Integrated Arctic Observation System

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Scientific analyses, summary of results, and exploitation: Sea ice and water vapor products from satellites

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6	IOPAN		**30**	GFZ	
7	DTU		**31**	ARMINE	
8	AU		**32**	IGPAN	
9	GEUS		**33**	U SLASKI	
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11	UNIS		**35**	DNV GL	
12	NORDECO		**36**	RIHMI-WDC	
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14	USFD		**38**	WHOI	
15	NUIM		**39**	SIO	
16	IFREMER		**40**	UAF	
17	MPG		**41**	U Laval	
18	EUROGOOS		**42**	ONC	
19	EUROCEAN		**43**	NMEFC	
20	UPM		**44**	RADI	
21	UB	**6**	**45**	KOPRI	
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EXECUTIVE SUMMARY
Deliverable D6.23 describes the work done mainly at the University of Bremen on satellite remote sensing of sea ice parameters and of total water vapor in the Arctic using microwave imagers (AMSR-E, AMSR2) and sounders (AMSU-B, MHS), i.e., work done in WP6 with links to data delivered through WP2. We present and assess the data that have been prepared, improved, and exploited during the INTAROS project. This refers to data characterization, making the data accessible, creating new datasets, extended the time series from satellites. This also includes data further developed in the framework of overlapping projects but not made available before INTAROS. This document focus on how existing observations and data products can enhance the existing observation system through data exploitation.

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1. Introduction

For the vast area of Arctic sea-ice, satellite observations are the only means to obtain daily Arctic-wide information about the surface and the atmosphere. While data are available from various sources, the challenge is to provide them for the different users in appropriate and homogeneous formats and qualities, which in addition are well documented. This Deliverable demonstrates several usages of satellite Earth Observation data in the hostile environment of the Arctic where in situ observations are sparse, with focus on observing sea ice parameters (Section 2) and atmospheric water vapor (Section 3).

2. Sea Ice

For sea ice satellite data, the INTAROS consortium is contributing six new or improved data products: from UB high resolution sea ice concentration (SIC) thin sea ice thickness and sea ice type, i.e., the multiyear ice concentration, and from IFREMER sea ice displacement at large and at medium scale (D6.22). All products are available from the INTAROS data repository, and, as a backup, from the web pages of the contributing institutes, see references to data sets.
For sea ice concentration (SIC), the most important sea ice parameter, there are two data products available from the consortium: From Project Partner UB, ASI sea ice concentration based on AMSR observations, and from IFREMER, ASI sea ice concentrations using SSM/I observations. Figure 1 demonstrates how the different sea ice parameters combine to a more complete overview of the Arctic sea-ice situation.

All satellite data products are scientifically well documented have been evaluated against the requirements of the WMO OSCAR data base of Observational Requirements (INTAROS Deliverable 2.10, Section 3 Satellite products). Their spatial and temporal coverage and timeliness practically fulfill the requirements, as well as the temporal resolution of one day. Based on the evaluation results, improvements have been applied and user guides provided, see references below.

The usefulness of the sea ice thickness and multiyear ice products has been improved by providing a User guide (References below) and adding metadata at the collection and file levels.

Application example: Support of CAATEX campaign with NRT sea ice information

An example for the usefulness of the sea ice data has been the support of the Campaign CAATEX (Coordinated Arctic Acoustic Thermometry Experiment (see https://caatex.nersc.no/node/14) where ASI sea ice concentrations were overlaid with MODIS sea ice maps. In autumn 2019 six tomographic moorings and one oceanographic mooring were deployed. The sea ice data were used to plan the deployment of the CAATEX moorings as well as the INTAROS moorings in WP 3. In particular, the ice concentration data were used in planning the routes for the ice breaker KV Svalbard to reach the North Pole in 2019 and to the Beaufort Sea in 2020 as part of the CAATEX campaigns.

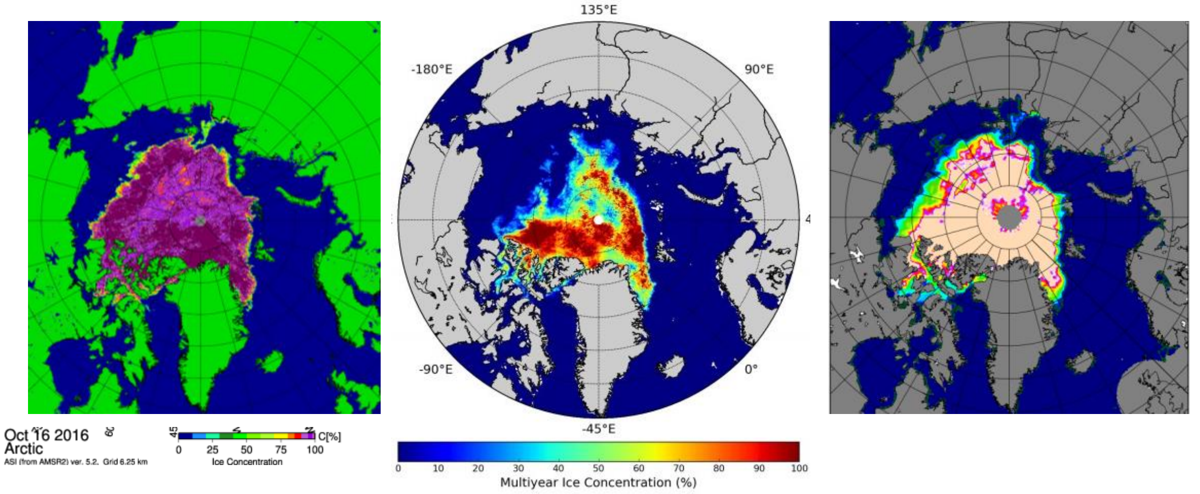

Figure 1. ASI Sea ice concentration (left), multiyear ice concentration (middle) and thickness of thin sea ice (right) as of 16 Oct 2016. Total ice concentration is described in Deliverable 2.1 (present capabilities), multiyear ice concentration and thickness of thin sea ice Deliverable 2.2.

The deployment of the three tomographic moorings (NERSC 1-3) was carried out from 14/8 to 9/9, using icebreaker KV Svalbard from the Norwegian Coastguard. To support navigation in the ice infested waters, overlays of ASI (ARTIST sea ice) sea ice concentration (SIC) maps (Spreen et al., 2008) with MODIS false color maps were produced. The ASI data, based on observations of the passive microwave sensor AMSR2 onboard GCOM-W are the highest resolving SIC maps available daily and globally, with a resolution of 6 km. The MODIS sensors onboard the NOAA satellites AQUA and TERRA provide optical data in various optical bands at 1 km resolution. However, the ice information provided from them is frequently hampered by clouds.

Therefore, at UB a system overlaying ASI SICs and MODIS false color representation was developed. It combines MODIS Band 1 (645 nm), Band 2 (859 nm) and Band 5 (81240 nm) into an RGB-image.

Cloud droplets and atmospheric ice crystals are smaller than the snow and ice crystals on surface. The former appears in yellow and brownish tones, while the surface ice appears grey (Fig. 2).

The MODIS Level 1 data are provided within 24 hours after data capture by the LAADS DAAC (Level-1 Atmosphere Archive & Distribution System Distributed Active Archive Center) at Goddard Space Flight Center, one of twelve NASA EOSDIS DAACs.

The MODIS data are organized in granules, each covering an area of about 2000 x 2000 km² corresponding to 5 minutes of observation. Based on the corner coordinates of each granule, extracted from the small kmz files accompanying each granule, granules covering the region of interested and having sufficient sunlight were identified, downloaded, and processed. Data from both MODIS instruments on AQUA and TERRA have been provided, providing in about 12 scenes per day.

In regions of clear sky or partly transparent clouds, sea ice cover and single floes can be recognized at the MODIS resolution of 500 m. The representation is supported by isolines of 15%, 30% and 90% ASI SIC isolines. In regions of opaque cloud cover this information still gives an overview of the sea ice situation suitable for route definition in ice infested waters

(Fig. 2). This example from the ACLOUD campaign 2017 demonstrates the easy visual distinguishing of surface ice (yellow) and cloud (grey).

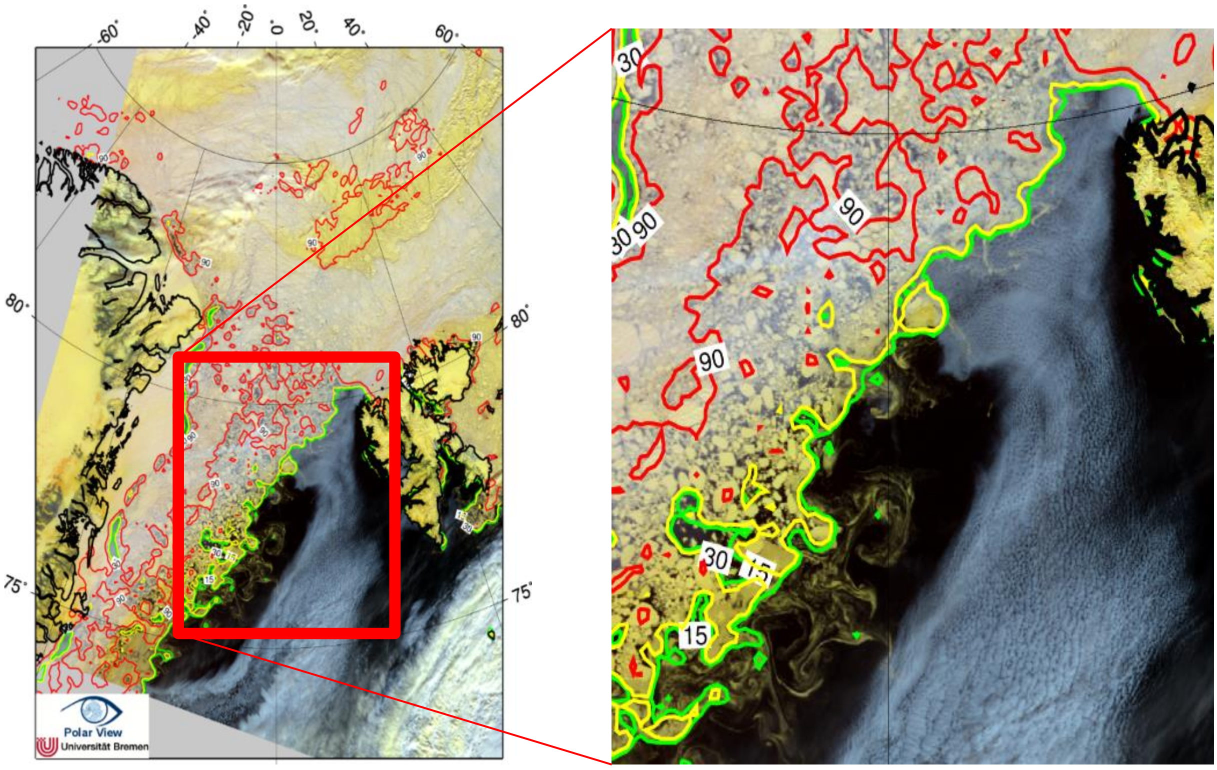

Figure 2. MODIS and ASI SIC overlay example from the ACLOUD campaign 2017 illustrating the easy visual distinguishing of surface ice (yellow) and cloud (grey). SIC isolines at 15% (green), 30% (yellow), and 90% (red).

Results

For the period of the campaign, from 2019 06 15 to and from 2019 08 01 to 2019 10 05, these maps were provided for each overflight over the region of investigation. Due to the daily sunlight reducing over the campaign period, the number of daily images decreased from initially about 15 to 2 at the end. All maps available in discovery (png) and analysis (hdf) format at
https://www.seaice.uni-bremen.de/data/temporary/Modis_for_Stein.
The combination of daily averaged ASI sea ice concentration (SIC) contours with false color images allows in cloud free and thin cloud cases for a much more detailed ice information. In cloudy cases, the ASI SIC information alone is available. The added valued of this representation is most helpful in the marginal ice zone with intermediate ice concentrations, while in the Central Arctic SIC is near 100% in most cases. These sea ice data were used to plan the deployment of the CAATEX moorings (see https://caatex.nersc.no/node/14) as well as the INTAROS moorings in WP 3. In particular, the ice concentration data were used in planning the routes for the ice breaker KV Svalbard to reach the North Pole in 2019 and to the Beaufort Sea in 2020 as part of the CAATEX campaigns.

Conclusion

Sea-ice maps are helpful overview information for strategic and tactic route planning of research vessels in little frequented waters which experience less attention by the national ice services. While SAR images deliver information at higher horizontal resolution, they do not cover the whole Arctic daily, despite their increasing number. The combination of PM-derived SIC retrieval with higher resolving optical images contributes closing this gap, here demonstrated with optical MODIS images and ASI sea-ice concentrations (Spreen et al., 2008, Melsheimer 2019).

References to data sets and user guides

***Data sets*:**
- INTAROS data repositories: https://catalog-intaros.nersc.no/organization/universitat-bremen-ub
- At UB: https://www.seaice.uni-bremen.de/start/
- At IFREMER: http://cersat.ifremer.fr

User guides:
- ASI SIC: https://seaice.uni-bremen.de/fileadmin/user_upload/ASIuserguide.pdf
- Multiyear ice concentration: https://seaice.uni-bremen.de/data/MultiYearIce/MYIuserguide.pdf
- Thickness of thin sea ice: https://seaice.uni-bremen.de/thin-ice-thickness/
- Sea ice displacement: http://cersat.ifremer.fr/

Outreach Info-sheets
- Info-sheets on sea ice concentration, concentration of thickness of thin ice, and multiyear ice are available on the INTAROS project website

3. A seamless data set of Arctic total water vapor data

Water vapor is the most important greenhouse gas, and it is the source of any precipitation and contributes to atmospheric dynamics. Therefore, we need daily global water vapor observations for numerical weather prediction and climate research. In the polar regions, in situ observations are sparse, but in times of global warming, which is particularly pronounced in the Arctic, satellite observations are essential for water vapor data (Wendisch et al. 2017). Water vapor observations are available from two types of satellite sensors, namely microwave imagers and microwave humidity sounders. Data of the atmospheric water vapor column, called total water vapor (TWV) has been continuously available over open ocean from the microwave imagers since 1987. These sensors mainly observe at the atmospheric window frequencies where the atmosphere is nearly transparent so that they image the surface (marked blue in Fig. 3). However, over land and sea ice, the retrieval of TWV from observations at the imager frequencies is hampered by the high surface emissivity which makes it difficult to separate the smaller atmospheric signal. Microwave humidity sounders are intended to observe the vertical humidity profile. They use frequencies near the strong water vapor absorption line at 183 GHz, marked red in Figure 3. The observations have for a long time been considered un-exploitable in the cold and dry polar atmosphere because there the weighting functions of the different channels all peak near the surface so that the observations do not carry information about the profile.

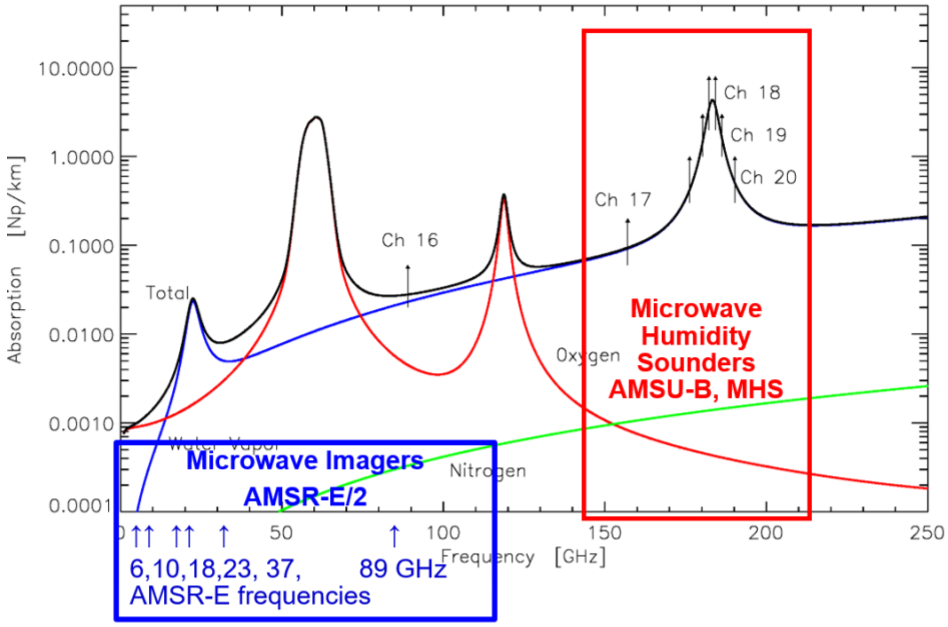

Figure 3. **Atmospheric absorption and observing frequencies of microwave imagers and humidity sounders.**

However, Miao et al. (2001) have shown a way to still extract the TWV value from the sounder observations. The basic idea of the procedure is to consider the ratio

$$\frac{TBi-TBj}{TBj-TBk} = exp \text{ -}2\tau \sec \theta)$$

of two brightness temperature differences. In this expression, the surface contributions in the three channels *i, j, k* approximately cancel out because they only contribute to constant and linear terms of the brightness temperatures so that, based on the formulation of the radiative transfer equation by Guissard and Sobiesky (1994), the TWV can be determined from the atmospheric opacity τ where θ is the known incidence angle. From the five channels of the sounders, different triplet can be formed, with different sensitivities and upper retrieval limits, see Table I. The method has been further developed by Scarlat et al. (2017).

Table 1. Channel triplets used for sub-algorithms. AMSU-B channel definitions see qualitatively Figure 3 and quantitatively Triana-Gomez et al. (2020)

Channel Triplet	Sub-algorithm	Approx. TWV range [kg/m²]
(18, 19, 20)	1	0…1.5
(19, 20, 17)	2	1…6
(20, 17, 16)	3	5…16

In the INTAROS project, three improvements have been developed:

1. Inter-calibration between and validation of retrievals from sounders AMSU-B and MHS which have slightly different channel definitions (Triana-Gomez et al., 2020).
2. Masking erroneously low retrievals caused by high ice clouds.
3. Sub-algorithm (channel triplet) merging optimized.

Improvements 1 and 2 are described in Triana-Gomez et al. (2020), therefore here we focus on the sub-algorithm merging procedure.

For each sub-algorithm i, an error estimate $e_i(TWV_i)$ as a function of the retrieved TWV is derived from the comparison with radiosonde derived TWV values. Then, in overlap range of the sub-algorithms i and j, we estimate the resulting TWV as linear combination of the two sub-algorithm results, weighted with their inverse error:

$$TWV = \frac{1}{1/ei + 1/ej}\left[\frac{1}{ei} TWVi + \frac{1}{ej} TWVj\right] .$$

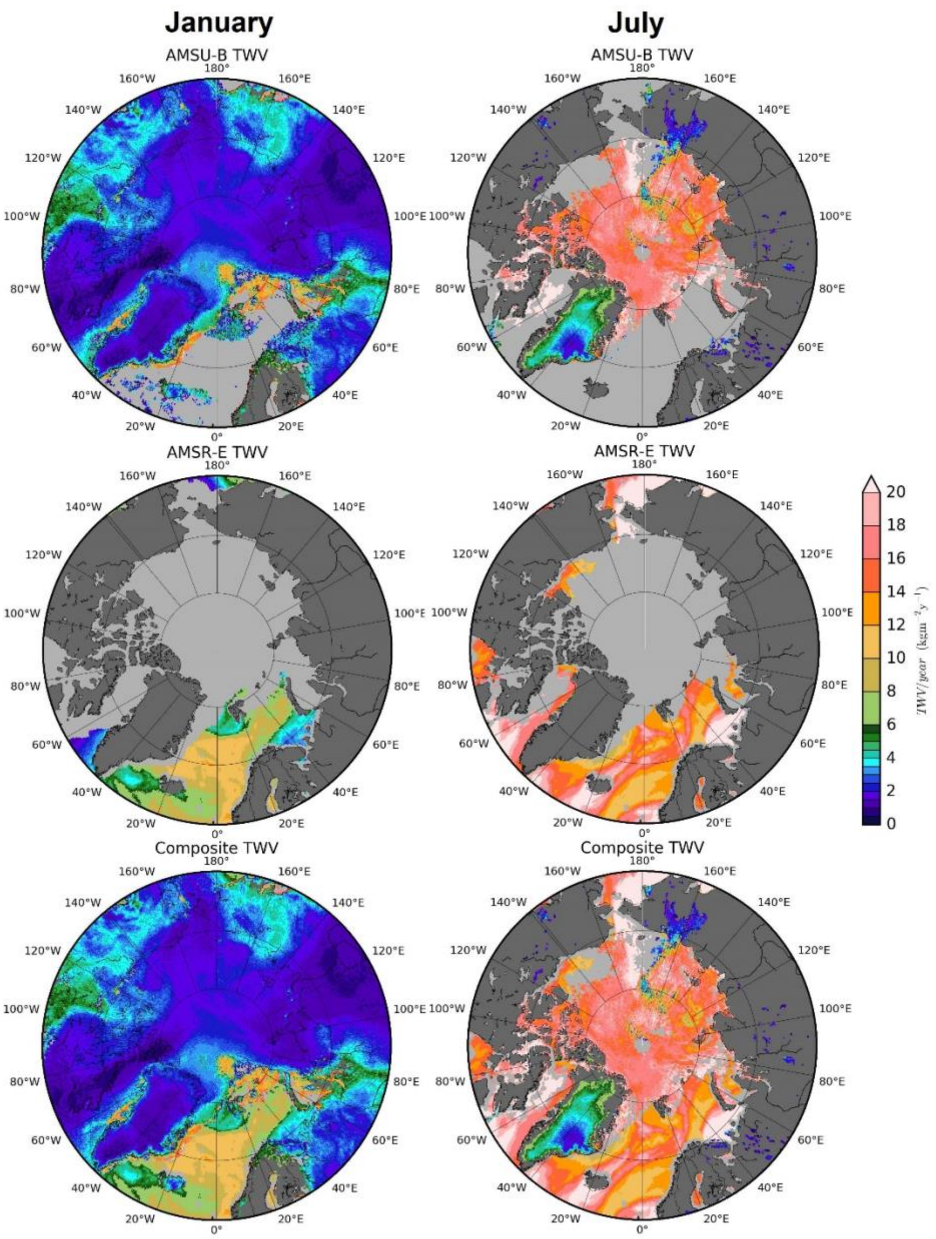

Figure 4. AMSU-B (top), AMSR-E (center) and combined (bottom) TWV retrievals for (left) winter (7 January 2008), and (right) summer (7 July 2008).

Combining imager and sounder retrievals.

A procedure for merging of the imager and sounder data is only required in regions where both retrievals are available, i.e., over open water with low water vapor burden. In that case, the decision is based on the difference $D = |TWV_I - TWV_S|$ between the imager retrieval

TWV_I and the sounder retrieval TWV_S . If D < 4 kg/m², then the sigmoid weighting function

$$w = 1 - \frac{1}{(1+3\exp(-2D))^4}$$

provides a smooth transition between the imager retrieval if D is small and taking the sounder retrieval if D approaches 4 kg/m². For larger D values, TWV_S is taken right away.

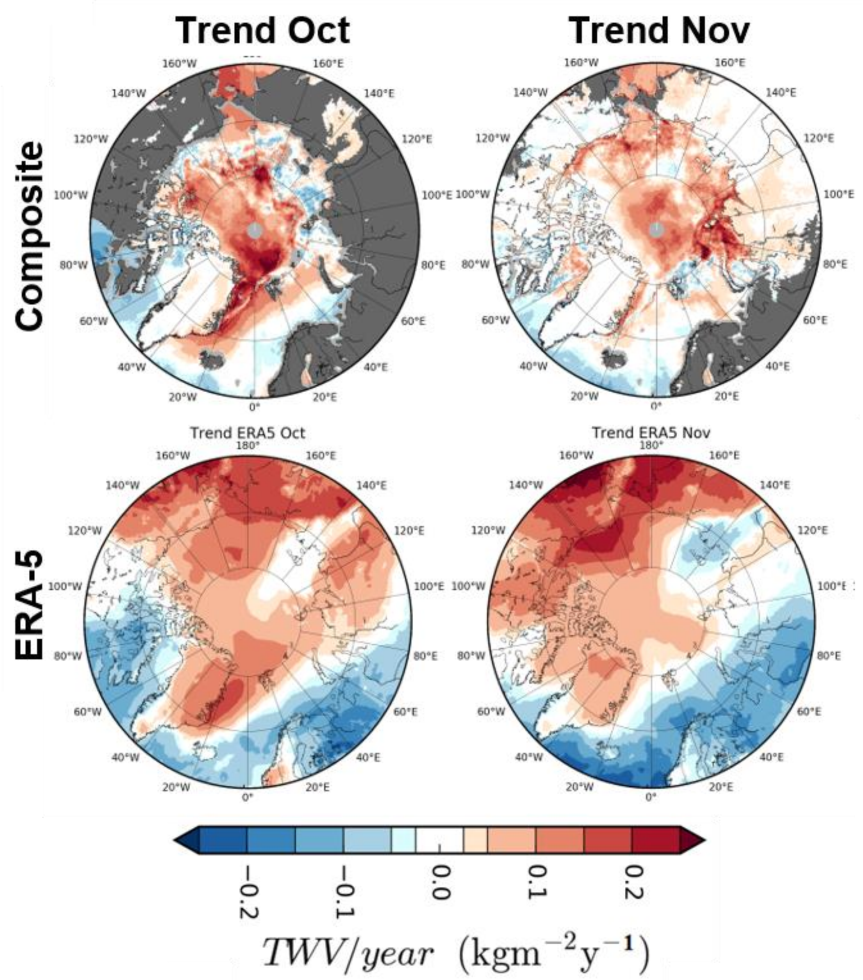

Figure 5. October and November TWV trends 2003-2020 in the composite data set (top) and in model ERA-5 (bottom).

Results

Based on the described methods, daily TWV maps have been calculated for the 18 years 2003 to 2020, the period of complete AMSR-E and AMSR2 years. All data including the User guide (Triana-Gomez et al., 2021) are available in png format for discovery and netcdf for analysis at the INTAROS data repository
https://catalog-intaros.nersc.no/organization/universitat-bremen-ub
and at the University of Bremen repository https://seaice.uni-bremen.de/water-vapor/. Figure 4 shows as example each one of a daily average from January and July 2008 based on AMSR-E, AMSU-B and the combined data sets. The AMSU based retrieval (top) in winter covers the Central Arctic almost completely except the North Atlantic, but in summer only most of the ice-covered regions. The AMSR-E retrievals in the middle row cover the open water only. The combined product in the bottom row in both winter and summer covers the complete

Arctic. Only in summer small regions in the Beaufort and Laptev seas the TWV is not retrieved.

As first application examples, the monthly trends over the 18 years were determined. October and November are the months with the highest trends, most pronounced over the Central Arctic and the Greenland Sea. They agree qualitatively with those in ERA-5, but with more details (Fig. 5).

References to TWV data sets and user guide from this deliverable

https://catalog-intaros.nersc.no/organization/universitat-bremen-ub https://seaice.uni-bremen.de/water-vapor

Triana-Gómez, A., C. Melsheimer, G. Heygster, G. Spreen: Composite Total Water Vapor dataset from AMSU-B/MHS and AMSR-E/AMSR2. User Guide. Institute of Environmental Physics, University of Bremen, 2021.

An Info-sheet on atmospheric water vapor are available on the INTAROS project website.

4. Exploitation

Sea Ice

The various remote sensing sea ice data sets are publicly available at the data repositories given in the references. As an application example, the combination of passive microwave sea ice concentration data based on the ASI algorithm has been combined with higher resolving MODIS images in support of the CAATEX campaign. Combination of passive and active remote sensing have been also demonstrated to be very useful to estimate sea ice displacement (INTAROS Report D6.22).

Water vapor

The data set allows a wealth of applications and is publicly available. An analysis of the TWV role as greenhouse gas in the covered period is given in INTAROS Deliverable 6.7. A few more applications have been given above.

General public info-sheets

Info-sheets on sea ice concentration, concentration of thickness of thin ice, multiyear ice and atmospheric water vapor are available on the INTAROS project website.

5. Contribution to Roadmap

Satellite based observations of the Arctic Ocean and atmosphere

It is important to daily increment the satellite-based data sets for the two purposes of (a) operational support in near real time (NRT) for ship route selection and (b) to keep up to date

the long time series which now reach climatological scales (20 to 30-year sea ice time series). While the NRT data products require a fast processing, for the climatological data the best possible accuracy is needed to provide high level, continuous and homogeneous long-term sea ice datasets to the scientific community. Therefore, these two applications may require different processing. However, they are so intimately related that they should be understood as a joint processing. The value of a time series increases with its length and decreases dramatically if interrupted. Therefore, it is essential to continue the time series provided here and not to interrupt them.
Currently, after the end of INTAROS, the data sets will be continued on a best effort basis, but with uncertain funding. It is important to find funding opportunities on an international, best European level.

Sea ice

The improvements of the ASI sea ice concentration algorithm (Lu et al., 2019, 2021) should be brought to operational application. They are based on observations of the passive microwave sensors AMSR-E (2001-2011) and AMSR2 (2012-date). As the Japanese Space Agency JAXA plans continuing this sensor series with AMSR3 on GOSAT (launch planned 2024), the perspective for long-time consistent and daily global brightness temperature observations is excellent, and continuation and further improvements of the downstream generation of Arctic geophysical data products is essential for surveying and better understanding the global change which is particularly pronounced in high latitudes through the Arctic amplification.
AMSR3 (Maeda et a., 2021) should bridge the gap until the launch planned for 2028 of CIMR, the Copernicus Imaging Microwave Radiometer, one of six High Priority Satellite Mission for Earth observation ESA and EU are planning. CIMR will have an antenna reflector of 7 m diameter, allowing for Earth surface observations at 37 GHz with an unprecedented resolution of ~ 5 km. Other observing frequencies are 1.4, 7, 10, and 18 GHz. Expected performances for retrieval of sea ice parameters have e.g., been investigated by Kilic et al. (2018).

Water vapor

The seamless Arctic total water vapor data set presented here combines observations of the microwave imagers AMSR-E and AMSR2 with those of the microwave humidity sounders AMSU-B and MHS. The data situation for this retrieval will improve with the launch of the microwave imager AMSR3 which in addition will carry two additional channels at the sounding frequencies near 183 GHz (Maeda et al. 2021). Then, the errors due to different overflight times of the two involved sensors will fall apart, improving the accuracy of the retrieval.

6. References

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INTAROS

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