax conditions a bit in light of the smaller amount of evaluation data and in light of the sometimes larger time intervals at which buoy (or NP-station) positions were recorded. We will modify the collocation strategy to include the NSIDC buoy sea-ice motion and AVHRR sea-ice motion products. The quantity that is going to be compared is the displacement over a time period of 24-hours into the dX and dY directions of the EASE2 grid that will be used for the sea-ice motion product.


We will use bias and root mean squared error (RMSE) as the standard statistical metrics for the motion components and will also report on the comparison of the resulting displacement. Also, for the comparison of the time series of sea-ice type or age class, we will use bias and RMSE where useful, together with trend analyses.

We are going to reuse Python tools that have been developed in the framework of the sea-ice motion data set production and valuation (Lavergne and Down, 2023) as much as deemed useful.

3.4. Mismatches between the ECV products and the data sets used for intercomparison


In the evaluation work, we need to take into account a number of mismatches.

- Buoy observations come at different temporal samplings, some 1-hourly, others 6-hourly. While this could create a difference in the mean (or median) daily sea-ice motion, the overall net displacement of a buoy that reports every hour and a buoy that reports 6-hourly should be the same. Hence, we are confident that different temporal sampling of buoy positions will not have an impact on the evaluation results.
- We are providing daily maps of sea-ice type and sea-ice age. Many of the independent products we can use for evaluation and intercomparison - namely ice charts - come at a different spatial sampling and also with a different coverage over time. While the latter only influences the number of

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matching data pairs between the intercomparison and our product, the different spatial sampling could have an impact on the evaluation results. Intercomparison data that are provided every 10 days could result in different results than using intercomparison data that are provided every 7 days.

- Ice charts are derived from a multitude of observations. The common practice is to use observations of the most recent day (i.e. closest to the day of issuing the chart) as possible. But the metadata of especially the older ice charts does not inform about the days for which most (and which) data were used to infer the sea ice information. It is not possible to quantify the exact validity date of a sea ice chart.
- The fact that ice charts are derived as much as possible from observations of the most recent day might also have implications for the quality and/or reliability of the sea ice information given. Since 1995 and certainly after 2012, more and more SAR images have been used - known to provide fine-resolution daylight- and weather-independent high-quality (if interpreted by a skilled observer) estimates of the sea-ice type - the lack of such data might severely downgrade the quality of the ice charts - especially if the fall-back solution is coarse-resolution passive microwave observations. Also, here that lack of adequate information about the data that were used to create the respective ice chart results in an unknown uncertainty.
- For the limitations of the ship-based observations, we refer to the respective sub-section in Section 2. In addition to what is mentioned there, one needs to keep in mind that ship observations only represent sea-ice conditions around the ship, in the best case of an area of approximately 10 km along by 2 km across-track (see Kern et al., 2019). Hence, there is a representation uncertainty using such observations, independent of the bias caused by the ship's track.

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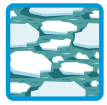
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5. Annex A - Buoy observations available for the sea-ice motion extension time period.

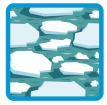
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IABP	1920	NH	1979-02-19	1979-12-20
IABP	1918	NH	1979-02-18	1979-12-28
IABP	1914	NH	1979-02-18	1979-12-31
IABP	1927	NH	1980-01-02	1980-02-18
IABP	1925	NH	1979-02-19	1980-04-25
IABP	1915	NH	1979-11-01	1980-05-21
IABP	1913	NH	1979-02-18	1980-06-22
IABP	1923	NH	1979-03-01	1980-07-08
IABP	1933	NH	1980-04-23	1980-08-09
IABP	1931	NH	1980-04-23	1980-08-23
IABP	1937	NH	1980-04-26	1980-10-08
IABP	1938	NH	1980-04-24	1980-10-16
IABP	1940	NH	1980-04-24	1980-10-26
IABP	1934	NH	1980-04-23	1980-12-11
IABP	1929	NH	1980-04-23	1981-01-17
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IABP	1932	NH	1980-04-23	1981-04-14
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IABP	1930	NH	1980-04-24	1981-06-17
IABP	1936	NH	1980-04-24	1981-06-24



IABP	1943	NH	1980-11-24	1981-06-25
IABP	1935	NH	1980-04-24	1981-07-05
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IABP	1947	NH	1985-04-01	1985-11-15	
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IABP	3817	NH	1982-04-30	1986-01-11	



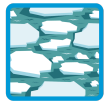
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IABP	3836	NH	1985-08-18	1986-01-31	
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IABP	3848	NH	1984-10-02	1986-12-17	
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ANT	1986_3314_6pT	SH	1986-10-17	1986-12-31	
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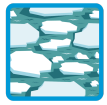
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IABP	7011 NH	1987-03-20	1987-04-10	
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ANT	1987_1166_24pT	SH	1987-03-20	1987-04-15
ANT	1987_1161_2pT	SH	1987-03-01	1987-04-20
ANT	1987_3310_6pT	SH	1987-01-01	1987-04-21
IABP	1895 NH	1987-01-01	1987-05-31	
IABP	3880 NH	1986-04-18	1987-06-01	
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IABP	7024 NH	1987-04-29	1987-06-19	
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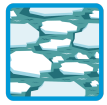
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IABP	7050	NH	1988-06-22	1988-06-26
IABP	9266	NH	1988-05-04	1988-06-30
IABP	7002	NH	1986-08-13	1988-07-01
IABP	2380	NH	1988-06-01	1988-07-16
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IABP	3283	NH	1988-04-27	1989-03-23
IABP	7042	NH	1986-10-02	1989-03-26
IABP	2765	NH	1989-01-07	1989-03-31
IABP	8887	NH	1988-09-16	1989-04-19
IABP	6117	NH	1989-04-04	1989-04-26
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IABP	6115	NH	1989-04-01	1989-04-30
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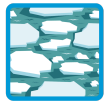
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ANT	1989_8064_3pT		SH	1989-09-27	1989-12-31
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