Integrated Arctic Observation System

Research and Innovation Action under EC Horizon2020
Grant Agreement no. 727890

Project coordinator:
Nansen Environmental and Remote Sensing Center, Norway

Deliverable 6.20

Observing systems for sea level in the Arctic

Start date of project:	01 December 2016	Duration:	63 months
Due date of deliverable:	31 October 2021	Actual submission date:	15 November 2021
Lead beneficiary for preparing the deliverable:		DTU	
Person-months used to produce deliverable:		2 pm	

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Version	DATE	CHANGE RECORDS	LEAD AUTHOR
1.0	24/01/2017	Template	Hanne Sagen
1.1	27/10/2021	Draft	Carsten B Ludwigsen
1.2	27/10/2021	Minor modifications after project meeting review	Carsten Bjerre Ludwigsen
1.3	29.10.2021	Technical review and formatting	Kjetil Lygre
1.4	15.11.2021	Final Review and submission	Stein Sandven/Hanne Sagen

Approval **X**	Date: 15 November 2021	Sign. Stein Sandven Coordinator

USED PERSON-MONTHS FOR THIS DELIVERABLE					
No	***Beneficiary***	***PM***	***No***	***Beneficiary***	***PM***
1	NERSC		**24**	TDUE	
2	UiB		**25**	GINR	
3	IMR		**26**	UNEXE	
4	MISU		**27**	NIVA	
5	AWI		**28**	CNRS	
6	IOPAN		**29**	U Helsinki	
7	**DTU**	***2***	**30**	GFZ	
8	AU		**31**	ARMINE	
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15	NUIM		**38**	WHOI	
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17	MPG		**40**	UAF	
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19	EUROCEAN		**42**	ONC	
20	UPM		**43**	NMEFC	
21	UB		**44**	RADI	
22	UHAM		**45**	KOPRI	
23	NORUT		**46**	NIPR	
			47	PRIC	

DISSEMINATION LEVEL		
PU	Public, fully open	**X**
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

EXECUTIVE SUMMARY

The Arctic Ocean is at the frontier of the fast-changing climate in the northern latitudes and sea level trends is a bulk measure of ongoing processes related climate change. Observations of sea level in the Arctic Ocean are nonetheless difficult to validate with independent measurements and is globally the region where the sea level change is most uncertain.

By using specialized methods for observing sea level with satellite altimetry over sea ice regions in the Arctic, we are able to construct an altimetric sea level record that is in good agreement with the sea level observed by tide gauges.

However, long-term changes of tide-gauges are influenced by vertical land motion (VLM) caused by past and present changes of ice. A novel model of the elastic rebound from present changes of Arctic ice has been applied to create a VLM-model that agrees well with GNSS.

Sea level change from altimetry and VLM-corrected tide gauges are compared to a reconstructed sea level estimate, derived from the sea level fingerprints of present-day mass changes and steric sea level change derived from available arctic T/S-profiles. The comparison shows that the freshwater change is dominating the Arctic sea level change.

Several recommendations have been outlined, to improve future analysis and observations of Arctic Ocean sea level. The most important is the lack of in-situ data in several regions of the Arctic Ocean that are necessary to validate the observations from remote sensing.

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1. Introduction

This report describes the current sea level observing systems in the Arctic and how they have been exploited in INTAROS. It provides a synthesis of how sea level is currently observed, obtained results and improvements, and gives an extensive list of recommendations for further exploitation and improvement of the provided data.

2. Summary of current observing systems in the Arctic used in INTAROS relevant for sea level research

In-situ data

In-situ measurements have the advantage that minimal interpretation is necessary since the physical property is measured on location. Before the satellite era (starting in 1991), in-situ measurements were the only source of repeated physical data in the Arctic.

Tide-Gauges

Using tide gauges is the only direct way to measure sea level without using remote sensing. A tide gauge is fixed to the known local reference on land, which means it measures sea level change relative to Earth’s surface and thus called relative sea level (RSL). PSMSL (psmsl.org) is a global repository of long-term tide-gauge data, with a monthly or annual temporal resolution.

Since the 1980’s 127 tide-gauges from PSMSL are located above 60°N, with around 100 of them located towards the Arctic Ocean or its connecting seas. A significant shut down of stations in particular in the Russian Arctic means that less than half of the stations have data in 75% of the years since 1980. Most stations with complete or near-complete sea level records are located along the Norwegian Coast.

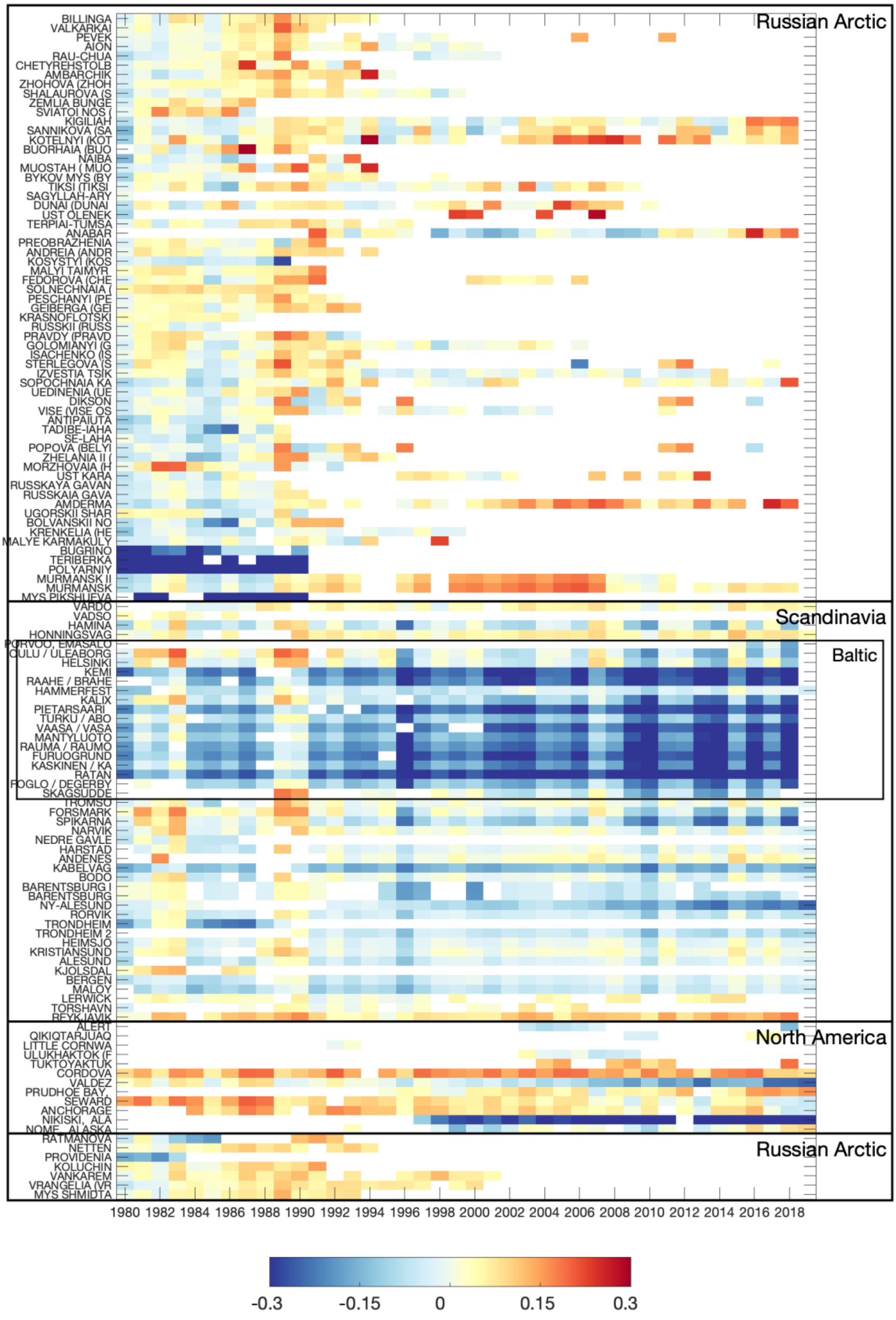

Figure 1. Matrix of relative sea level measurements (in meters) from 127 tide gauges from PSMSL since 1980, sorted from most east (top) to most west (bottom). White spots indicate where there is no data or too few measurements to make a meaningful annual mean.

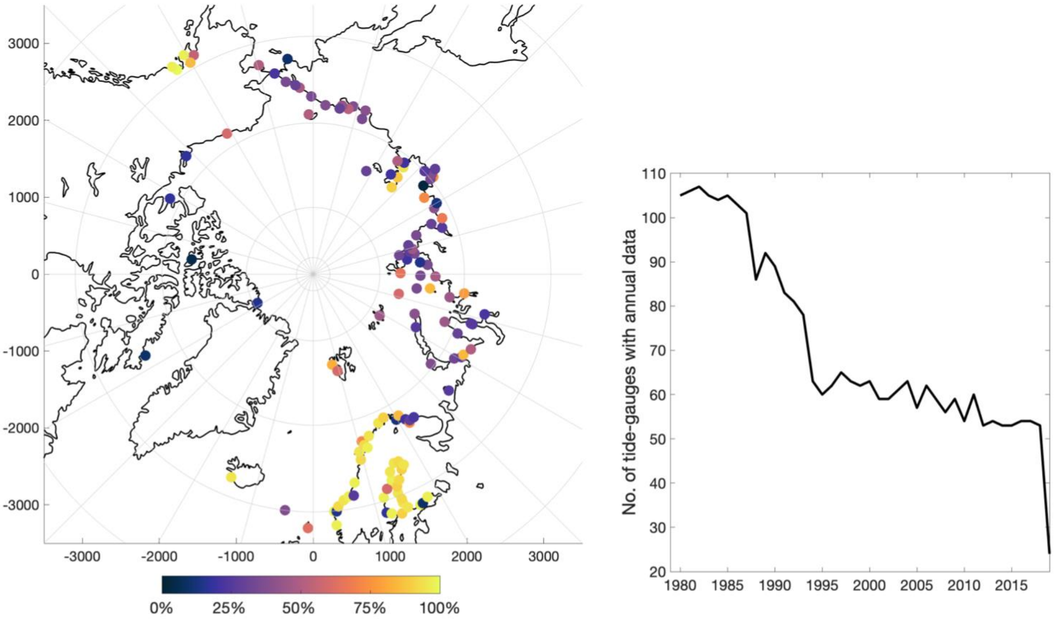

Figure 2. Left: Map of the 127 tide gauges with data since 1980. The color indicates how many years since 1980 have valid data. Right: Chart showing the decline of tide- gauges since 1980. The drop from 2018 to 2019 is due to that the annual value for some tide-gauges have not yet been validated by PSMSL (status mid-2020).

Temperature and salinity data

Hydrographic data are measures of the physical properties of water. Throughout this work, we only use temperature and salinity measurements of the water column, so-called T/S-profiles to generate steric sea level heights. Since the beginning of year 2000, the ARGO-mission has created a mask of floats, that repeatedly obtains T/S-profiles from the surface down to 2000 meters depth. At present, nearly 4000 floats have been deployed by ARGO, but due to the sea ice cover in the Arctic, only very few T/S-profiles have been collected in the northern latitudes, and most of them in the Norwegian Sea with few in the Chukchi Sea.

Buoys designed for Arctic environment that dive below the sea ice, so called Ice Tethered Profilers (ITP) take consistent measurements below the sea ice down to 500-800 meters depth. Most of the ITPs are deployed by Woods Hole Oceanography Institution (WHOI in the Canadian Arctic and the Beaufort Sea. The ITPs are part of the International Arctic Buoy Program (https://iabp.apl.uw.edu/maps.html). Most profiles in the Arctic Ocean are obtained from ships, that either breaks through the ice or sail in the ice-free ocean during the summer. These mission-based data collections are creating a spatial and temporal bias, because areas with no or thin ice can be visited more frequently during summer months. The Unified Database for Arctic and Subarctic Hydrography (UDASH), is a repository at the Alfred Wegener Institute that collects all available T/S-profiles north of 60°N from 1980 to 2015. Data from the World Ocean Database, Institute of Marine Research in Norway, ARGO and ITP’s from WHOI have been added to extend the dataset up to 2018.

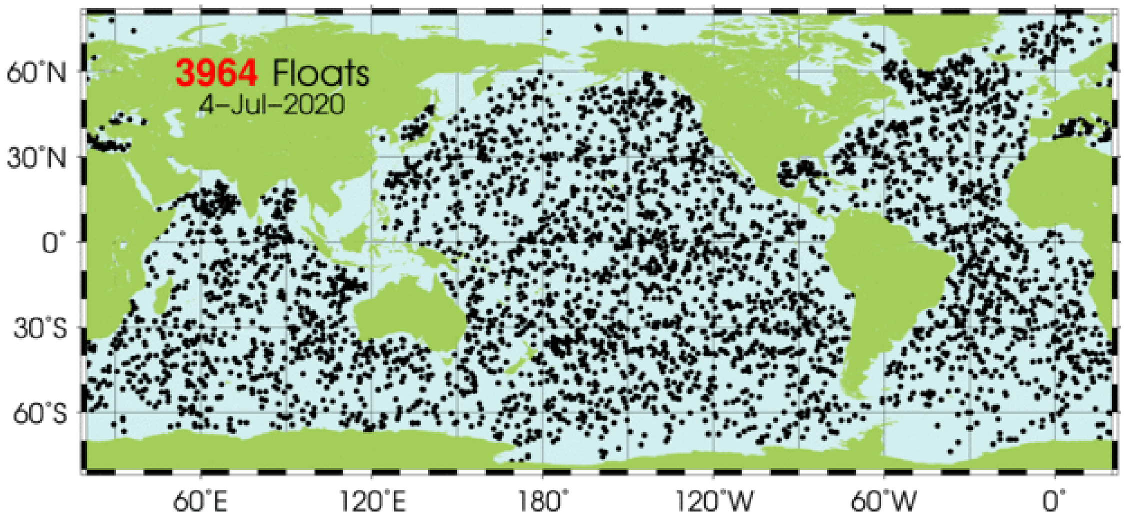

Figure 3. Location of active ARGO floats on 4th July 2020. From the Argo Program website (argo.ucsd.edu).

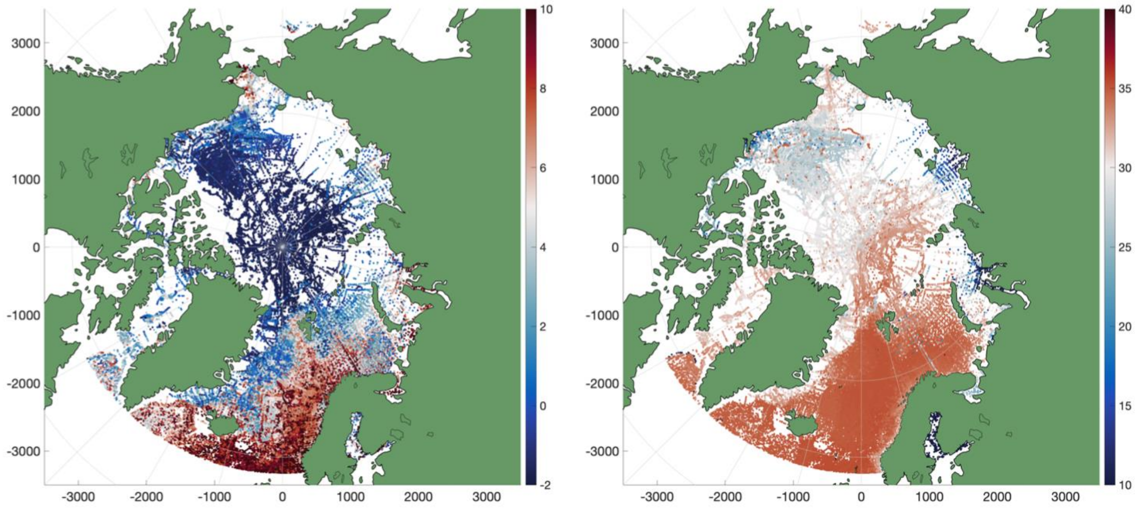

Figure 4. Left: Ocean temperature (C°) within at max 5m depth for all hydrographic data available since 1990 used for the steric sea level data product. Right: Same as left, but with salinity (psu).

Satellite data

Measuring the Arctic Ocean from satellites is a convenient way to get repeated and con sistent data with extensive spatial coverage. While measurements from flights and in some cases, drones are also widely used in the Arctic, in particular for the purpose of validation and localized research, only remote sensing data from satellites are included in this work - more specifically satellite radar altimetry and gravitational measurements from GRACE.

Altimetry

Radar altimetry from satellites (henceforth called satellite altimetry) measures the travel time of the return radar pulse from a satellite orbiting in a known height relative to the reference ellipsoid. If the travel time is multiplied by the speed of light is the distance between the satellite and the surface obtained. Over the ocean, the height between the reference ellipsoid and the surface is called sea surface height (SSH). The shape and power of the reflected signal, the waveform, is used to estimate the range, but can also be used to estimate different physical surface properties, such as wind speed, significant wave-height (SWH) and surface type. Even though efforts are made to obtain as many in situ measurements from leads as possible, the Arctic Ocean is poorly covered. Since 1991 various satellites cover the Arctic Ocean which together creates a complete timeseries from 1991 until present.

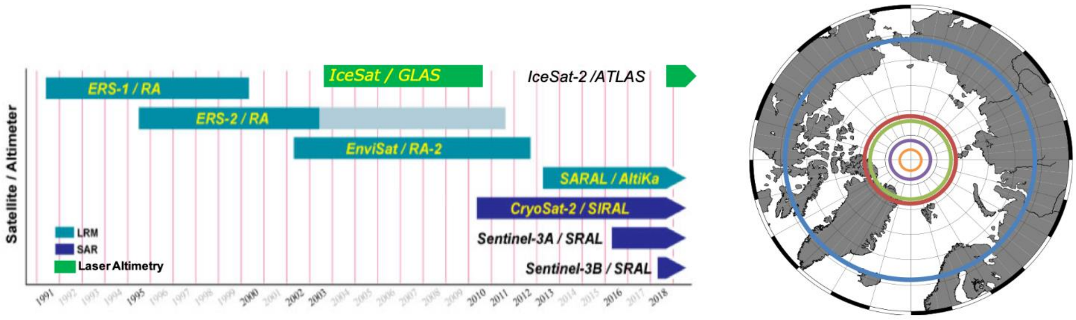

Figure 5. Left: Temporal extent of all altimeters covering the Arctic. The color indicates the type of altimeter attached to the satellite. (Adaptated from Quartly et al. (2019)) Right: Maximum latitude reached by satellite missions. Blue (66°N) indicates max latitude by th Jason/Topex/Poseidon-mission (sometimes refered to as reference missions), dark or- ange (81°N) for Sentinel-3A/B, green (81.5°N) for ERS-1/2, Envisat and SARAL, purple (86°N) for IceSat and orange (88°N) for CryoSat-2 and IceSat-2.

GRACE

The Gravity Recovery and Climate Experiment (GRACE) was launched in 2002 and lasted until mid-2017. Since mid-2018, has the follow-on mission, GRACE-FO, succeeded GRACE with almost the same configuration. GRACE consists of two identical satellites separated at a distance of around 220 km in a polar orbit. The exact distance is monitored with microwave ranging. A small gravitational pull or push experienced by one of the satellites due to a gravitational anomaly, is measured as a change in separation distance.

The gravitational products from GRACE have a theoretical spatial resolution limit of 300-500 km, which is coarse compared to satellite altimetry measurements. The coarse resolution also results in significant leakage effects. Ice sheet changes can be equivalent to several meters of water, while changes in the ocean often are in the magnitude of millimeters. Thereby is GRACE detecting changes in ice mass even though it is several hundreds km away from land.

The leakage effect is in particular significant in the Arctic Ocean because of the close proximity to Greenland and other glaciers. To avoid leakage, JPL, CSR and the Goddard Space Flight Center (GSFC) have constrained the measured gravity anomalies into mass concentration blocks (mascons) of the Earths surface (Wiese et al., 2016; Luthcke et al., 2013; Save et al., 2016). For every mascon are geophysical constraints applied ’a priori’. The block size varies between products, with JPL being most coarse with 3°equal area blocks, but with a coastal filter applied, so blocks in coastal areas are split between land and ocean. CSR-mascons are given in 0.5x0.5° (Save et al., 2016) while GSFC uses blocks with a radius of 67 km (Luthcke et al., 2013). Over the ocean are gravity anomalies from GRACE often expressed as changes in ocean bottom pressure (OBP), which is the same as the change in ocean mass of the total water column.

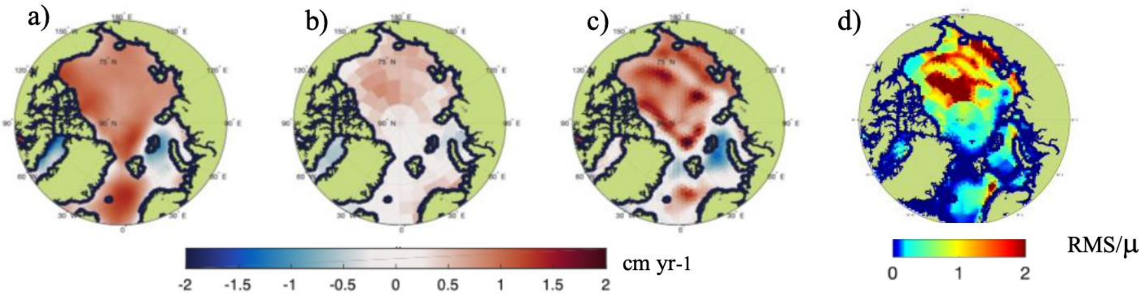

Figure 6. Sea level trends from 3 different GRACE mascon products from 2003-2015. a) GSFC (Luthcke, et al., 2013), b) JPL (Wiese, et al., 2016), c) CSR (Save, et al., 2016) and d) normalized RMS (RMS divided by the mean trend) between a-c. From Ludwigsen and Andersen, 2021.

3. Results obtained during the INTAROS-project

Mean Sea Level and Dynamic Topography

A new Mean Sea Surface (DTU21MSS) for referencing sea level anomalies from satellite altimetry has been developed as part of the INTAROS project. The major new advance leading up to the release of this MSS the use of 5 years of Sentinel-3A and an improved 10 years Cryosat-2 LRM+SAR+SARin record including retracked altimetry in Polar regions using the SAMOSA+ physical retracker via the ESA GPOD facility.

A new processing chain with updated editing and data filtering has been implemented. The filtering implies, that the 20 Hz sea surface height data are filtered using the Parks-McClellan filter to derive 1Hz. This has a clear advantage over the 1 Hz boxcar filter in not introducing sidelobes degrading the MSS in the 10-40 km wavelength band. Similarly, the use of consistent ocean tide model for the Mean sea surface improves the usage of sun-syncronous satellites in high latitudes.

Arctic Steric Sea Level

The DTU steric sea level change is computed as described in Ludwigsen and Andersen (2020). Salinity and temperature measurements from buoys, ice-tethered profiles and ship expeditions in the Arctic Ocean are spatial and temporal unevenly distributed and also depends on seasonal accessibility (Behrendt et al., 2017). Especially, the data density is poor in the shallow seas along the Siberian Coast (Ludwigsen and Andersen, 2020), which is cause to large uncertainties. Temperature and salinity data are interpolated by kriging into a monthly 50x50 km spatial grid on 41 depth levels. If values are more than 3σ away from the mean of neighbouring grid cells, values from the same month in adjacent years is used.

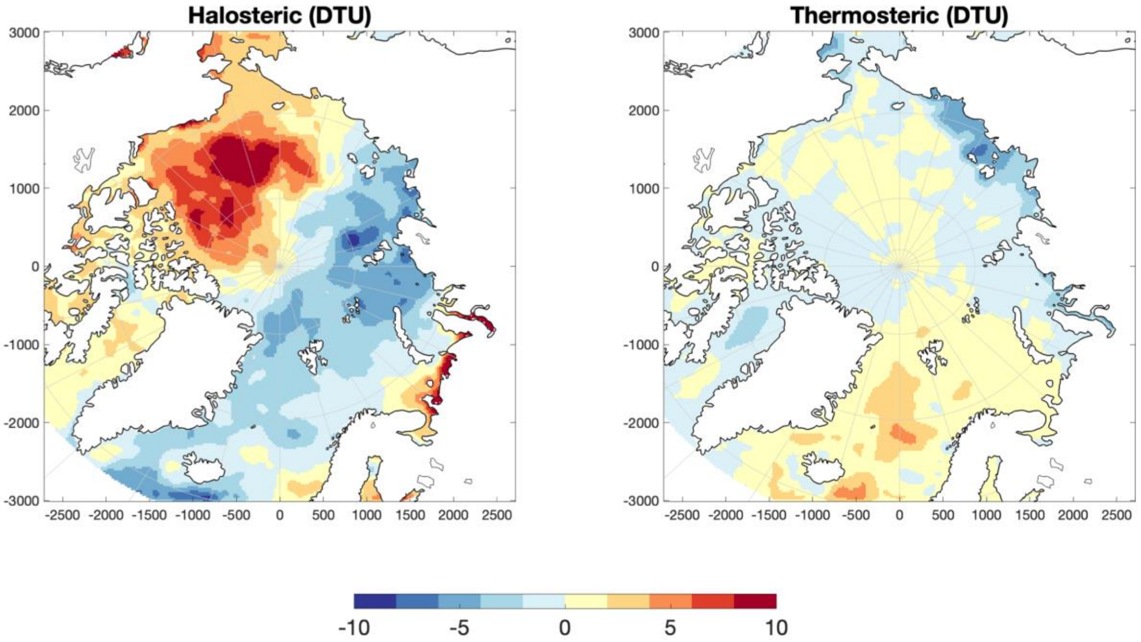

Figure 7. Halo- and thermosteric sea level trend [mm y^{-1}] from 1995-2015 derived from the DTU product which was used in Ludwigsen and Andersen (2020).

Vertical Land Motion

Quantifying Vertical Land Motion (VLM) is essential when relative sea level measurements from tide gauges is compared with any other model or satellite-based estimates of sea level (e.g. Altimetry, GRACE, steric sea level). VLM is a composite of multiple ongoing processes with GIA being the most prominent. Glacial Isostatic Adjustment (GIA), which is rebound from the retreat of the large ice caps during the last ice age, has been modeled by the scientific community for decades. Only in recent years has attention been given to the immediate elastic response to present-day ice loading (PDIL). In the Arctic, where considerable land ice loss due to climate change is observed in every region, is the elastic vertical deformation essential for tide-gauge corrections. Estimates of ice loading changes from GRACE has recently been used to estimate elastic VLM. The limited spatial resolution of GRACE is however insufficient when tide gauges are located close to glaciated areas, since the mass loss from GRACE is spread over large areas which results in area-averaged uplift rates.

Similar to other studies, we assume the viscoelastic GIA-like response from PDIL on annual scales is small but can accumulate to be significant after decades of deglaciation. The uplift associated with GIA, is constrained to the viscoelastic uplift associated with the deglaciation on millennial scales starting 122 kyr ago (Caron et al., 2018). Adding the elastic VLM-response from PDIL-change to GIA, creates a VLM-model that is comparable with VLM measured by GNSS. The results of the model were presented in Ludwigsen et al., 2020b.

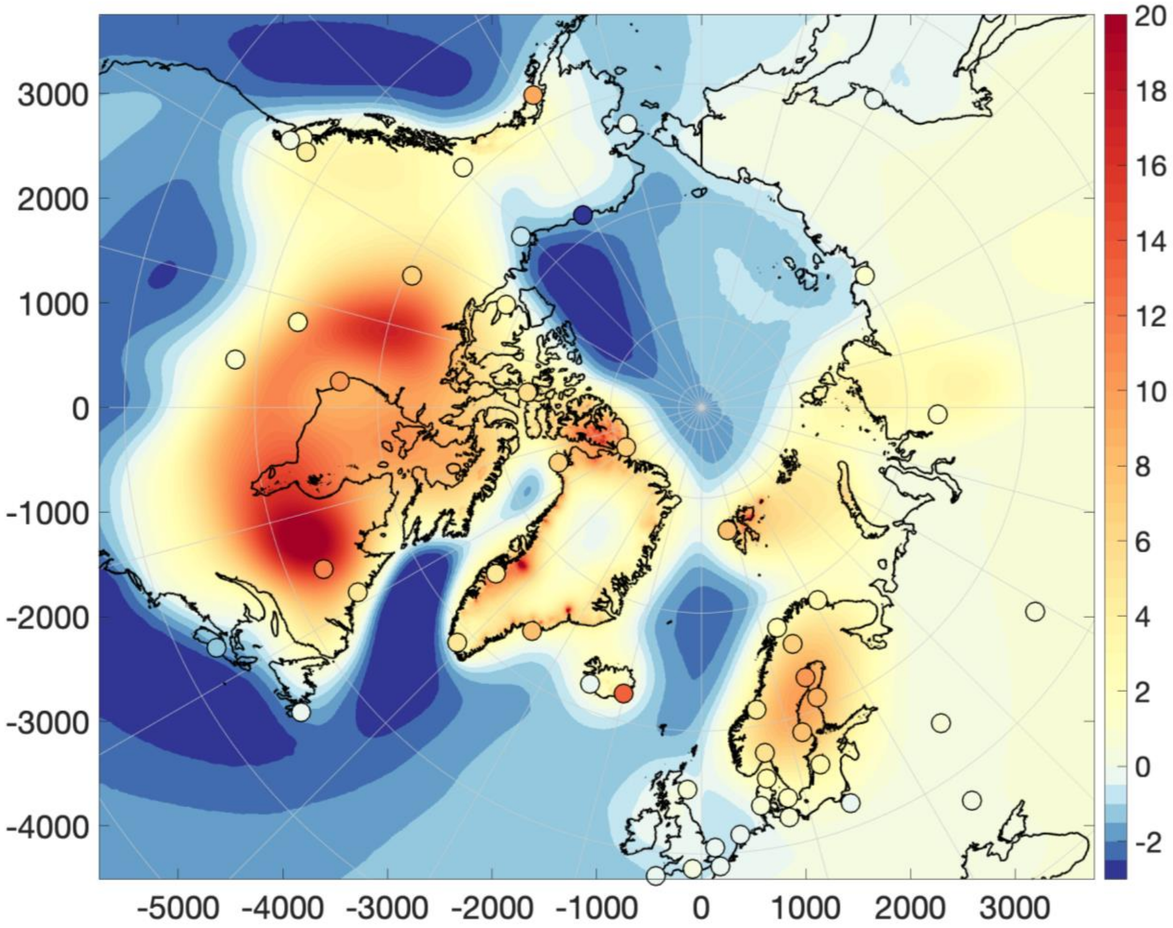

Figure 8. 1995-2015 VLM-trend [mm/y] from the model of Ludwigsen et al. (2020b) combined with GIA (Caron et al, 2018). The VLM-trend from the GNSS-sites is shown with round markers.

Arctic Sea Level Budget

The sea level budget is composed from the sum of mass-driven sea level change and steric sea level change, which can be compared to the sea level change observed by altimetry and VLM-corrected tide gauges. The sea level budget has been resolved on global and basin-wide scales for observations since the begin of the 19th century by using a combination of in-situ data, satellite observations and probabilistic analysis, but studies are often neglecting the polar regions due to large uncertainties and the relatively small area of the Arctic Ocean in a global context.

Previous studies have made attempts to reconstruct sea level in the Arctic spatially (Carret et al., 2017; Raj et al., 2020; Ludwigsen and Andersen, 2020), while Armitage et al. (2016) estimates the mass and steric sea level trend components as basin-wide average. All previous studies are using different solutions of GRACE to obtain their results, which can vary with 5-10 mm/y (Ludwigsen and Andersen, 2020). This disagreement among GRACE solutions has been attributed to different methods to remove contamination from land mass changes that leaks into the ocean signal observed by GRACE (Mu et al., 2020). Hence is the chosen GRACE-solution consequential for the closing of the sea level budget and its ability to validate altimetric observations.

In contrast to the other Arctic sea level budget studies, this study bypasses GRACE-based ocean mass estimates by calculating the sea level fingerprints of contemporary land ice loss, glacial isostatic adjustment (GIA) and atmospheric pressure (inverse barometer, IB) which results in a long-term manometric sea level trend estimate. This approach gives three advantages over GRACE: (i) Insights of the different contributions to manometric sea level change, (ii) a longer time series that extends into the pre-GRACE era, which has the advantage, that non-secular and inter-annual ocean dynamic mass effects, which are mainly driven by the Arctic Oscillation (AO) are reduced and (iii) the mentioned problem of leakage from effects caused by the low spatial resolution (300-500 km) is avoided.

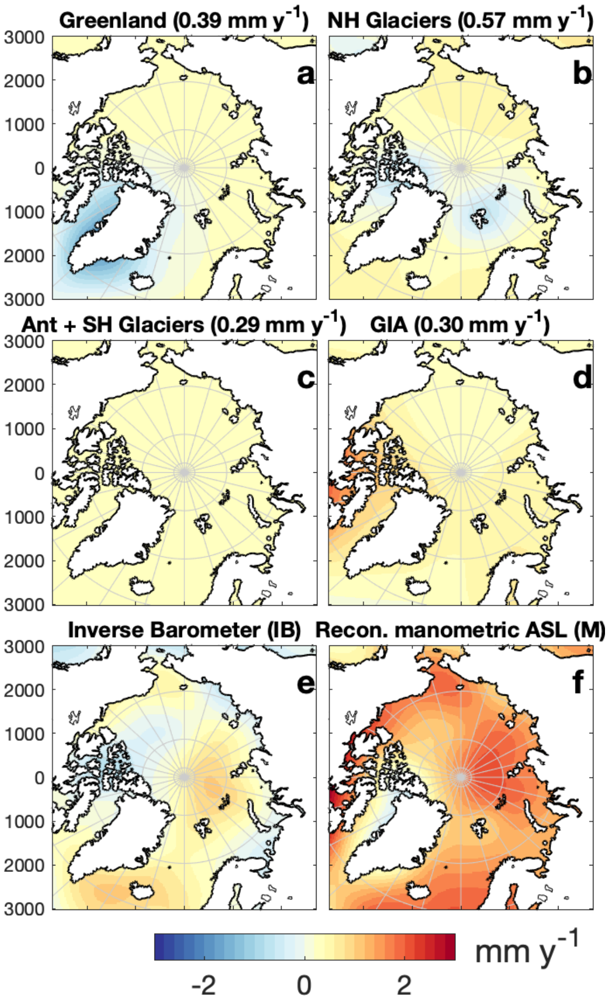

Figure 9. Contributions to the Arctic mass driven sea level trend [mm y−1] from 1995-2015. a-d shows the sea level trend contribution for different sources of land-to-ocean mass changes with the global mean sea level contribution (c) written in brackets: Greenland (incl. peripheral glaciers) (a), Northern Hemisphere (NH) glaciers (b), Antarctica (Ant) + Southern Hemisphere (SH) glaciers (c), and GIA (d). e shows the estimated Inverse Barometer trend.

Using the mass-drive sea level estimates the absolute sea level (ASL) trend is reconstructed and compared to altimetry-derived ASL trend from DTU (Rose et al, 2019) and tide-gauge data. The comparison shows that the spatial pattern from altimetry is well-recognized in the reconstructed estimate.

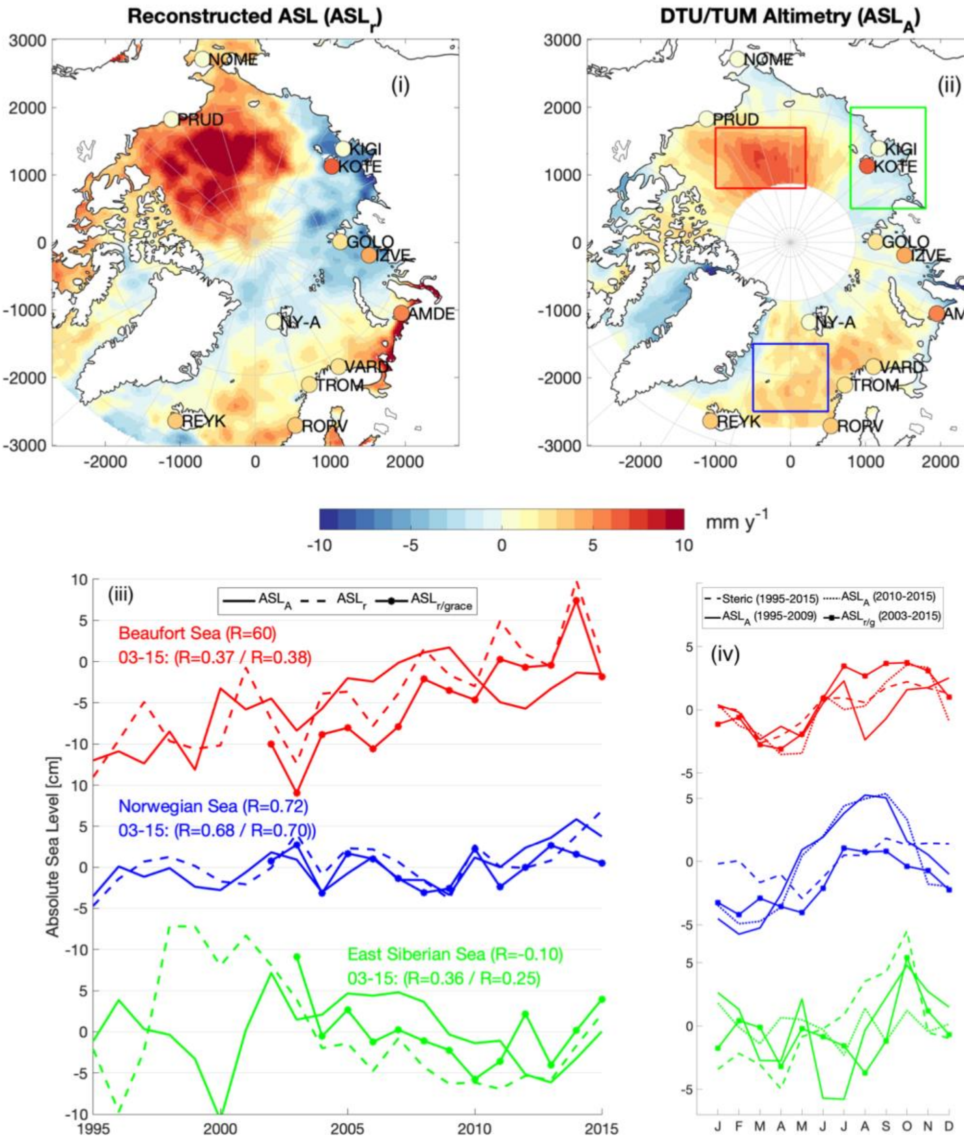

Figure 10. Absolute sea level trend of the reconstructed product (ASL_r) (first map from left (i)) and from DTU/TUM Altimetry (ASL_A) (second map (ii)) from 1995 to 2015 [mm/y]. In both maps is the sea level trend of the 12 VLM-corrected tide gauges (ASL_{TG}) shown with circles. Third panel from left (iii) shows the timeseries of ASL_A, ASL_r and $ASL_{r/grace}$ (ASL reconstructed with GRACE (mean of the two GRACE estimates used in this study) for three selected regions, Beaufort Sea (red), Norwegian Sea (blue) and East Siberian Sea (green) (areas marked in the DTU/TUM Altimetry map). The top R-coefficient for each region shows the correlation between ASL_A and ASL_r and beneath is shown the R-coefficient between ASL_A and ASL_r/ ASL_A and $ASL_{r/grace}$ for 2003 to 2015. The right panel (iv) shows the mean seasonal cycle for two periods of ASLA (solid line: 1995-2009, dotted line: 2010-2015), $ASL_{r/grace}$ ($ASL_{r/g}$) and steric sea level (Steric) for the same three regions as in (iii).

4. Conclusions

The DTU involvement in INTAROS have been focused on investigating Arctic Ocean sea level change and help validate observed sea level change in one of the least accessible and harsh regions of the world. We have focused on in-situ measurements, satellite observations and modeling which have been employed and combined to give an overview of Arctic sea level change. The conclusion is a clear and rapid warming of the Arctic which has been manifested in significant changes in the Arctic Ocean.

Further exploitation and development of results obtained

- The largest challenge in the Arctic is still the limited number of observations of sea level by satellite and tide gauges. There are roughly 50 usable tide gauges in the Arctic Region (north of 65N), but only a few with GNSS ties. As an example Ny Aalesund (Svalbard) is the only station north of 75N equipped with GNSS. It is paramount to maintain and develop the tide gauge data sets in the Arctic. Even without additional tide gauge data, the present investigations have highlighted a number of ways in which immediate progress can be made based on observations which are currently available or will become available in the next few years.

- Steric sea level from interpolated T/S has proven to be a good product that resembles the major spatial patterns of sea level change in the Arctic Ocean. Integrating satellite surface temperatures and salinity data (from SMOS), should improve the observed trends. Validating against models from latest release of ECCO (NASA JPL), GECCO (University of Hamburg) or EN4 (British Met Office), could further constrain the results of the 4D gridded temperature and salinity dataset used for steric calculations in DTU Steric developed here.

- Sea level observations from satellites are in constant development. The launch of IceSAT-2 and the upcoming Surface Water and Ocean Topography (SWOT)-mission significantly improves the spatial resolution of altimetric observations in the Arctic and should improve future versions of absolute sea level products from altimetry.

- The calculated elastic mass component and VLM is **not** obtained by solving the sea level equation, which would also include the viscoelastic part of present-day ice loading change. Applying models of Little Ice Age deglaciation and 3D-earth models could further help separate PDIL from past changes. Recent work by Shijie Zhong (CU Boulder, yet unpublished) significantly improved the computational workload needed to utilize high resolution 3D-models, making it feasible to conduct region-wide 3D GIA models.

- The mass and VLM predictions did not include the effect of terrestrial water storage (TWS), which has limited effect in the Arctic, but is the largest land-to-ocean mass flux in mid and low-latitudes. TWS-estimates from GRACE could be used for the purpose of creating global predictions of VLM and mass-fingerprint.

- Ifthe steric contribution to sea level is improved, a complete Arctic sea level budget assessment should include temporal variations. This would enable the possibility of accurately estimate freshwater in and outflow of the Arctic Ocean. Predicting the freshwater contribution that goes into the North Atlantic is important for predicting the behavior of the Atlantic meridional overturning circulation (AMOC) and thus influences the Earth’s climate system.

- Extending tide gauge data using GNSS reflectometry: It has recently been convincingly shown (Larson et al., 2017; Williams and Nievinski, 2017) that the signal to noise ratio of coastal GNSS receivers can, in favorable circumstances, be used to make a geocentric coastal sea level measurement with centimetric accuracy. This sidesteps many of the difficulties with tide gauges, of tracing documentation and levelling ties, as the relevant measurement is made directly, in combination with monitoring of changes in the sensor position. The immediate recommendation is therefore to extend altimetric timeseries and to make use of the new SAR and SARin altimetry which are particularly useful in sea-ice covered regions, and to prepare for the SWOT mission which is expected to improve the coastal resolution still further.

- Maintain and refine global mean sea surface maps extending the work of DTU21MSS presented in the INTAROS project increasing the averaging period for the Mean sea surface. Care must be taken to ensure appropriate altimeter corrections, such as tide corrections, are used and do not degrade the spatial coverage which is problematic in ice-covered regions.

Contribution to the roadmap

The important findings from DTU to INTAROS has emerged into three papers published in the scientific literature, that combined gives a comprehensive analysis of the effects of climate change on the contributions to Arctic Ocean sea level. Here the results and roadmap are synthesized via the conclusions of the papers:

The initial study (Ludwigsen and Andersen, 2021) presented the available sea level products in the Arctic Ocean in the era of the GRACE-satellites. In previous studies of sea level change in the Arctic Ocean, the steric component was derived from models, which in early stages proved to be insufficient and not assembling the difference between GRACE-observed mass estimates and altimetry. Therefore, we derived an Arctic steric product developed, DTU Steric, which integrated all available temperature and salinity profiles which is made available to INTAROS. The main findings of this work is:

1. Gravimetric observations from GRACE-mascon products showed very different mass-driven sea level patterns that in some regions showed difference with 10 mm/y, with the largest disagreement in the Beaufort Gyre and East Siberian Sea.
2. Steric calculations from modeled temperature and salinity profiles from ECCOv4r3 underestimates the halosteric signal in the Beaufort Gyre. Satellite-derived steric observations (Altimetry - GRACE) showed in Armitage et al. (2016) agrees well with changes estimated by DTU Steric.
3. Reasonable well spatial correlation was found between DTU Steric + JPL Mascons (Wiese et al., 2016) and CPOM altimetry (Armitage et al., 2016). The temporal correlation was however less significant because the AO-driven sea level change is less pronounced in DTU Steric and JPL Mascons. Areas with disagreement coincides with areas of low hydrographic data density.
4. The halosteric contribution because of additional freshwater is the major driver of sea level change in the Arctic Ocean and that it is able to explain large parts of the spatial variability in the Arctic. This is in contrast to the findings of Raj et al., 2020 and Carret et al., 2017, which showed that mass-driven sea level change dominates Arctic sea level trend.

In the second paper (Ludwigsen et al, 2020) a high-resolution ice model that reflects the spatial variability of mass loss of glaciers was created to compute elastic uplift in an equal high resolution. The high resolution of the VLM-model enables it to be used in glaciated regions, which would not be properly represented with the relatively low spatial resolution of GRACE. Conclusions of this study were

1. GNSS-measurement throughout the wider Arctic showed that a combination of the GIA-model from Caron et al. (2018) and the produced elastic model was able to restore the GNSS-measured vertical deformation and clearly outperformed a model only considering GIA.
2. Residuals between the combined VLM-model and GNSS was combined with information from other localized effects contributing to VLM. In Alaska a post-seismic signal from a major earthquake (M9.2) causes rapid uplift, Greenland and Svalbard experiences some viscoelastic deformation from deglaciation after the Little Ice Age and East-Greenland and Iceland has soft mantle structures, causing a more rapid uplift with a smaller footprint. The residuals matched the estimated VLM from other studies.
3. The elastic VLM has far-reaching effects and should be accounted for when projecting coastal sea level. In Denmark, about 30% of the sea level change from land-ice deglaciation is mitigated by elastic uplift caused by present-day is loss in the Arctic.
4. Contrary GIA is the elastic deformation time-varying and depends on glacial and icesheet mass balance. This is an important property in the future, where deglaciation is expected to accelerate, and the impact on tide-gauges might not be the same every year.
5. GIA-models are in some regions inadequate, and it can be difficult to separate present day elastic signals from viscoelastic deformation because of uncertain GIA estimates.

The VLM-model derived in the second paper made it possible to integrate tide-gauge stations into the analysis of Arctic sea level. This was presented in Ludwigsen et al, 2021. Rather than using GRACE for mass estimates, the sea level fingerprint of the ice model used in the second paper and GIA was used to estimate the mass component of Arctic sea level from 1995 to 2015. From the assessment we conclude that:

1. Large spatial variability of halosteric sea level change (-5 - 15 mm/y) and a smaller mass component (≃ 1 mm/y) confirmed the analysis of the first paper.
2. In the Norwegian Sea, where the steric component and VLM is well-constrained, the sea level measured from tide gauges are restored in the derived mass + steric sea level estimate. The sea level trend of the mass component equals the steric sea-level change along the Norwegian coast.
3. A sea level rise in the Kara and Laptev seas because of freshwater outflow is not captured by altimetry but is clearly visible from the halosteric contribution and matches the sea level rise measured with tide gauges. A sea level decline in the East Siberian Seas in both the halo- and thermosteric sea level is not recognized by the tide gauges, which show a sea level rise. Large differences between neighboring tide gauges, indicate that tide gauges are affected by unknown local contributions. However, assessment of multiple Siberian tide-gauges shows that the sea level rise on the Siberian Shelf has been consistent since the 1980’s (Proshutinsky et al., 2004).

4. Large variability associated with the dynamic mass component is estimated from ECCOv4r4. It contributes to the general spatial (and temporal) variability of the Arctic Ocean. Dynamic changes are associated with Arctic Oscillation and is not necessarily a climate change signal.
5. The 1995-2015 sea level trend is explained within the uncertainty in 95% of the Arctic and at 7 out of 12 utilized tide gauges. However, large uncertainties in the steric and dynamic mass component contributes to the result. Large differences with altimetry are evident in the Beaufort Gyre and Siberian Seas.

On basis of this research, and from the third paper, is it clear that many of the observations and models are showing large uncertainties, mainly due to poor and inconsistent data from remote sensing and hydrographic T/S profiles that are difficult to validate.

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INTAROS

This report is made under the project
Integrated Arctic Observation System (INTAROS)
funded by the European Commission Horizon 2020 program
Grant Agreement no. 727890.

Project partners: