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SUMMARY
The Monarch-A 50 years Mean Sea Surface model for the Arctic Ocean is made available on a 2 minute resolution for the Arctic Ocean covering the region north of 60.98333N and have been made available relative to two ellipsoids: Relative to the TOPEX ellipsoid MONARCH-A_MSS_TP Relative to the WGS-84 Ellipsoid MONARCH-A_MSS_WGS84 Both models are available for download at the Technical University of Denmark, DTU Space official website, but will shortly become available at the Monarch-A website as well. The official web address for currently download via the DTU space is ftp.space.dtu.dk/pub/MONARCH-A/MSS Both models are available as .grd ASCII file format and .xyz ASCII file format.

MONARCH-A CONSORTIUM

Participant no.	Participant organisation name	Short name	Country
1 (Coordinator)	Nansen Environmental and Remote Sensing Center	NERSC	NO
2	The University of Sheffield	USFD	UK
3	Universität Hamburg	UHAM	NO
4	Centre National de la Recherche Scientifique	CNRS	FR
5	Scientific foundation Nansen International Environmental and Remote Sensing Center	NIERSC	RU
6	Universitetet i Bergen	UiB	NO
7	Danmarks Tekniske Universitet	DTU	DK
8	Institut Francais de Recherche pour l'Exploitation de la Mer	IFREMER	FR

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1. Deliverable in framework of MONARCH-A project

1.1 Main objectives of MONARCH-A project

The Arctic and northern hemisphere high latitude regions experience significant changes during past few decades, associated with climate change. Arctic itself is an important part of the climate system, and changes that occur in this region, in turn, influence the rest of the Planet.

Due to harsh environmental conditions and inaccessibility of some of the Arctic areas, especially during the winter, there is a lack of consistent historical and modern observational data. As a result, our understanding of Arctic climate related processes and ability to predict consequences of changes in this region for Europe is limited.

The ultimate objective of the MONARCH-A project is to provide the scientific community with subset of multidisciplinary Essential Climate Variables for the Arctic region. The information package will be based on generation of time series of observation datasets and reanalyses of past observational data enabling adequate descriptions of the status and evolution of the high latitude and Arctic region Earth system components.

1.2 WP 2.2 Improved mean sea surface and mean dynamic topography

The mean sea surface is an important reference surface for the pre-processing of sea level data – especially for combining in situ and satellite data. For the assimilation of sea level data into the models the mean dynamic topography model becomes important. Existing models are not of a sufficient quality due to the problems related to poor coverage, effects of sea ice, and lack of sufficiently long time series, as described above.

The Mean sea surface (MSS) is the sum of the geoid height G and the temporal mean of the ocean mean dynamic topography (MDT) like

$$MSS = G + MDT$$

The MDT is the central quantity bridging the geoid and the ocean circulation, providing the absolute reference surface for ocean circulation. Consequently, a better estimation of the geoid and altimetric MSS is, in particular, expected to improve the determination of the mean ocean circulation.

1.3 D2.2.1 Improved mean sea surface model covering 50 years for the Arctic Ocean

Existing models of the mean sea surface covering the Arctic ocean are assessed and combined with the sea level time series derived in WP2.1. Hereby, a mean sea surface covering the time period of 50 years will be derived.

2. Results

2.1 Available MSS models for the Arctic Ocean.

Over the past decade several MSS models have been published. A summary of these is presented in Table 1. All of these MSS models are based on less than one decade of TOPEX/POSEIDON altimetry and spatially they are limited to the south by the South Pole and to the north by the 72°N, 80°N or the 82°N parallel, so none of these have complete global coverage. During the ArcGICE project (**ESA contract** 18753 / 05 / NL / CB) one further mean sea surface model is created from 8 years of ERS-2 radar altimetry data using Cycles 01 through to 84 of the mission for the Arctic Ocean. This corresponds to the period from 16-May-1995 to 02-Jun-2003. The mean sea surface heights are computed relative to the WGS84 reference ellipsoid and are output on a 0.05 (latitude) by 0.2 (longitude) degree grid. This model for the Arctic Ocean in shown in Figure 1.

Table 1. Recent Mean Sea surface Models.

Name	Released Year	Spatial coverage	Temporal Coverage	Web	Reference
CLS01	2001	+/- 82°N	1993-1999	www.aviso.fr	Hernandez and Schaeffer, 2002
CNES/CLS10	2010	+/- 82°N	1993-1999	www.aviso.fr	
ArcGICE	2003	+/- 82°N	1995-2001		ArcGICE final report (ESA)
CSR98	1998	+/- 82°N	1993-1995	www.csr.utexas.edu	
DNSC08	2008	+/- 90°N	1992-2004	space.dtu.dk	Andersen and Knudsen, 2008
DTU10	2010	+/- 90°N	1993-2009	space.dtu.dk	

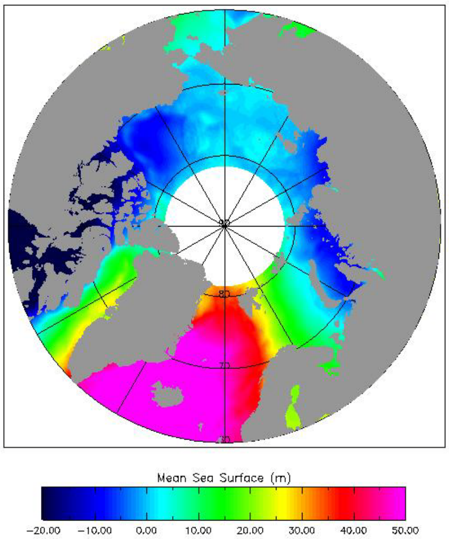

Figure 1*. The ArcGICE mean sea surface model derived from six years of ERS-2 satellite altimetry.*

The DNSC08MSS and more recently updated to DTU10 is the first fully geometrical MSS derived without the use of a geoid model in its development. The DNSC08 MSS/DTU10MSS is also the first MSS to include JASON-1, ENVISAT and ICESAT data and to extend the spatial coverage all the way to the North Pole. Furthermore these MSS models are the first MSS to use more than one decade for the temporal averaging. The prime difference between DNSC08 and DTU10 is an update of several range corrections and the extension of the time series from 12 to 17 years. The effect is generally within the 2-3 cm range and there is no direct effect seen in the Arctic Ocean.

DTU10MSS is derived from the physically observed time-averaged height of the ocean's surface from a total of 8 different satellite missions like i.e., the T/P, ERS, ENVISAT and ICESAT.) covering a period of 17 years (1993-2009) Seventeen years of repeated observations from TOPEX/Poseidon/J1/J2 measured along widely spaced ground-tracks are merged with dense non-repeating data from the Geodetic Mission satellites (GEOSAT and ERS satellite missions) to give a mean sea surface resolving surface structures down to better than 20 km wavelength. DTU10MSS model was designed to have an extended time-series (1993-2009) compared with DNSC08, improved range corrections (using MOG2D) and improved sea level determination at high latitudes using 14 month ICESAT lowest level filtered data. For the Arctic Ocean not covered by the satellite altimetry a novel method was used.

The final step in achieving global coverage is to create a fill-in in the Polar Gap north of 86°N. This was done by feathering in the most recent Arctic Geoid Model – ArcGP.06 (Kenyon and Forsberg, 2008) in the following way. A preliminary MSS was calculated up to 86°N using all satellite altimetry data described above. Subsequently the difference between MSS and the Arctic Geoid Model was computed and the mean value removed. The residual was transformed into Polar coordinates and interpolated onto a regular grid covering the North Pole using a second order Gauss Markov covariance function with a correlation length of 800 km. These residuals were then transformed back into geographical coordinates and the ArcGP geoid added and quarter degree MSS heights were added to the dataset outside the 86°N with an accuracy of 20 cm.

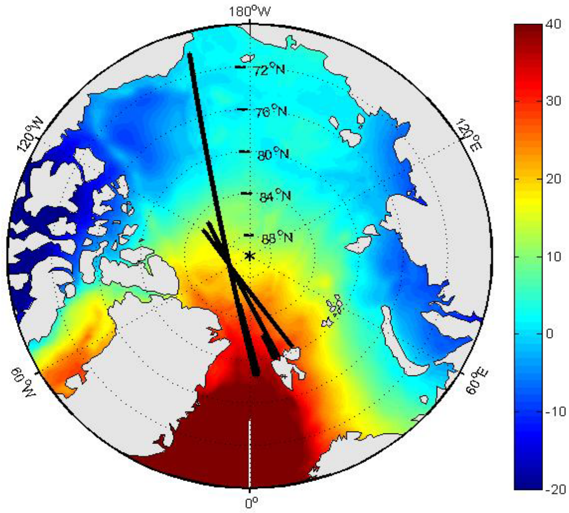

Figure 2*. The DTU10MSS relative to the Topex/Poseidon ellipsoid (scale is in meters).*

The DTU10MSS relative to the Topex/Poseidon ellipsoid is shown in Figure 2. The MSS is relatively similar to the ArcGICE mean sea surface in most of the Arctic Ocean covered by the ArcGICE MSS model. However a constant offset of 70 cm due to the ellipsoid used for plotting is visible.

The difference between the DNSC08 and CLS01 MSS are shown in Figure 3. This figure shows the large consistency between the two models (differences on the cm level). Close to Antarctica and in the Arctic Ocean large white regions represent voids in the CLS01 MSS due to lack of data. In the DNSC08MSS careful data editing and inclusion of Envisat and ICESat means that DNSC08 MSS has no significant voids. A comparison with CSR98 indicated that the temporal coverage of this model is too short to be used in the Arctic Ocean.

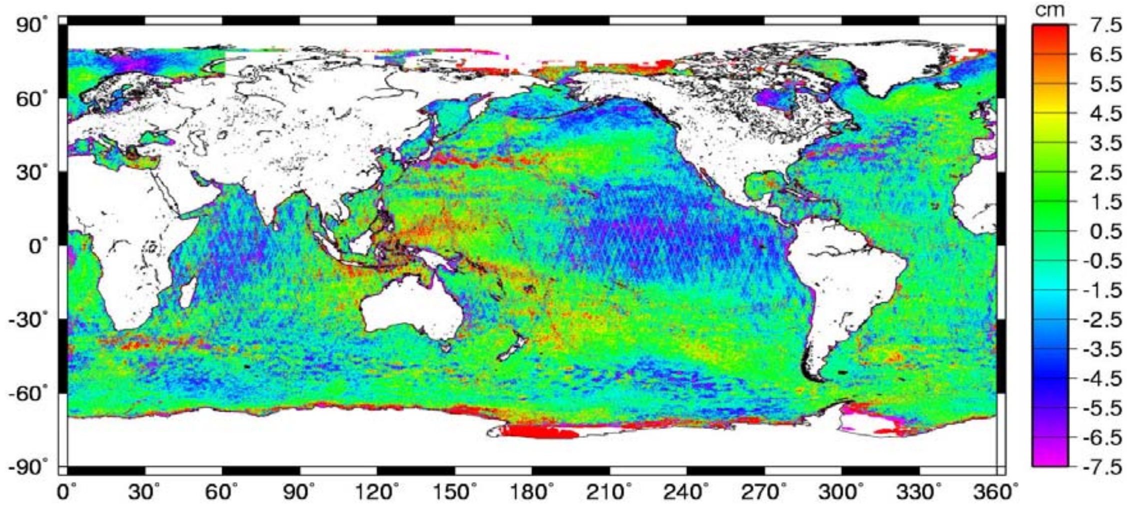

Figure 3. *The difference between DNSC08 and CLS01 Mean sea surfaces (IB corrected). An offset of 2 cm due to different IB correction between the two MSS have been removed. Figure courtesy of S. Holmes and N. Pavlis*

Consequently if was concluded that only the DNSC08 and the updated model DTU10 MSS developed for Monarch-A model was applicable for deriving a 50 years MSS model for the Monarch-A project.

In order to extend the MSS to 50 years it was important to study the sea level variation in the Arctic Ocean over the past 50 years to investigate possible sea level trend and regional features like changes in the Arctic Oscillation, that should be taken into account.

2.2 Sea level trend in the Arctic Ocean over the past 50 Years

DTU10MSS represent the period 1993-2009. In order to create a MSS representing the last fifty years period (1959-2009) the DTU10MSS must be extended to cover the period. The way this will be done is to account for decadal variability and sea level trend during the last 50 years using a smooth correction.

For this investigation two ocean models and tide gauges in the Arctic Ocean were investigated over the 50 years period to estimate the trend.

Initial investigation of the magnitude of the linear sea level trend from the DRAKKAR model is shown in Figure 2.1.3 courtesy of the LEGOS parner in Monarch-A. DRAKKAR is a version of the NEMO model **(Nucleus for European Modelling of the Ocean)** is a state-of-the-art modeling framework for oceanographic research, operational oceanography seasonal forecast and climate studies (http://www.drakkar-ocean.eu). This shows a linear sea level trend of up to 4 mm/year which will represent a correction of the Mean sea surface of 10 cm if integrated over the 50 yeas period versus the 17 years period covered by the satellite altimetry period. A closer investigation of the spatial pattern of sea surface trends indicate its relation with the Arctic Oscillation which is related to inter-decadal variability in the Arctic Ocean.

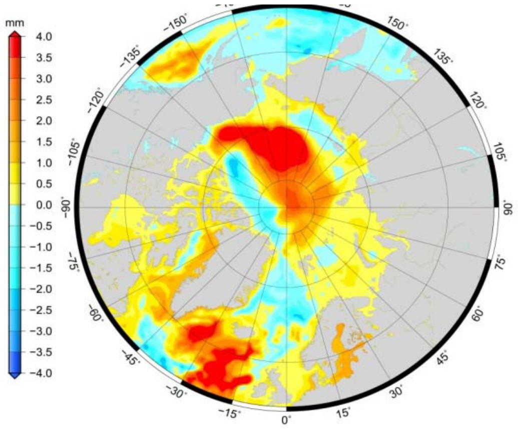

***Figure 4** Sea level trend from the DRAKKAR model estimated by O. Henry (LEGOS)*

As the MSS correction is critically dependent on the accuracy of the model, it was decided to investigate another ocean model as well. The SODA-Model (**S**imple **O**cean **D**ata **A**ssimilation) reconstructs historical ocean climate variability in space and time. The idea behind it is to use direct observations to correct model errors and thereby improve the reanalysis of the ocean variables with an assimilation algorithm.

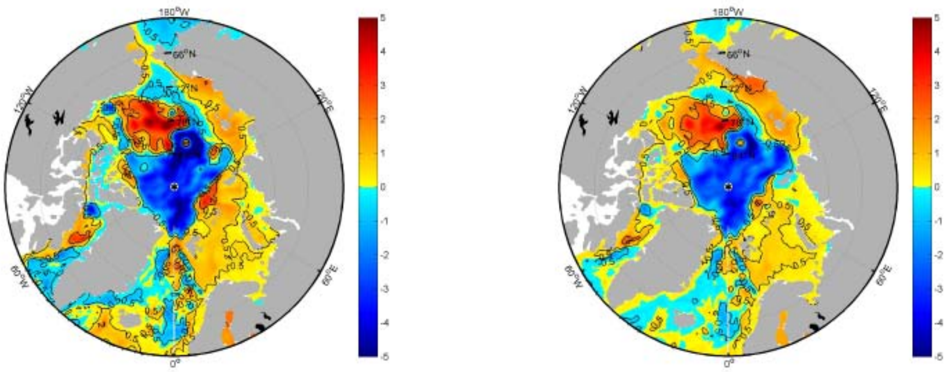

***Figure 5**. Sea level trend from the SODA model for the similar period as the DRAKKAR (1970 -2007) and for the 50 year Monarch-A period 1959-2009 (values in mm/year)*

The linear sea level trend from the SODA model for the similar period as the DRAKKAR (1970 -2007) is shown in Figure 6 along with the similar trend for the 60 year Monarch-A period 1950-2009 (values in mm/year). The most apparent difference to the sea level trend determined from the DRAKKAR model is the difference in trend in the central part of the Arctic Ocean. Whereas DRAKKAR estimate a positive trend of 1-2 mm/year, the SODA model foresee a negative trend of 2-3 mm year for the 1970-2007 period. A trend that is persistent over the 1950-2009 Monarch-A period as well.

All available tide gauges from the PSMSL were investigated by the LEGOS group as part of the Monarch-A study. A total of 66 gauges were found in the Russian and Norwegian sector of the Arctic Ocean, but no stations with long enough temporal coverage were found in the American and Canadian section. Consequently on the Russian and Norwegian stations could be used for this investigation, which will bias the result towards these sectors. However, it was considered the “best” that could be done for the Arctic Region.

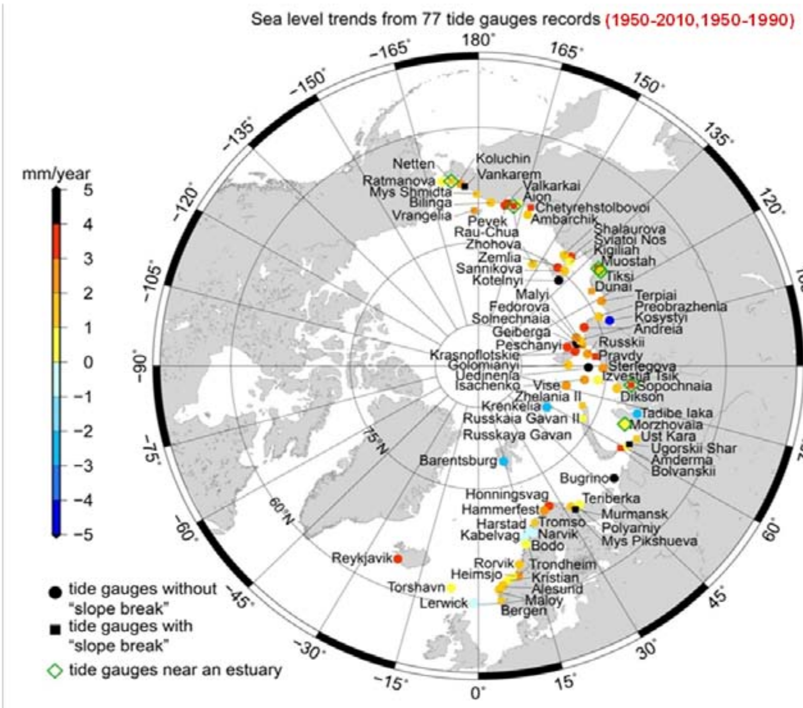

Figure 6. *Sea level trend from all available tide gauges in the Arctic Ocean (from O. Henry, LEGOS) for the1950-1990 and the 1950-2010 period (for applicable gauges). GIA correction using the ICE-5G model has been applied to the tide gauge readings.*

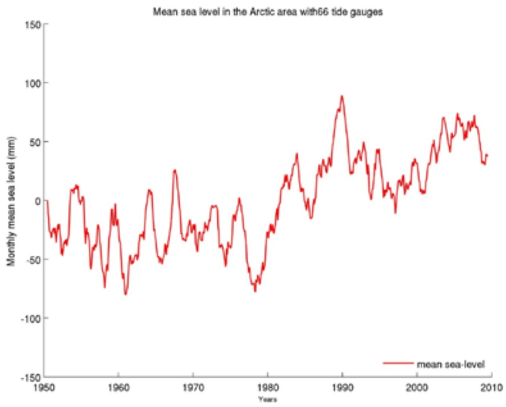

Figure 7. *Averaged sea level trend from 66 Tide gauges in the Arctic Ocean (from O. Henry, LEGOS) for the 1950 – 2010 period.*

The averaged sea level trend from 66 Tide gauges in the Arctic Ocean (from O. Henry, LEGOS) for the 1950 – 2010 period is shown in Figure 7.

The average sea level trend over the 1950-1980 period roughly in-significant from 0 mm/year whereas the average over the 1980-2010 period is slightly higher than 2 mm year. The average over the entire period is 1.4 mm/year.

2.3 Deriving a 50 years MSS model for the Arctic Ocean

The initial approach considered for this WP was to await the outcome of the sea level reconstruction in WP 2.1.1 and to use the outcome of this reconstruction, considered to be the he most reliable data, to update the MSS to the 1950-2010 period. The current alternative is to use hydrodynamic models or tide gauges. An initial investigation indicated that trend estimated from both DRAKKAR and SODA agrees reasonably well with trend estimates interpolated to the tide gauges over the identical period.

However, the two models strongly disagree in the interior of the Arctic Ocean, where no tide gauge data are available, so it is impossible to determine which is the most correct. It is well known that sea level change on annual to decadal scales are largely wind-driven circulation changes and a good approximation for these are the Arctic Oscillation Index. The models response to wind and to changes in the Arctic Oscillation also seems to be the cause of different the sea level trend results seen in Figure 4 and 5.

Considering the tide gauges to be the most physical reliable data these were subsequently considered for the derivation of the Monarch-A 50 years MSS model for the Arctic Ocean.

As the tide gauge data suffers from a very biased spatial distribution towards the Russian and Norwegian sector of the Arctic Ocean, it was decided to use a constant mean value as determined from the tide gauges for the entire Arctic Ocean for the correction of the mean sea surface to cover the 60 years period. This value of 1.4 mm/year was subsequently used to adjust the DTU10 MSS model to create the Monarch-A MSS model for the 1950-2010 period. Integrating the 1.4 mm/year sea level change over the 21.5 years temporal averaging period yields a correction of more or less exactly 3 cm.

2.4 Model download

The Monarch-A 50 years MSS model for the Arctic Ocean was made available on a 2 minute resolution for the Arctic Ocean covering the region north of 60.98333N and have been made available relative to two ellipsoids:

Relative to the TOPEX ellipsoid MONARCH-A_MSS_TP

Relative to the WGS-84 Ellipsoid MONARCH-A_MSS_WGS84

Both models are available for download at the Technical University of Denmark, DTU Space official website, but will shortly become available at the Monarch-A website as well. The official web address for currently download via the DTU space is ftp.space.dtu.dk/pub/MONARCH-A/MSS

Both models are available as .grd ASCII file format and .xyz ASCII file format.

The .grd file format is the GRAVSOFT file format often used by the Geodetic community. The file contain a header and a data block.
The header contains info on min latitude, max latitude, min longitude, max longitude, delta latitude and delta longitude.
The number of elements in the grid is calculated from:
N_lat =(max latitude – min latitude) / delta latitude + 1
N_lon =(max longitude – min longitude) / delta longitude + 1
Subsequent the data are stored starting in upper west corner (max latitude, and min longitude) in a scan line fashion where the first N-lon elements are the first latitude line and so forth for the next latitude line.

The .xyz file ASCII format is an ASCII line file format which can be imported into most commercial programs. The file contains on each line:

Station id, latitude, longitude, height, model

Normally the station id and height (set constant to 0.0) is not used and only the latitude, longitude and model value is read.

2.5 References.

Andersen O. B, Knudsen P (2009) The DNSC08 mean sea surface and mean dynamic topography. J. Geophys. Res., 114, C11, doi:10.1029/2008JC005179, 2009

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