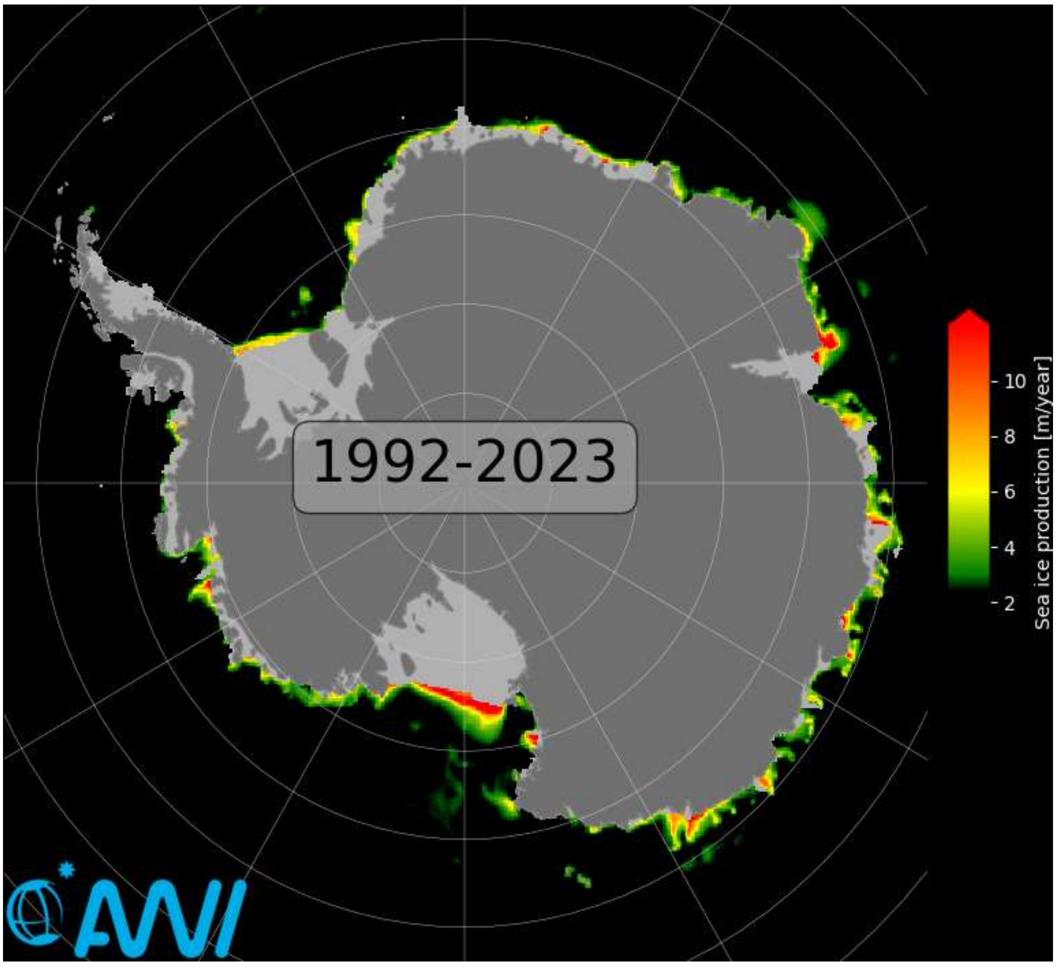
Ocean Cryosphere Exchanges in Antarctica:

Impacts on Climate and the Earth system

Gridded European circumpolar sea ice production fluxes

Deliverable D1.4



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Cover sheet: Mean sea ice production flux [m/year] over the period 1992-2023 derived from SSM/I sea ice concentration and ERA5 reanalysis. Credit: Lars Kaleschke / AWI Bremerhaven, July 2024.

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1. Publishable summary

This deliverable is a new dataset of sea ice production (SIP) in Antarctic coastal polynyas, critical regions for sea ice formation and dense water formation. Using Earth Observation data and atmospheric reanalysis, we use a heat budget method to estimate the SIP. We use sea ice concentration (SIC) from passive microwave sensors and ECMWF ERA5 reanalysis for near-surface wind speed and surface air temperature. Comparison against previous literature shows broad consistency in spatial patterns and magnitude of ice production, with notable variations across larger polynyas. Despite simplifications and thereby increased uncertainties in the absolute ice production values, the data set provides valuable insights into the dynamics and variability of Antarctic polynya SIP for the period 1992-2023.

2. Work performed and main achievements

2.1 Description of the work performed

Antarctic coastal polynyas play a crucial role for sea ice production (SIP), which is closely linked to the formation of dense water (e.g. Barber and Massom, 2007). Various methods have previously been developed to derive the SIP from Earth Observation data combined with atmospheric reanalysis. The most commonly used approach is a heat budget (HB) method, which relates the sea ice growth to heat loss at the ocean-ice-atmosphere interface. The different methods differ mainly by the use of different sea ice parameters, the thin sea ice thickness (SIT) or sea ice concentration (SIC), as well as reanalysis products and the parameterization of heat fluxes (e.g. Tamura et al. 2016, Macdonal et al. 2023).

Here we use the SIC derived from passive microwave sensors with the wind speed and surface air temperature from ERA5 reanalysis (Hersbach et al., 2023). The formulation (Eq. 9) of Pease (1987) is used to estimate the heat flux over the ocean at the freezing point. This provides the freezing rate (FR) and associated SIP weighted with the open water fraction (1-SIC). The main assumption is that the SIP corresponds to the ocean-atmosphere heat flux through a constant latent heat of fusion. Moreover, the heat flux through the ice with 100% concentration, the shortwave radiation, the evaporative, and the oceanic heat flux are neglected.

The selection of the ice concentration product considers on the one hand that a reasonable high spatial resolution is needed to resolve the relatively small scale coastal polynyas, and on the other hand that a long consistent time series is required for climatological applications. For these reasons, we chose an SSM/I-based SIC product, which utilises the 85 GHz channels to provide a rather coarse spatial resolution of 12.5 km at the benefit of a long time series. The 85 GHz SSM/I data has been available since the end of 1991. The specific data product is generated at CERSAT/IFREMER using the ASI algorithm (Kaleschke et al., 2001, Ezrathy et al. 2007). The same method could also be used with the AMSR-E/AMSR-2 sensors with similar results (e.g. MacDonald et al., 2023) at higher resolution (6.25 km for AMSR-E, and 3.125 km for AMSR-2), but only since 2001 with a data gap between AMSR-E and AMSR-2 in 2012. Since the need for a long data set for climatological applications predominates, we choose the specific 85 GHz SSM/I product here. Other SSMI/I SIC products covering an even longer period since 1978 could also be used, but with significantly poorer spatial resolution, which is strongly limiting the observation of smaller polynyas.

We use the wind speed (*ws*) and air temperature (*t2m*) from ERA5 to calculate the heat loss over the ice-free ocean at the freezing point. Daily averages (Δt = 1 day) were calculated from hourly surface level data and interpolated on the same 12.5 km polar stereographic grid as the SIC product. The resulting SIP was calculated from the product of 1-SIC and FR(*t2m,ws*) for each grid pixel (*x,y*) and time step *t*.

$$SIP(t,x,y) = (1 - SIC) * FR * \Delta t$$

To eliminate unrealistic ice production over the open ocean where the freezing point assumption was not met, we applied an additional open water mask. Finally, a user-friendly NetCDF product was generated by calculating monthly means from the daily SIP (Fig. 1).

The units of SIP are given in m/month, i.e. the growth of thickness in one month. Due to the permanent advection of the sea ice away from the coast, this thickness is not reached in the polynya, but contributes to the total Antarctic sea ice growth. The polynya area necessary to calculate the total SIP in units of km^3 is defined as the area exceeding 3 m/year SIP following Oshima et al. (2016).

A validation of the SIP product is difficult due to the lack of suitable ground data. In the following we compare the presented SIP product with previous results published in the literature.

Oshima et al. (2016) and Tamura et al. (2016) calculated the heat flux through thin ice using a method that depends on the polarization ratio (PR) at 37 GHz and 85 GHz to estimate the thin ice thickness (Tamura et al. 2007). Cho et al. (2024) recently questioned the physical foundation of the method because of a limited sensitivity to ice thickness at the used frequencies during tank experiments. However, the satellite-based results of Oshima et al. (2016) and Tamura et al. (2016) look in general plausible and will serve as a basis for a comparison in the following.

The annual SIP average shown in Fig. 2 is very similar to Fig. 3 in Oshima et al. (2016). Both the spatial pattern and the strength of ice production agree very well in most cases, although there are some major differences, such as a stronger SIP of the largest polynyas (Ross and FRIS) in the new product.

The monthly ice production for selected polynyas is shown in Fig. 3 and can be compared with Fig. 4 in Tamura et al. (2016). Both the shape and magnitude are very similar with a bimodal structure in many cases. However, comparison of the ice production in units of km^3 is more difficult due to the different polygons that define the area of the polynyas.

An example time series of interannual variability is shown for the Amundsen polynya in Fig. 4. It can be seen that the significance of potential trends depends on the length of the time series and the selected period. Tamura et al. (2016) reported a significant positive trend over the period 1992-2013. However, when the trend is calculated over the period 1992-2023 it is not anymore statistically significant.

Table 1 provides a summary of the annual cumulative SIP for selected coastal polynyas compared with the values from the literature. Overall there is a broad general consistency of the magnitude and variability of the SIP given that there are potential large differences in the defined polynya area. The largest ice production takes place in the Ross Sea in line with previously published results, although the magnitude exceeds previous estimates.

In summary, we delivered a new SIP data set that is broadly consistent with previous estimates from the same sensor family (SSM/I) and covers a long time period suitable for ocean and climate studies. We emphasise that the absolute values of the SIP estimates have large uncertainties but that the interannual and seasonal variability are useful parameters for various applications (e.g. Tamura et al. 2016). Estimates from other sensors and with other methods differ more (e.g. Lin et al. 2023).

```
xarray.Dataset

► Dimensions:        (time: 384, x: 632, y: 664)

▼ Coordinates:
  time               (time)      datetime64[ns]  1992-01-31 ... 2023-12-31
  x                  (x)         float64         -3.95e+03 -3.937e+03 ... 3.95e+03
  y                  (y)         float64         -3.95e+03 -3.937e+03 ... 4.35e+03

▼ Data variables:
  sea_ice_produc…    (time, y, x)  float32       ...
  latitude           (y, x)        float64       -41.51 -41.58 ... -39.36 -39.29
  longitude          (y, x)        float64       -135.0 -135.1 ... 42.14 42.23
  land               (y, x)        bool          ...

▼ Attributes:
  CDI :              Climate Data Interface version 2.3.0 (https://mpimet.mpg.de/cdi)
  Conventions :      CF-1.6
  grid :             EPSG:3412 # NSIDC Polar Stereographic for South
  spatial_resoluti…  12.5 km
  time_resolution :  monthly
  netCDF_create…     Lars.Kaleschke@AWI.de
  acknowledgem…      EU OCEAN:ICE Deliverable D1.4 (June 2024)
                     Gridded European circumpolar sea ice production fluxes
                     OCEAN:ICE is co-funded by the European Union, Horizon Europe Funding Programm
                     e for research and innovation under grant agreement Nr. 101060452 and by UK Resea
                     rch and Innovation
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Fig. 1: Content of the NetCDF SIP product, dimensions, coordinates, variables and attributes.

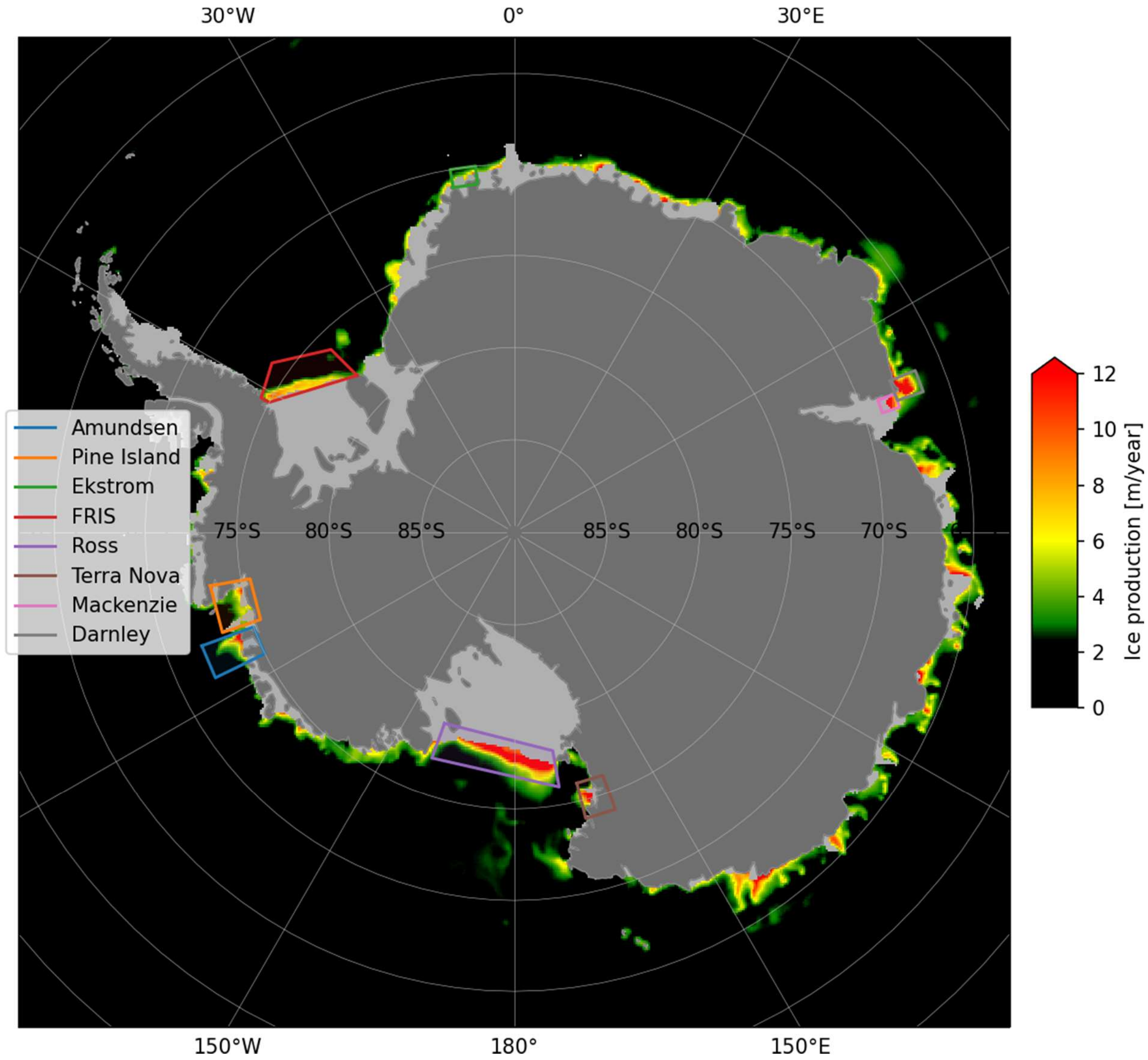

Fig. 2: Map of annual SIP, averaged over 1992-2023, based on the SSMI ASI ice concentration and ERA5 wind speed and surface air temperature. Some selected polynyas are shown with their corresponding colour-coded polygons (own approximations). The SIP colour scale was designed to match Fig 3 in Oshima et al. (2016) for a direct comparison.

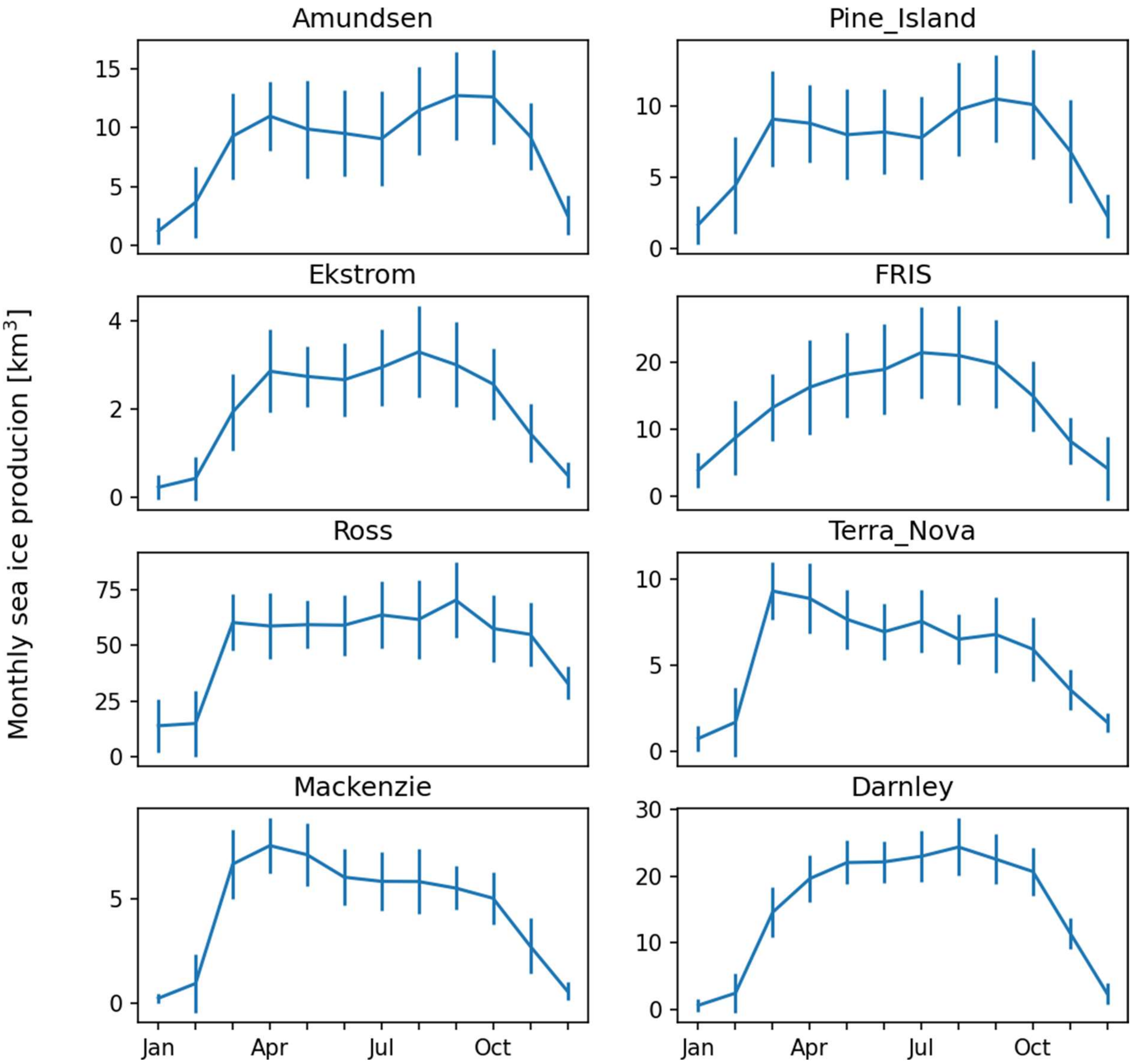

Fig. 3: Monthly sea ice production for selected polynyas, based on the SSMI ASI ice concentration and ERA5 wind speed and surface air temperature. The solid line is the mean averaged over 1992-2023, the error bar indicates the standard deviation of the interannual changes.

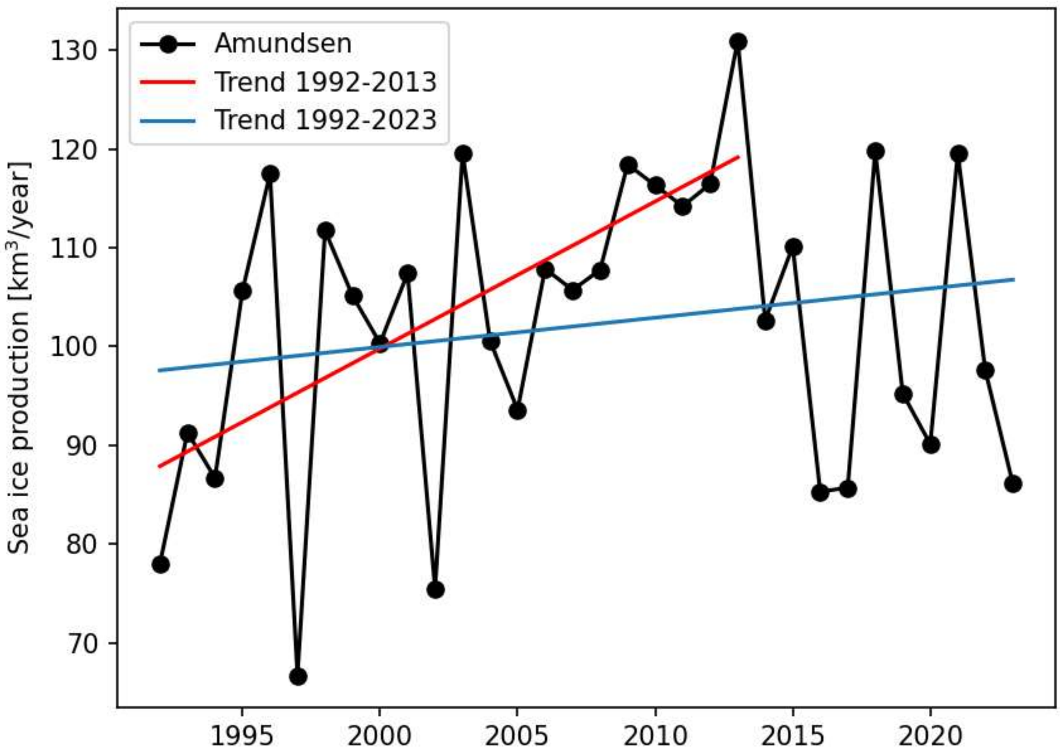

Fig. 4: Time series of annual SIP for the Amundsen polynya with two linear trend lines. The trend over the period 1992-2013 is statistically significant (p=0.003) while it is not significant (p=0.3) over the longer period 1992-2023.

Table 1: Annual cumulative SIP for selected coastal polynyas.

Polynya	Total ice production (km^3/year)	Averaged ice production (m/year)	Total ice production (km^3/year)	Averaged ice production (m/year)
	This product (1992-2023)		Oshima et al. (2016) Tamura et al. (2016), only total	
Cape Darnley	186 ± 15	8.9 ± 0.7	127 ± 12 182 ± 12	8.2 ± 0.8
Mackenzie Bay	54 ± 5	11.3 ± 1.1	57 ± 5 89 ± 9	8.0 ± 0.8
Terra Nova Bay	67 ± 7	8.4 ± 0.9	53 ± 5 56 ± 9	8.4 ± 0.8
Ross Sea	608 ± 67	8.2 ± 0.9	253 ± 17 382 ± 63	7.5 ± 0.5
Amundsen	102 ± 15	5.8 ± 0.	83 ± 13 123 ± 24	6.6 ± 1.0
Ronne / Weddell Sea / FRIS	169 ± 35	5.7 ± 1.2	27 ± 11 271 ± 50	4.7 ± 1.9

2.3 Open Science

The Python codes to generate the SIP data from SSM/I SIC and ERA5 input data are provided for full transparency and reproducibility of the results.

ASI SSM/I sea ice concentration data used as input are available at IFREMER/CERSAT ftp://ftp.ifremer.fr/ifremer/cersat/products/gridded/psi-concentration

ECMWF ERA5 hourly data on single levels from 1940 to present https://doi.org/10.24381/cds.adbb2d47

3. Results

3.1 Achieved results

Results of the project need to be encoded carefully. Results are what is generated during the project implementation. This may include, for example, know-how, innovative solutions, algorithms, proof of feasibility, new business models, policy recommendations, guidelines, prototypes, demonstrators, databases, trained researchers, new infrastructures, networks, etc.

3.3 Datasets

A new dataset of sea ice production (SIP) in Antarctic coastal polynyas, critical regions for sea ice formation and dense water formation is available on Zenodo: https://doi.org/10.5281/zenodo.11652686

The data set consists of a NetCDF file, csv examples, code and documentation. The repository is the following: https://gitlab.awi.de/ocean-ice/deliverable

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