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(1) Tide gauge-based sea level time series since 1950 along the Norwegian and Russian coasts
(2) Satellite altimetry-based gridded sea level time series since 1993 in the Arctic Ocean
(3) Past sea level reconstruction (gridded time series) since 1950 in the Arctic Ocean

Deliverables N°2.1.3

(4) Ocean mass gridded time series from GRACE since august 2002 in the Arctic Ocean

Deliverables N°2.1.4

(5) Thermosteric gridded sea level time series since 1970 in the North Atlantic (>50°N) and Nordic Seas (WOD09/Levitus et al data and Ishii et al 2009 data)
(6) Steric (thermosteric and halosteric) gridded sea level time series since 1993 in the North Atlantic (>50°N) and Nordic Seas (Ishii et al data)
(7) Thermosteric sea level time series since 1970 at Norwegian tide gauges (Ishii et al data)

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SUMMARY

The aim of this working paper is to investigate sea level change and variability in the Arctic region over the 1950-2009 time span and provide a description of the sea level products computed over the Arctic region during this time span (since 1950 and during the altimetry era since 1993). The sea level products consist of :

(1) Tide gauge-based sea level time series since 1950 along the Norwegian and Russian coasts
(2) Satellite altimetry-based gridded sea level time series since 1993 in the Arctic ocean
(3) Past sea level reconstruction (gridded time series) since 1950 in the Arctic Ocean
(4) Ocean mass gridded time series from GRACE since august 2002 in the Arctic Ocean
(5) Thermosteric gridded sea level time series since 1970 in the North Atlantic (>50°N) and Nordic Seas (WOD09/Levitus et al. 2009 data and Ishii et al. 2009 data)
(6) Steric (thermosteric and halosteric) gridded sea level time series since 1993 in the North Atlantic (>50°N) and Nordic Seas (Ishii et al data)
(7) Thermosteric sea level time series since 1970 at Norwegian tide gauges (Ishii et al data)

MONARCH-A CONSORTIUM

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1 Introduction: Objective of the work and generalities of Arctic Sea level

The aim of this working paper is to provide a description of the sea level products computed for workpackage 2.1 over the Arctic region during the last decades (since 1950 and during the altimetry era since 1993). These products consist of:
(1) Tide gauge-based sea level time series since 1950 along the Norwegian and Russian coasts
(2) Satellite altimetry-based gridded sea level time series since 1993 in the Arctic Ocean
(3) Thermosteric gridded sea level time series since 1970 in the North Atlantic (>50°N) and Nordic Seas (WOD09/Levitus et al data and Ishii et al 2009 data)
(4) Steric (thermosteric and halosteric) gridded sea level time series since 1993 in the North Atlantic (>50°N) and Nordic Seas (Ishii et al data)
(5) Thermosteric sea level time series since 1970 at Norwegian tide gauges (Ishii et al data)
Results about the analysis of these data are also provided.

During the past few decades, the Arctic region has warmed at a faster rate than the rest of the globe in response to anthropogenic climate change (IPCC, 2007). Increase air temperature (e.g., Chylek et al., 2010), sea ice extent and thickness decrease (e.g., Kwok et al., 2009, Stroeve et al., 2010) and Greenland ice sheet mass loss (e.g., Holland et al., 2008, Rignot et al., 2011) are among the most visible effects of global warming in the Arctic. But other phenomena have been reported such as permafrost thawing (Lawrence et al., 2008), drying of Siberian lakes (Smith, 2009), Arctic ocean surface warming (Karcher et al., 2003, Polyakov et al., 2005), decline in snow cover and lake ice (Lemke et al., 2007) , etc. As sea level is a very sensible indicator of climate change and variability, one may also wonder whether Arctic sea level is rising at a rate different than the global mean sea level and what are the main patterns of regional variability. Only a few studies have been dedicated to study Arctic sea level (Proshutinsky et al. 2001, 2004). Proshutinsky et al. (2004) estimated sea level change in the Russian sector of the Arctic Ocean using tide gauge data released in 2003 by the Arctic and Antarctic Research Institute in St Petersburg (Russia). These authors found that over ~1950-2000, the mean sea level along the Russian coastlines rose at a mean rate of 1.85 mm/yr after correcting for the Glacial Isostatic Adjustment (GIA) process.

Here we revisit the Arctic sea level variations over the longer time span (1950-2009), considering all available tide gauge data in the Arctic Ocean, north of 55°N. This leads us to consider tide gauge data along the Norwegian coastlines, in addition to those of the Russian sector (no tide gauge records from the Canadian Arctic region are long enough to be usable). We derive mean sea level time series for these two areas and a combined mean sea level time series representative of the whole Eurasian sector. We next estimate the thermosteric sea level (due to ocean temperature only) in the Norwegian sector using three ocean temperature and salinity data bases (too sparse data coverage prevents us from computing the thermosteric sea level in the Russian sector). Analysis of the gridded thermosteric data allows us to also estimate spatial trend patterns in sea level in the North Atlantic and Nordic Seas and their spatio temporal variability since 1970 as well. The spatial sea level trend patterns over the altimetry era (since 1993) are also analyzed and compared to the thermosteric patterns.

2 Data source, methodology and data processing

2.1 Raw tide gauge data

We use monthly RLR (Revised Local Reference) tide gauge records from the Permanent Service for Mean Sea Level (PSMSL Woodworth and Player 2003). Data have been downloaded at http://www.pol.ac.uk/psmsl. These records include 11 sites along the Norwegian coast, 48 sites along the Russian coast and 3 island sites (Reykjavik, Lerwick and Torshavn). Tide gauge data from the Russian sector have been released only a few years ago (2003) and start in the 1950s. These data were used by Proshutinsky et al. (2004) but at that time no data beyond 1999 were available. Fortunately, updated (up to 2009) sea level data from the Russian tide gauges are now available in the PSMSL data base. We consider two sets of data : (1) almost continuous records over the period 1950-2009 (hereafter dataset1) and (2) combination of records covering the whole 1950-2009 period and shorter records also starting in the 1950s but ending around year 2000 (dataset2). In some cases a few data gaps are observed. If the gap is less than 3 years, we linearly interpolate the missing data. Otherwise we exclude the time series. This leaves us with to 27 tide gauges records for dataset1 (11 sites along the Norwegian coast, 3 island sites and 13 sites along the Russian coast with almost continuous data over 1950-2009). When adding to the Russian tide gauges of dataset1 the shorter records all located along the Russian coastline, we obtain dataset 2 corresponding to a total of 48 time series. Location and site name for the 62 sites are shown in Fig.1. Colours in Fig.1 correspond to the length of the dataset2 records. As seen in Fig.1, there are no tide gauges along the Canadian coastlines. In the PSMSL data base a few tide gauge records from this region are available but non exploitable because much too short and generally multidecade-long gaps. We explored the possibility to collect data in other data bases (i.e., Fisheries and Oceans Canada) but could not find usable data for the purpose of the present study.

We corrected the tide gauge time series for the inverted barometer response of sea level to atmospheric loading using surface pressure fields from the National Centers for Environmental Prediction (NCEP; Kalnay et al., 1996, http://www.ncep.noaa.gov/). We tried 3 methods to compute an inverted barometer value for each tide gauge site: 1) using pressure data from the nearest grid point of the tide gauge site, 2) computing an average pressure within a 1°x1° radius around the tide gauge, and 3) interpolating gridded pressure data at the tide gauge site. The 3 methods give similar results. In the following the correction is based on method 1. We also corrected sea level for GIA. The GIA correction is crucial in the Arctic region because this effect is of the same order of magnitude as (or even larger than) the sea level rates. We used different GIA models: the Peltier (2004, 2009)'s models with different deglaciation histories (ICE-3G and ICE-5G) and different Earth's mantle viscosity structures (VM2 and VM4). We noticed quite large differences between the models in a number of sites. In particular, ICE-5G model gives GIA rates of much larger amplitude than ICE-3G. To a lesser degree, some difference is also noticed between the ICE-5G VM2 and VM4 viscosity structures. To discriminate between the various solutions, we decided to choose the model version that minimizes sea level trend differences between tide gauge-based and altimetry-based data during the altimetry period (1993-2009) at the considered tide gauge sites. This led us to retain the ICE-5G/VM2 model to correct for GIA the tide gauge records. However, differences between ICE-5G/VM2 and ICE-5G/VM4 are small in the Norwegian and Russian sectors, the region of interest in this study. As we focus here on interannual to multidecadal time scales, we removed the seasonal cycles from the monthly sea level time series, by fitting sinusoids with periods of 12 and 6 months. As this procedure may not be optimal if seasonal cycles are not purely sinusoidal, we further applied a 12-month moving average to each tide gauge time series. Fig.2 shows individual corrected tide gauge time series over 1950-2009 along the Norwegian and Russian coasts (dataset1). Fig.3 shows mean sea level evolution for 1950-2009 for the Norwegian sector (dataset1) and Russian sector (dataset 1 and dataset2).

2.2 Satellite altimetry data

For the altimetry data, we use the DT-MSLA "Ref" series provided by Collecte Localisation Satellite (CLS; http://www.aviso.oceanobs.com/en/data/products/sea-surface-height_products/_global/msla/index.html). This data set is used over the time span from January 1993 to December 2009. It is available as 1/4°×1/4° Mercator projection grids at weekly interval. The DT-MSLA "Ref" series are based on the combination of several altimetry missions, namely: Topex/Poseidon (T/P), Jason-1 and 2, Envisat and ERS 1 and 2. It is a global homogenous inter-calibrated dataset based on a global crossover adjustment (Le Traon and Ogor, 1998) using T/P and then Jason-1 as reference missions. One main limitation results from the low data availability due uncovered high latitudes areas by most altimetry missions and the presence of sea ice. T/P, Jason-1 and Jason-2 share the same ground track and have an orbit inclination of 66°. As a consequence there is no data available from these missions at latitudes higher than 66°N. Parts of high latitudes are sampled up to 82°N by the

ERS-1, ERS-2 and Envisat altimetry missions. However, north of 82°N, no satellite altimeter data is available. Any satellite altimetry-derived SSH dataset leaves uncovered large portions of the Arctic Ocean. In addition, the Arctic Ocean is partly covered by sea-ice, whose extent varies on seasonal and inter-annual timescales. Typical values for annual sea-ice cover variations range from 7 millions km² in Arctic summer to 15 millions km² in Arctic winter. The presence of sea-ice makes a large portion of the Artic Ocean either unobservable by radar altimeters, or unevenly sampled through time. We investigated corresponding SLA data availability by computing the number of valid values in each ¼° grid cell over the whole studied period, consisting of 899 weekly grids. Fig.4a shows a map of AVISO sea level anomalies (SLA) data availability. In Fig.4a, the impact of the sea-ice cover is quite clear. Sampling is good in the North Atlantic, in the Nordic Seas and the Barents Sea where the inflow of warm water from the Atlantic Ocean allows an ice-free ocean to be observed by the altimeter satellites at every time step. Except for this small area, data availability is very low in all other parts of the Arctic Ocean, with values lower than 30% almost everywhere. Large parts of the Arctic interior are not sampled at all. Such a low sampling of the Arctic Ocean identified in the AVISO database is a major limitation to the use of this data for sea level studies at high latitudes and triggers the need for a reprocessing of satellite altimetry data in this region. We analyzed Envisat and ERS-2-derived SLA variances as a function of the latitude, using the standard global processing. The variance is anomalously high at latitudes higher than 74° North, with values greater than 800 cm² (typical values at lower latitudes are less than 100 cm²). As there is no physical reason for such a strong increase in oceanic variability at high latitudes, these high variance levels can be attributed to poor performances of the satellite altimetry data processing. Using the ice flag in the along-track altimetry products, we computed the distance of each measurement to the nearest sea-ice. Results show that SLA variance increases when distance to sea-ice decreases (not shown). This SLA data degradation in the vicinity of sea-ice may have multiple causes, acting at different distances from sea-ice. The first one is the degradation of the SLA quality close to sea-ice (within a window of 20 km corresponding to the radar footprint). Most spurious measurements areremoved by the editing process but not all. Not much can be done to retrieve valid SLA measurements from echoes polluted by the presence of sea-ice without using a specific retracking algorithm. A similar problem affects the radiometer measurements, also impacted by sea-ice. The quality of the wet troposphere correction also decreases close to sea-ice (within a window of 50 km corresponding to the radiometer footprint). The SLA variance explained by the radiometer-derived wet troposphere correction decreases with the distance to sea-ice, indicating a degradation of the correction quality. Using the wet troposphere correction derived from models prevents the decrease of the explained variance near sea-ice, but the correction is less accurate farther from sea-ice. Spurious measurements are removed by the editing process but the low values observed for the wet troposphere correction at high latitudes make it hard to discriminate between affected and unaffected radiometer measurements. Other geophysical corrections applied to the sea level measurements are also degraded in high-latitude regions. The GOT4.7 ocean tide model (Ray 1999) used for the generation of AVISO grids is based on satellite altimetry data. The previously described errors on satellite altimetry, mainly the low data coverage in the Arctic Ocean, therefore affect the quality of the ocean tide correction.

The reference mean sea surface (MSS) to which SLA are referred is usually estimated from satellite altimetry data averaged over a given time span. In oceanic regions where satellite observations are scarce and of less good quality, the MSS will be less accurate. In AVISO products, the CLS01 MSS (Hernandez and Schaeffer 2000) is used. This mean sea surface is derived from T/P, ERS-1 and Geosat data over 1993-1999. Over continents and in areas where no altimetry data are available, the MSS is filled up with the EGM96 geoid model. In order to generate a new dataset suitable to study sea level variability and trend in the Arctic Ocean, we reprocessed satellite altimetry data from the T/P, ERS-1, ERS-2, GFO, Envisat, Jason-1 and Jason-2 missions. The aim of this reprocessing was to address some of the limitations previously described. We focused on the specific limitations discussed above, namely the low data quality and the uneven sampling of the ocean. The improvements concern: (1) the mean sea surface, (2), the ocean tide model, (3) the regional multi-mission merging, (4) the sea level grid computation using the objective analysis approach. These improvements lead to a much larger availability of the sea level data in the Arctic region, as illustrated in Fig.4b. The details of these improvements are described in Prandi et al. (2011). The spatial trend patterns in sea level over 1993-2009 of the original and reprocessed data are presented in Fig. 5a and 5b.

2.3 GRACE data

About 7 years of gravity data from the GRACE mission are now available. This satellite mission was launched in March 2002 to measure temporal change of the earth gravity field at monthly interval. On land, GRACE mainly measures change in land water storage while over the oceans GRACE provides variations of the mass of the oceans (Wahr et al. 2004). At regional scale, ocean mass change results from redistribution of sea water by the ocean circulation plus local exchange of water with the atmosphere (through precipitation and evaporation). Several GRACE products have been released from teams involved in the GRACE project (CRS, JPL and GFZ), each time with substantial improvement (Chambers 2006). Other teams (e.g., GRGS, NASA/GSFC) also provide GRACE solutions based on different processing approaches. Here, we have explored the latest releases (RL04) from three groups: CSR, GFZ and GRGS solutions (1°×1° ocean grids at monthly interval) and selected CSR data. This new data set includes an implementation of the carefully calibrated combination of destripping and smoothing, with different half-width Gaussian filters (the solutions need to be smoothed because errors increase with wavelength; Swenson and Wahr 2002). Compared to earlier products (contaminated by north– south strips due to aliasing by the GRACE coverage of high frequency signals of atmospheric and oceanic origin), the latest release is less noisy, mostly because of the destripping procedure applied to the data. The gridded ocean GRACE products are corrected for post-glacial rebound (the solid earth response to last deglaciation, also sensed by GRACE) using Paulson et al. (2007) model, and for the leakage due to land hydrology (Chambers 2006). The gridded time series we use in this study are based on the 300-km Gaussian smoothing and cover the following time spans: August 2002 to December 2010 (Fig.6). GRACE solutions are expressed in terms of equivalent water height.

2.4 Steric data

In this section we estimate the contribution of the steric (effect of ocean temperature T -thermosteric component- and salinity -halosteric component- variations) sea level to Arctic MSL. For that purpose, we use T data from 2 data bases: the WOD09 (Levitus et al., 2009) and the Ishii and Kimoto (2009) data bases. The depth and time coverage of these temperature and salinity data is very inhomogeneous in the studied region, leaving much of the Arctic Ocean uncovered. This is illustrated in Fig.7a and 7b which shows for three periods (1960-1969, 1980-1989 and 2000-2009) T and S data coverage down to 700m (coverage is shown for the 0-50m, 0-200m and 0-700m upper ocean layers). The coverage during the 1960s and earlier is far too sparse and limited to the near surface layers, preventing us to quantify the steric contribution in the whole Arctic and even along the Russian coasts. Before the 1990s, we also note that the S data coverage is poorer than for T data. This leads us to : (1) not consider data prior to 1970, (2) compute the thermosteric sea level as of 1970 and the halosteric sea level as of 1993 (the beginning of the altimetry era), and (3) only consider a limited geographical sector bounded by the 75°W-45°E longitudes and the 50°N 80°N parallels. For each data base, we computed the thermosteric/halosteric sea level on a 1°x1° grid at monthly interval since 1970, integrating T/S anomalies down to 700 m. Fig.8 show steric trend patterns computed over 1970-2009 with the WOD09 and Ishii et Kimoto 2009 data over the limited region described above. We further compare the altimetry-based with thermosteric and halosteric spatial patterns over the 1993-2009 time span over the North Atlantic and Nordic Seas regions. These are shown in Fig.9. In several areas the spatial trend patterns of altimetry-based and thermosteric sea level show very similar behaviour. In Fig.9 is also shown the residual (altimetry minus steric -sum of thermosteric plus halosteric-) trend map. Comparing thermosteric and halosteric trends indicates that the patterns appear anticorrelated (with higher magnitude for the thermosteric trends). This anticorrelation between the trend patterns in thermosteric and halosteric sea level suggests simultaneous increase of both temperature and salinity in the area of the North Atlantic and Nordic Seas sector during the past 17 years (the two factors having opposite effects on sea level).

2.5 Past 2-D sea level reconstruction

Satellite altimetry data provide information about regional variability in sea level since the beginning of the 1990's. But if we want to study sea level in the past we must produce reconstruction of sea level. Prior to the altimetry era, we do not have such an information but past sea level reconstruction methods can be developed to construct gridded sea level time series in the past.

The reconstruction process is described by Meyssignac et al (2012) and consists of 2 steps. In the first step an EOF (Empirical Orthogonal Function) decomposition of 2-D sea level grids (satellite altimetry or numerical ocean models) is done (Fig.10). This decomposition separate sea level signal (matrix H) into spatial modes (U(x,y)) and temporal amplitudes ($\alpha(t)$):

$$H(x,y,t) = U(x,y)\alpha(t)$$

Assuming that spatial modes are stationary with time, the reconstructed sea level in the past (called here $H_R(x,y,t)$) has an EOF decomposition as follow:

$H_R(x,y,t) = U(x,y)\alpha_R(t)$, where $\alpha_R(t)$ is the new temporal amplitudes of the EOFs.

The second step consists of computing these new $\alpha_R(t)$ amplitudes through a least squares adjustement that minimizes the reconstructed field and the tide gauge data (e.g., Fig.10) at the tide gauges locations. Combining spatial modes and new temporal amplitudes gives a reconstruction of past sea level in 2-dimension (Fig.11).

For Arctic region, the first step was performed using an EOF decomposition of altimetry grids provided by Pierre Prandi (CLS) (Fig.12). These satellite altimetry grids have been specially reprocessed, as described in Prandi et al (2012), to improve the sea level signal in the Arctic region. A selection of grid mesh has been done to only keep the best covered areas. For that purpose, the chose criterion was to have at least two monthly data per year and without gaps greater than 3 years. Finally data have been yearly averaged.

To obtain the new $\alpha_R(t)$ amplitudes, we selected 26 tide gauge records along the North Atlantic and Arctic coastlines (Norway and Russia) (Fig.12), showing a good temporal coverage, with at least 48 years of data, and without too long gaps or suspect behaviors. We also included 11 new tide gauge records (Denmark, Germany, Ireland, Norway, United Kingdom) below 60°N Latitude (these data were used in the global reconstruction by

Meyssignac et al., 2012). All records have been corrected for IB, GIA and seasonal cycles. Finally, we averaged monthly data to annual data to focus on interannual to multidecadal time scales.

The reconstruction covers the period 1958 – 2006 and concerns North Atlantic, Nordic Seas, Greenland Sea, Barents Sea, Kara Sea and Siberian Sea. It has been validated by comparing reconstructed and observed sea level at tide gauge sites not used in the reconstruction (Fig.13).

3 Summary of the data analysis

3.1 Tide gauge and steric sea level

Analysis of 62 long tide gauge records available during the studied time span along the Norwegian and Russian coastlines shows that coastal mean sea level of these two regions was almost stable until about 1980 but since then displays a clear increasing trend (Fig.14). Coastal mean sea level (averaged from the Norwegian and Russian tide gauge records) is highly influenced by natural climate modes, in particular the Arctic Oscillation (AO) which closely followed the mean sea level curve until the mid-1990s. Both quantities show in particular a marked positive anomaly around 1990 (Fig.14). However, since about 1995, the mean sea level curve departs from the AO influence and presents a large increasing trend of ~ 4 mm/yr between 1995 and 2009. Thermosteric sea level interpolated at the tide gauge sites of the Norwegian sector (the only region with good enough coverage over the past 40 years) shows a reasonably good correlation between observed (i.e., tide gauge-based) sea level over 1970- 2009 (Fig.15a). We also note that the recent (past ~15 years) increase in sea level has a dominant thermal origin. This may result from inflow of warm waters from the North Atlantic Ocean. Difference between observed and thermosteric sea level over 1970-2009 in the Norwegian sector is highly correlated with the AO index and is likely due to salinity effects (Fig.15b). Over the altimetry era (since 1993), comparison of altimetry-based sea level trend patterns with thermosteric and halosteric trend patterns in the North Atlantic (>50°N) and Nordic Seas region mostly results from a combination of temperature and salinity effects (Fig.9).

This work is the object of 2 scientific articles:

Henry O., P. Prandi, W. Llovel, A. Cazenave, S. Jevrejeva, D. Stammer , B. Meyssignac, N. Koldunov, Sea level variations since 1950 along the coasts of the Arctic Ocean, in revision, *J. Geophys. Res*., 2012.

Prandi P. Ablain M., Cazenave A. and Picot N., A new estimation of mean sea level in the Arctic Ocean from satellite altimetry, submitted, *Marine Geodesy*, 2012.

3.2 Past 2-D sea level reconstruction since 1950 in the Arctic region

We provide gridded sea level time series at yearly interval from 1958 to 2006 (Fig..

Related publications:

1. Meyssignac B., Becker M., Llovel W., Cazenave A. An assessment of two-dimensional past sea level reconstructions over 1950 -2009 based on tide gauge data and different input sea level grids, *Surveys in Geophysics*, in press, 2012.
2. Meyssignac B. , Henry O. , Prandi P., Cazenave A. , Past sea level reconstruction over the Arctic Ocean since the mid-1950s, in preparation

3.3 Ocean mass from GRACE

We provide gridded GRACE-based time series over the Arctic ocean at monthly interval from August 2002 to December 2010 products. The data are corrected for post-glacial rebound and for the leakage due to land hydrology.

Publication in preparation:

1. Henry O. et al: Arctic Ocean mass from GRACE and altimetry minus steric sea level, in preparation, 2012.

4 Output products

4.1 Tide gauge data

Good quality records from PSMSL, monthly data in ASCII files (.dat), corrected for Glacial Isostatic Adjustment (Ice-5G VM2, Peltier W.R., 2004) and Inverted Barometer (NCEP), filtered for seasonal cycles and smoothed over 12 months.

Website link : http://monarch-a.nersc.no/node/31

Data link : http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.1_tide_gauges_time_series_CNRS_LEGOS.zip

4.2 Satellite altimetry data

Altimetry data are reprocessed by Pierre Prandi (Prandi et al, 2012), from 51° to 82° North Latitude, since from 1992 October 14th to 2009 December 30th. Grids are in netcdf format, one grid for a week and the unit is centimeter.

Data link : http://monarch-a.nersc.no/node/43

4.3 Steric data

Steric sea level in Artic area is computed using temperature ans salinity data (WOA09, Ishi and kimoto 2009 and EN3 database from Met Office Hadley Center) from surface down to 700m for the whole period (1950-2009). Seasonal cycles have been removed. This deliverable contains 7 packages:

1) gridded halosteric sea level time series since 1970 to 2009 from Ishii and Kimoto 2009, in an ASCII file, with first colomn for longitudes, second colomn for latitudes and from third colomn to the last one for time series. Unit is centimeter. Link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_halosteric_gridded_time_series_ISHII_1970-2009.tar_.gz

2) gridded halosteric sea level time series since 1993 to 2009 from Ishii and Kimoto 2009, in an ASCII file, with first colomn for longitudes, second colomn for latitudes and from third colomn to the last one for time series. Unit is centimeter. Link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_halosteric_gridded_time_series_ISHII_1993-2009.tar_.gz

3) gridded thermosteric sea level time series since 1993 to 2009 from Ishii and Kimoto 2009, in an ASCII file, with first colomn for longitudes, second colomn for latitudes and from third colomn to the last one for time series. Unit is centimeter. Link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_thermosteric_gridded_time_series_ISHII_1993-2009.tar_.gz

4) gridded thermosteric sea level time series since 1970 to 2009 from Ishii and Kimoto 2009, in an ASCII file, with first colomn for longitudes, second colomn for latitudes and from third colomn to the last one for time series. Unit is centimeter. Link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_thermosteric_gridded_time_series_ISHII_1970-2009.tar_.gz

5) gridded thermosteric sea level time series since 1970 to 2009 from WOA 2009, in an ASCII file, with first colomn for longitudes, second colomn for latitudes and from third colomn to the last one for time series. Unit is centimeter. Link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_thermosteric_gridded_time_series_NOAA_1970-2009.tar_.gz

6) gridded complete steric sea level time series since 1950 to 2009, from EN3 database. This package contains 636 files (format : NetCDF), one file for one month. Each file contains 6 variables : LatLon, LatLonMin (minimum for latitude and longitude), LatLonStep (step between each latitude and longitude, grid resolution), NbLatitudes (all latitudes from 50 to 89°N), NbLongitudes (all longitudes from 0 to 359°E) and Grid_0001 (the steric sea level grid, lines for longitude, columns for latitude, cm). Link:

http://monarch-a.nersc.no/sites/monarch-a.nersc.no/files/D2.1.4_steric_ gridded_ time_series_EN3_1950-2009.zip

4.4 GRACE data

Ocean mass component of the Arctic Ocean is computed from GRACE data (CSR), from August 2002 to december 2010. Seasonal cycles have been removed. This package contains 3 directories: one for EOF, one for trend maps and one for 2 ascii files : the grid (format : [lon,lat,time serie], mm) and the time vector of the grid.

Website link: http://monarch-a.nersc.no/node/31

Data link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no /files/D2.1.3_GRACE_arctic_ocean_mass_time_series_2002-2010.tar_.gz

4.5 Past 2-D sea level reconstruction data

This package is computed from altimetry and tide gauge, from 1958 to 2006. Data are annual. This package contains 2 ascii files: the grid (format: [lon, lat, time serie]) and the time vector of the grid.

Website link: http://monarch-a.nersc.no/node/31

Data link: http://monarch-a.nersc.no/sites/monarch-a.nersc.no /files/D2.1.1_past_sea_level_reconstruction_1958_2006_V1.tar_.gz

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Figures

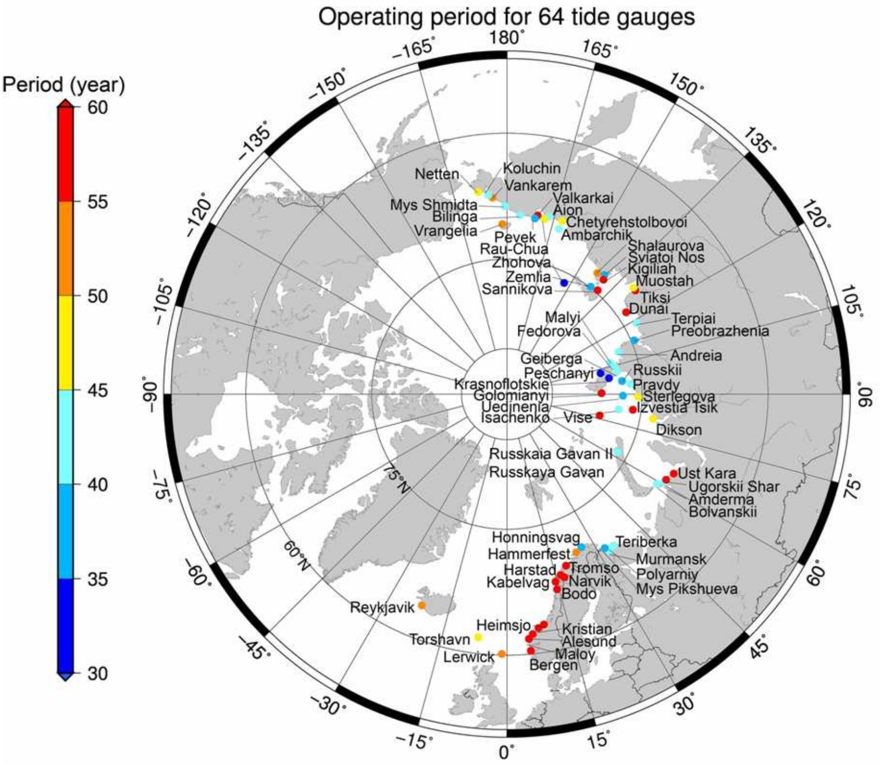

Fig.1: Distribution of the 64 tide gauges available in the Arctic region. Colour indicates the length of the record as of 1950.

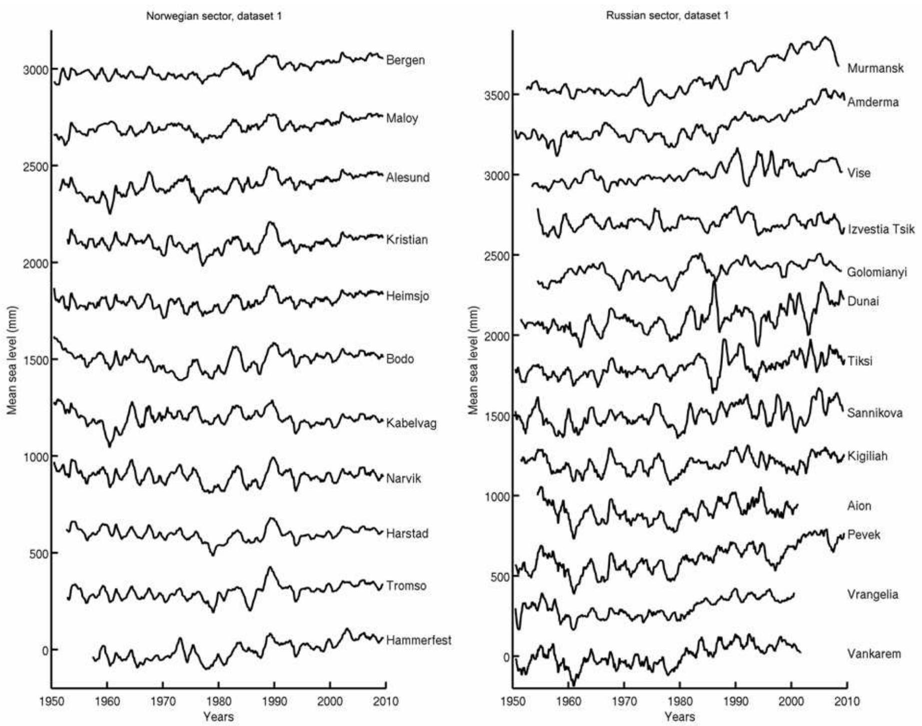

Fig.2 Plots of individual tide gauge time series over 1950-2009 for the Norwegian sector (11 tide gauges; left panel) and Russian sector (13 tide gauges; right panel).

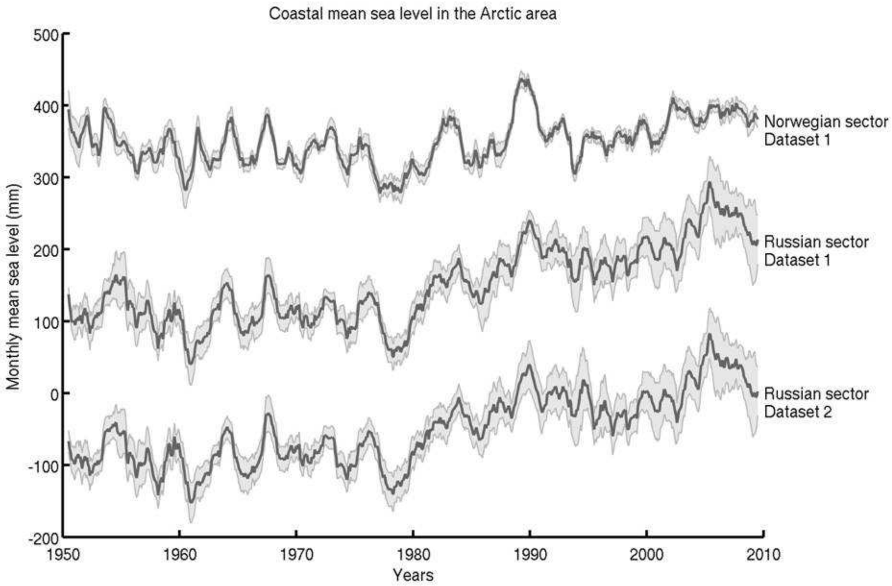

Fig.3: MSL curves in the Norwegian (dataset1) and Russian sectors (dataset1 and 2)

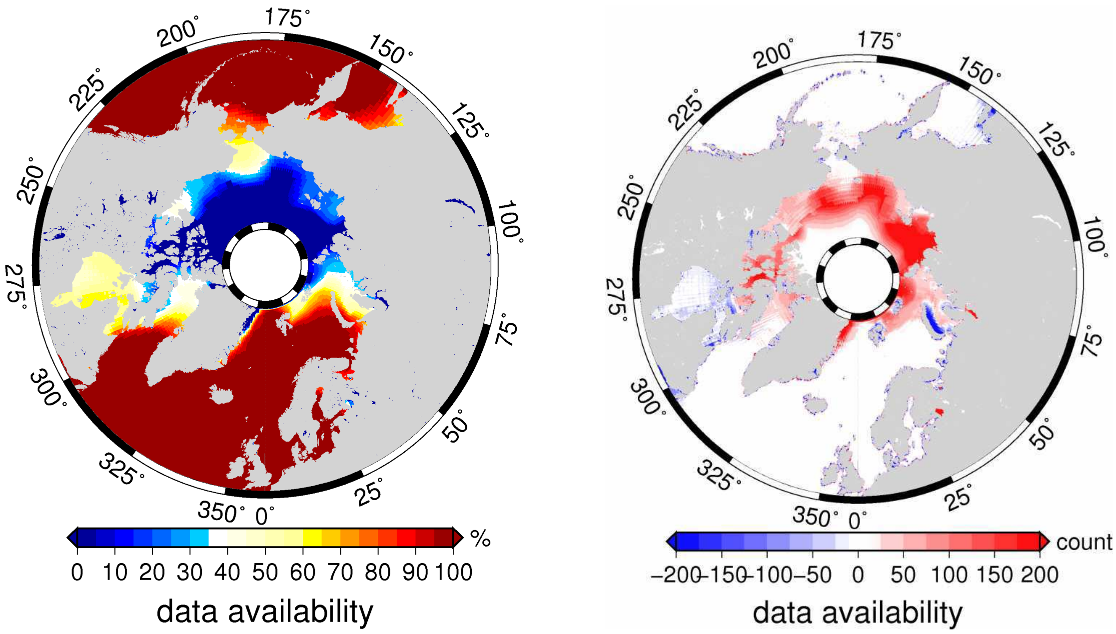

Fig.4: (a) SLA data availability (percentage) in the Arctic Ocean from the SSALTO/Duacs Up-To-Date dataset; (b) Map of data availability differences between SSALTO/Duacs and the reprocessed datasets expressed in number of points. Positive (red) values mean that the ocean observability is improved in the new dataset

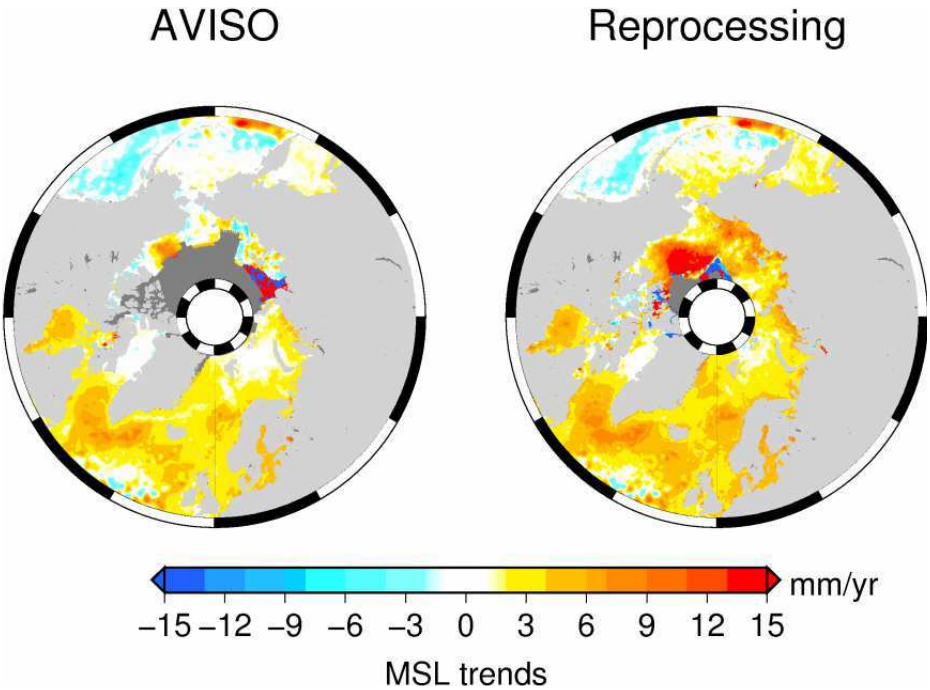

Fig.5: Map of altimetry-based sea level trends (mm/yr) between 1993 and 2009 in the Arctic Ocean from SSALTO/Duacs grids (left panel) and from the reprocessed grids (right panel) (this work)

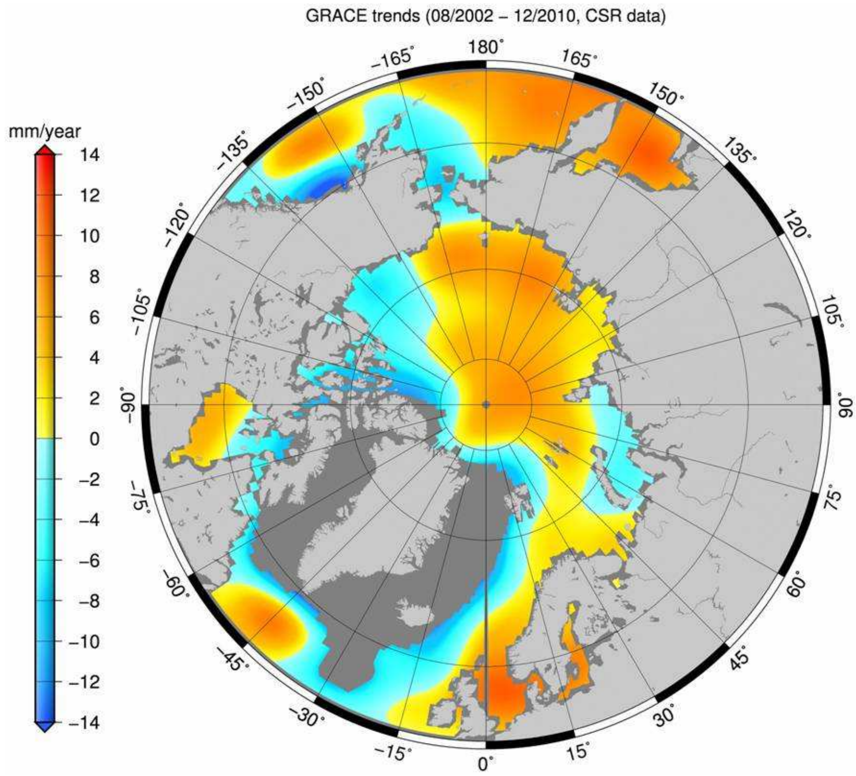

Fig.6: Map of Ocean mass trends (mm/yr) between August 2002 and December 2010 in the Arctic Ocean from CSR GRACE data.

a)

b)

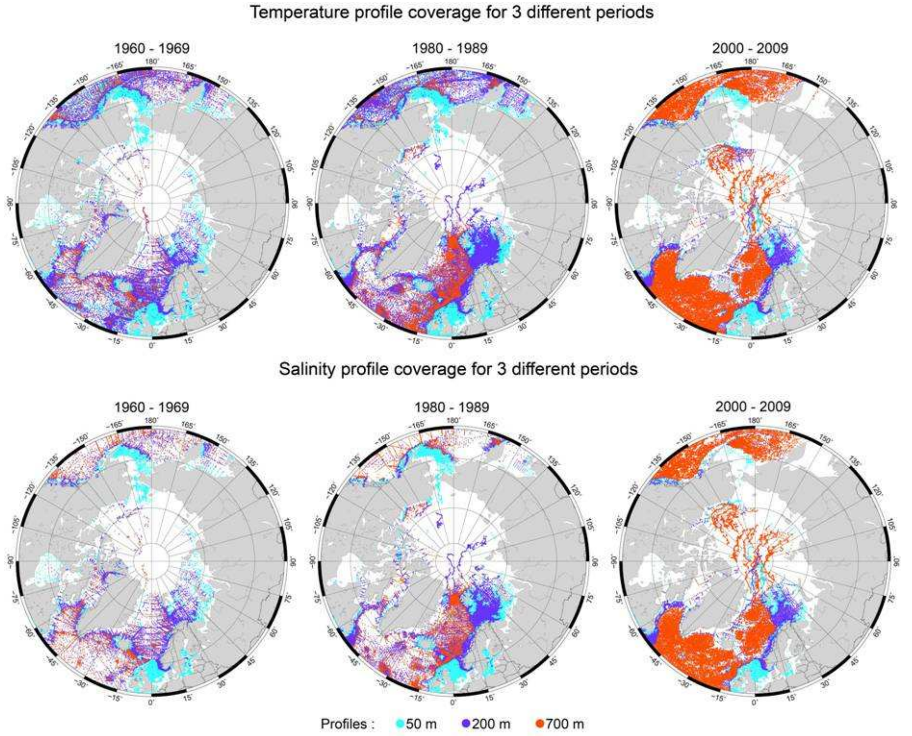

Fig.7: Temperature and salinity profile coverage in the Arctic region for 3 different depth ranges (0-50m, 0-200m and 0-700m) and 3 different periods (1960-1969, 1980- 1989 and 2000-2009). (a) temperature coverage; (b) salinity coverage.

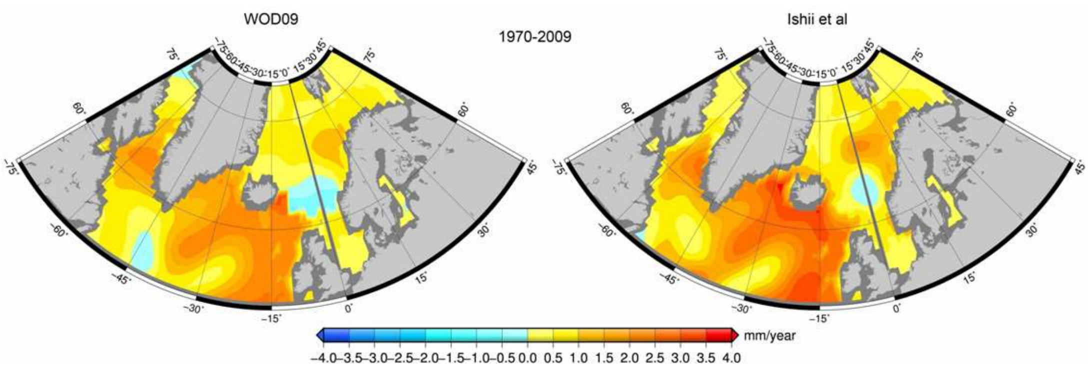

Fig.8: Spatial trend patterns in thermosteric sea level for 1970-2009 over the North Atlantic and Nordic sea; WOD09 (left panel); Ishii et al (2009) (right panel).

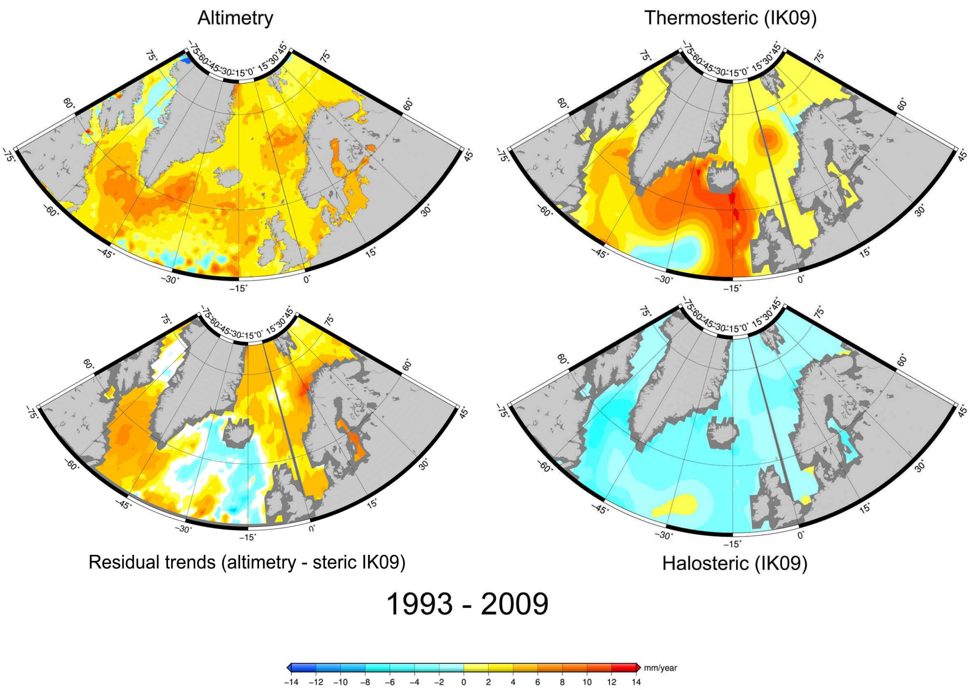

Fig.9: Altimetry-based, steric (from Ishii and Kimoto 2009 and EN3 database) and residual (altimetric minus steric) sea level trend patterns in the North Atlantic and Nordic Seas region over 1993-2009.

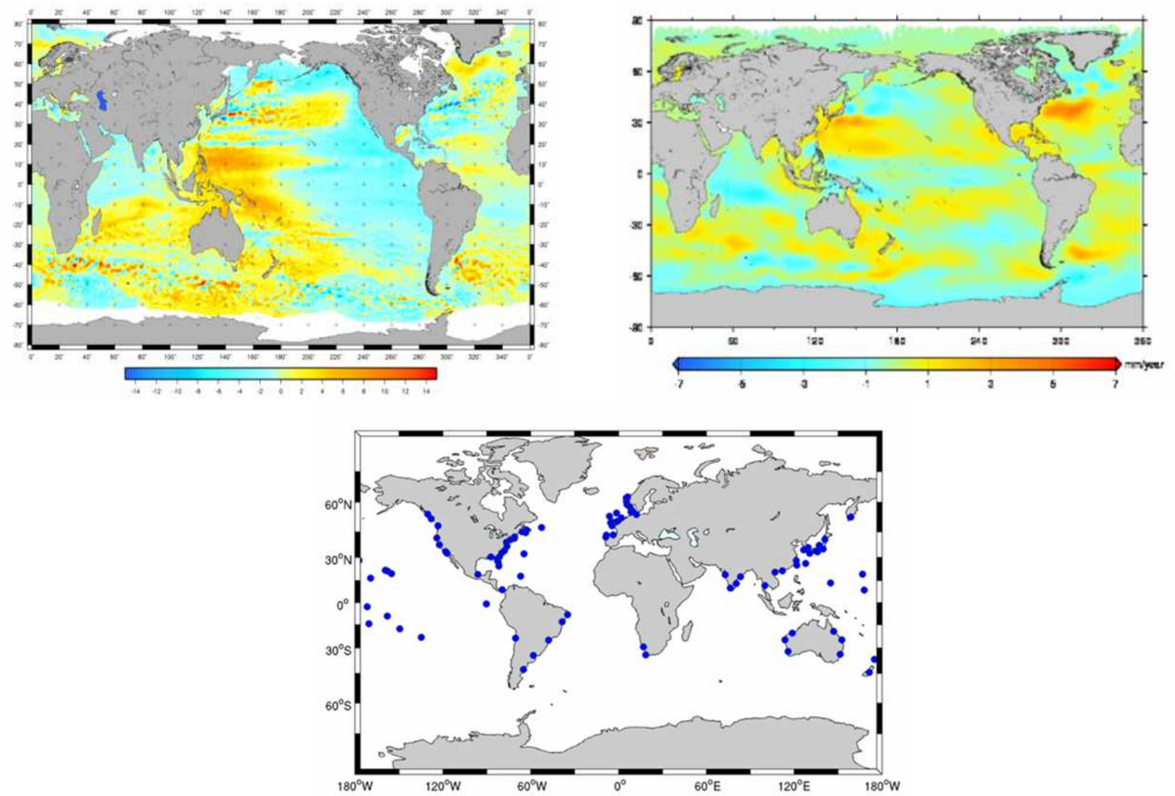

Fig.10: Altimetry-based sea level (left panel) and sea level from OGCM outputs (right panel) used in the reconstruction process

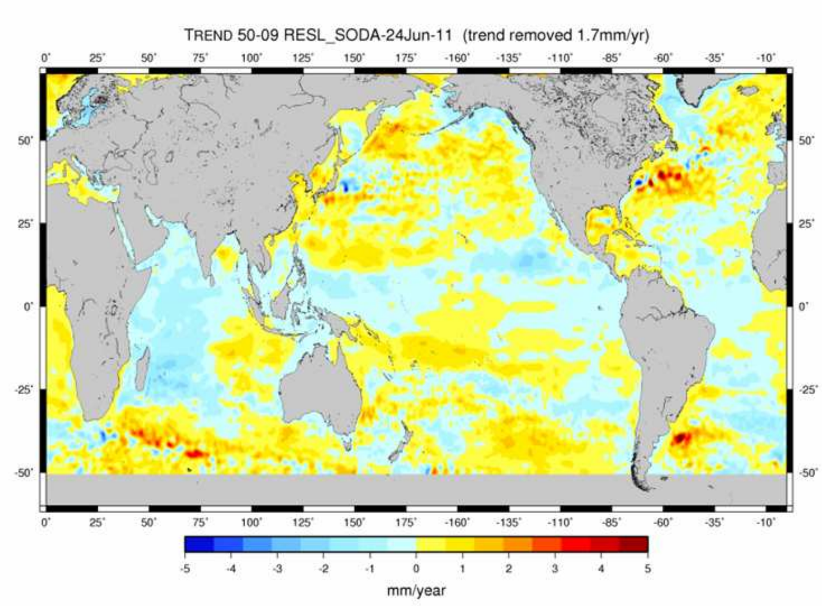

Fig.11: Past 2-D sea level reconstruction from an OGCM, SODA, over the period 1950-2009.

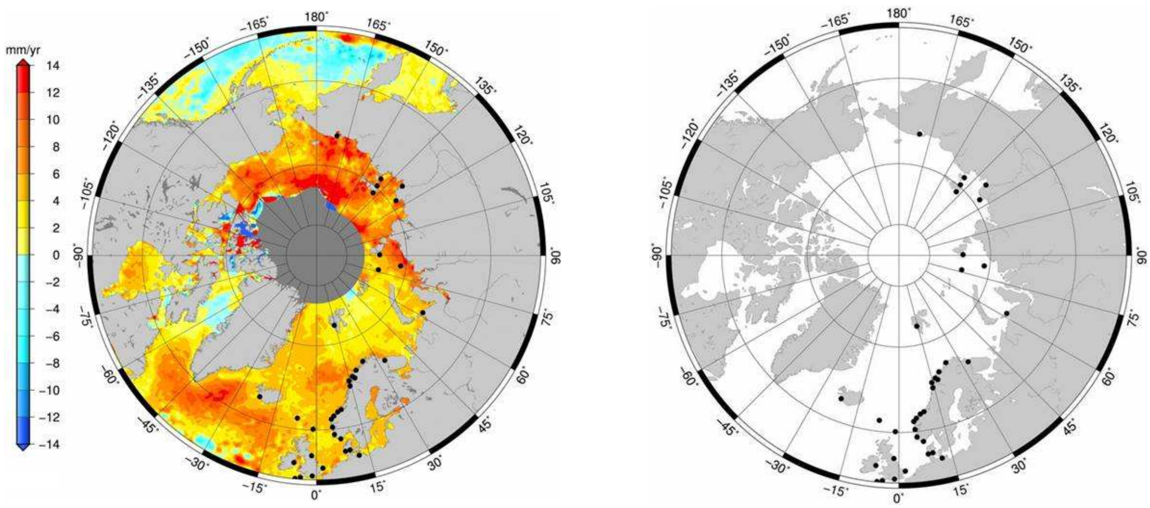

Fig.12: Altimetry-based sea level (left panel) used to obtain spatial modes in the Arctic reconstruction process; location of Arctic tide gauges (lower panel) used to compute new amplitudes.

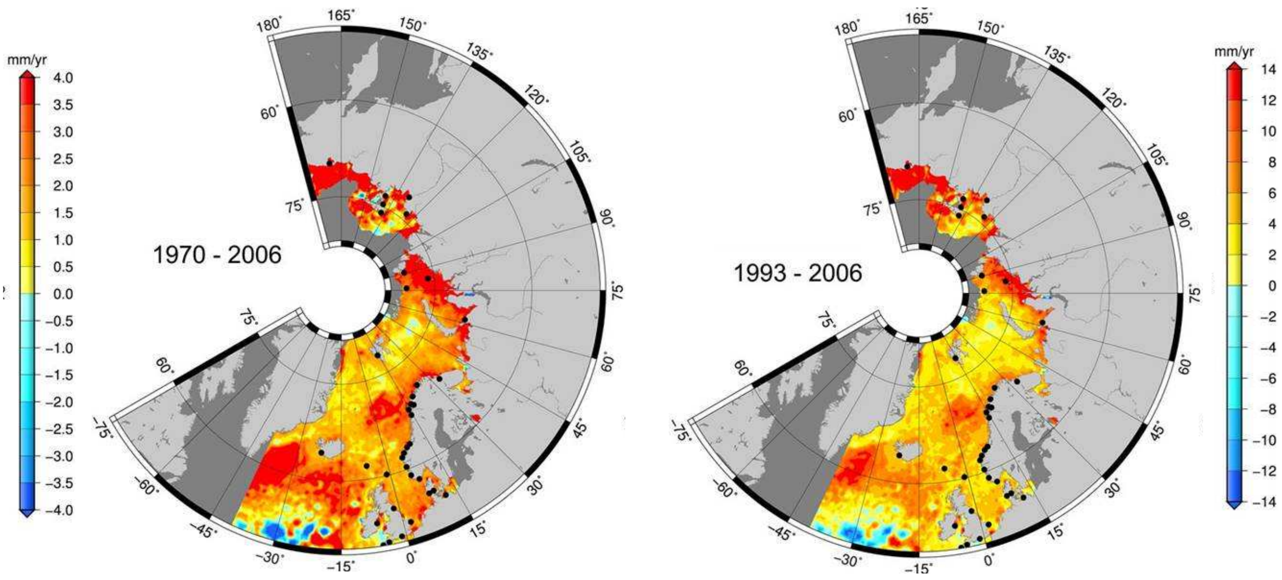

Fig.13: Past 2-D sea level reconstruction from 1970 to 2006 (left panel) and from 1993 to 2006 (right panel) in the Arctic region.

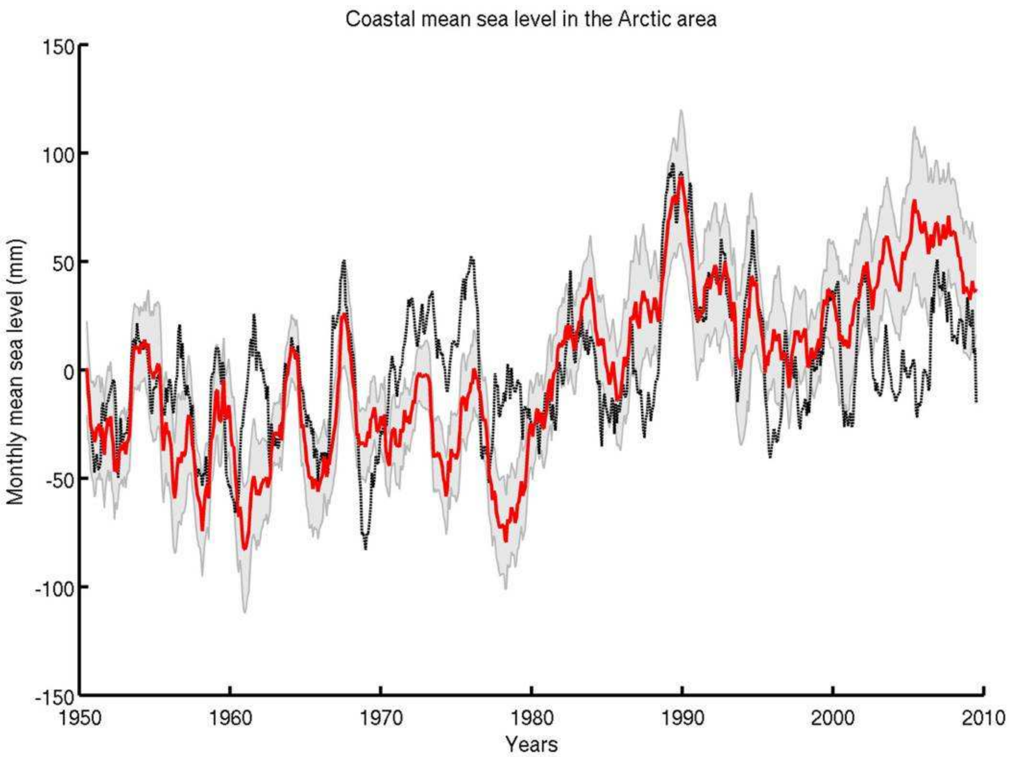

Fig.14: Arctic mean sea level curve (red curve). Arctic oscillation index is superimposed (black curve).

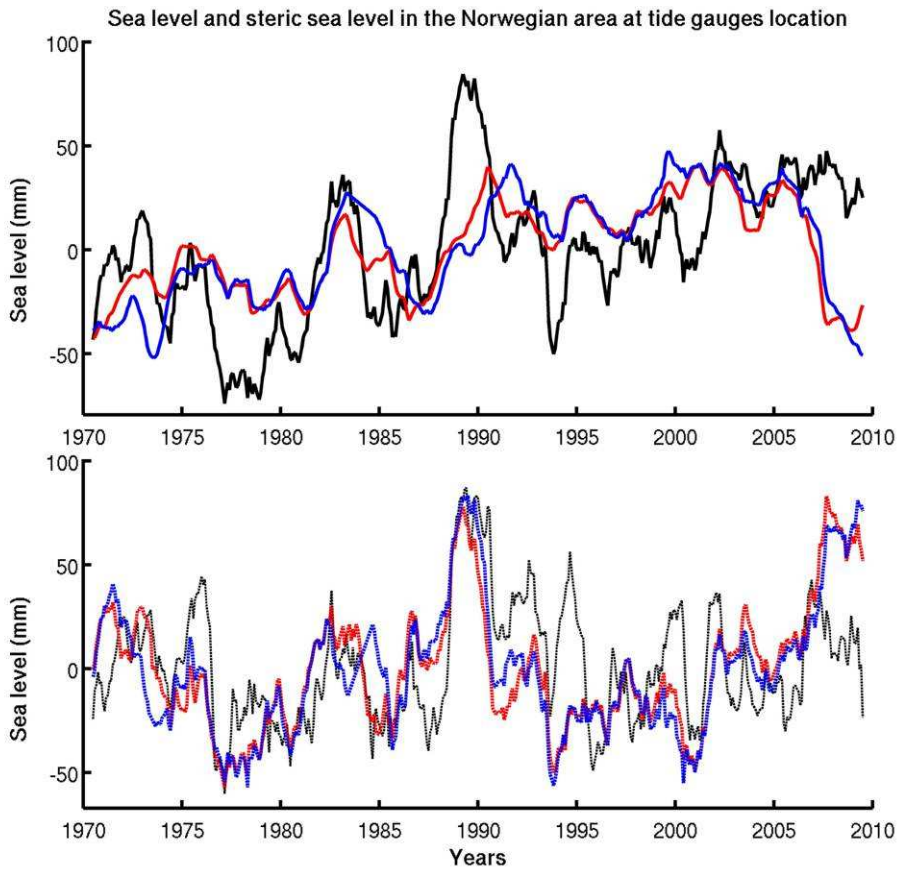

Fig.15: (a) Steric sea level curve (interpolated at the tide gauge sites, from Ishii and Kimoto 2009 in red and EN3 database in blue) along the Norwegian coast superimposed to the MSL curve (in black) over 1970-2009; (b) residual (observed minus thermosteric, in red with Ishii and Kimoto 2009, in blue with EN3 database) curve is also shown with the AO index superimposed (black dashed cuved).

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