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RESEARCH ARTICLE

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Key Points:
- Stable reconstruction obtained for the Arctic Ocean from tide gauge and satellite altimetry
- Datum-fit sea level reconstruction method is preferred to cumulative differences for Arctic Ocean
- Importance of virtual tide gauges away from coastal tide gauges in Arctic Ocean

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Stable reconstruction of Arctic sea level for the 1950–2010 period

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Abstract Reconstruction of historical Arctic sea level is generally difficult due to the limited coverage and quality of both tide gauge and altimetry data in the area. Here a strategy to achieve a stable and plausible reconstruction of Arctic sea level from 1950 to today is presented. This work is based on the combination of tide gauge records and a new 20 year reprocessed satellite altimetry-derived sea level pattern. Hence, the study is limited to the area covered by satellite altimetry (68°N and 82°N). It is found that time step cumulative reconstruction as suggested by Church and White (2011) may yield widely variable results and is difficult to stabilize due to the many gaps in both tide gauge and satellite data. A more robust sea level reconstruction approach is to use datum adjustment of the tide gauges in combination with satellite altimetry, as described by Ray and Douglas (2011). In this approach, a datum-fit of each tide gauges is used and the method takes into account the entirety of each tide gauge record. This makes the Arctic sea level reconstruction much less prone to drifting. From our reconstruction, we found that the Arctic mean sea level trend is around 1.5 mm $\pm$ 0.3 mm/yr for the period 1950–2010, between 68°N and 82°N. This value is in good agreement with the global mean trend of 1.8 $\pm$ 0.3 mm/yr over the same period as found by Church and White (2004).

1. Introduction

The primary record of historical decadal sea level change during the last century is tide gauges. Tide gauge records from around the world are collected in the Permanent Service for Mean Sea Level (PSMSL) database, and include data along the Arctic coasts. A reasonable amount of data are available along the Norwegian and Russian coasts since 1950, and most published research on Arctic sea level extends cautiously from these areas [e.g., *Proshutinsky et al*., 2004]. Very little tide gauge data are available elsewhere in the Arctic, and records of a length of several decades, as generally recommended for sea level reconstruction, are completely absent outside the Norwegian and Russian sectors.

Since the early 1990s, altimetric satellite missions have provided more spatially complete observations of sea level in the Arctic Ocean up to 82°N. This allows extraction of the primary sea level variation patterns, which can be used as calibration for sea level reconstruction of the Arctic Ocean. The altimetric record over the Arctic Ocean is sparse and inferior in quality to that of moderate latitudes, but nonetheless an extremely valuable data set. During this project, a new reprocessed 20 years Arctic altimetry record by *Cheng et al*. [2015], merging data from the three ERS-1, ERS-2, and Envisat mission has been used.

Due to the harsh environment, many Arctic tide gauges have been established in sheltered environments like in river mouth or even considerably up rivers. Consequently, these are not primarily representing Arctic sea level variation and careful editing of the tide gauges must be performed. Furthermore, a large proportion of the Russian-sector tide gauge records were discontinued around 1990, leaving a fairly sparse record after this. This project further examines the effect of introducing a subset of the altimetric data set as "virtual tide gauges" to remedy this sparsity in tide gauges after 1990. Introduction of this virtual data set further stabilize the reconstruction. Arctic sea level changes are particularly large in the Beaufort Gyre area north of Canada and Alaska, where there are no tide gauges [*Proshutinsky et al*., 2001]. Consequently, the introduction of satellite altimetry is particularly important to define the spatial patterns of the sea level change for the reconstruction. However, the reconstruction will rely on relatively stationary pattern before the altimetric era to some extent.

The Arctic Ocean, surrounding and including the North Pole, is a Mediterranean sea [see, e.g., *Tomczak and Godfrey*, 2005]. That is, it is an isolated sea with limited water exchange with the large oceans of the world;

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the major connection is the Fram Strait/Barents sea connecting the Arctic Ocean to the North Atlantic Ocean. Smaller connection to the Pacific Ocean through the Bering Strait and to the Atlantic Ocean through the Canadian Arctic Archipelago and Lincoln Strait to Greenland is also seen.

Large parts of the Arctic Ocean is covered by sea ice and the movement of this on seasonal to interseasonal scales is the result of wind forcing and the ocean circulation is mainly dominated by thermohaline forcing. *Volkov and Landerer* [2013] found that nonseasonal variations in Arctic Ocean mass (OcM) are mostly explained by wind forcing. Interestingly for sea level studies, *Volkov* [2014] finds a strong correlation between mass observations (from GRACE) and altimetry.

There are only few studies dealing with Arctic Sea Level rise over the last 50 period. *Proshutinsky et al*. [2001, 2004] used tide gauges to estimate that the Russian-sector sea level rose by 1.85 mm/yr for the period 1954–1989. The study attributes the rise to steric effects (35%), barometric contribution (30%), wind action (10%), and changing ocean mass (approximately 25%). In a study based on 62 tide gauges in the Norwegian and Russian sectors of the Arctic Ocean, Henry et al. (2012) also attempted to attribute the rise in sea level to its various contributions from river runoff and steric changes. They found that mean sea level seemed to be largely stable until 1980, after which an increasing trend of approximately 4 mm/yr was seen.

2. Tide Gauge and Altimetric Sea Level Data

2.1. Tide Gauges

The 102 tide gauges from the Permanent Service of mean sea level (PSMSL) [*Woodworth and Player*, 2003; *Holgate et al*., 2013] around the Arctic Ocean are shown in Figure 1. An overview of the availability of tide gauge records around the Arctic is given in *Plag* [2000].

A substantial problem with many of the Arctic gauges is their location in rivers-mouth and even in rivers which is illustrated in Figure 1. Due to harsh conditions tide gauges are frequently placed in a sheltered environment rather than facing the open ocean. The tide gauge Antipaiuta (69°N, 76°E) in the lower part of the right panel in Figure 1 is nearly 900 km from the Arctic Ocean (station 54 in Figure 2 below). Consequently, the sea level observations will be largely dominated by river runoff. Eight of the nine largest rivers contributing freshwater to the Arctic Ocean are located in the Russian sector. The Siberian rivers, Yenisei, Ob, and Lena, each provide up to 600 km^3 of water per year and the Canadian-sector Mackenzie River provides of the order of 340 km^3 per year [*Aagaard and Carmack*, 1989]. Consequently, it is of fundamental importance to carefully edit tide gauges which are affected by large rivers as they are dominated by outflow of freshwater during the melting season [*Svendsen*, 2015].

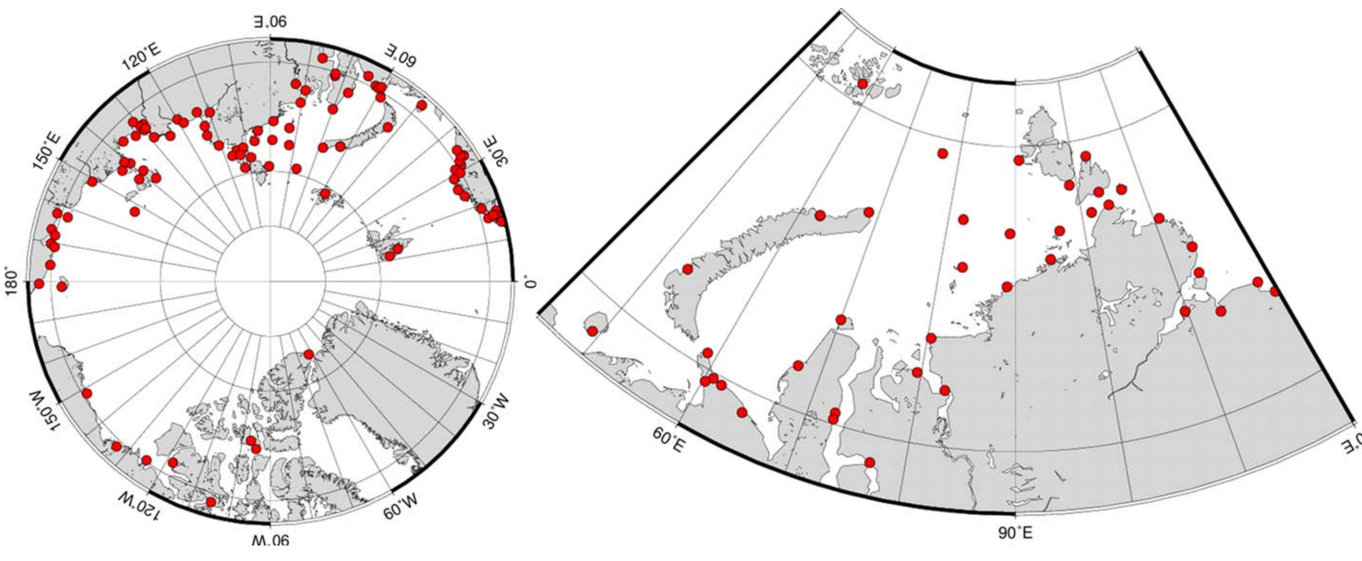

Figure 1. The study area in the Arctic Ocean with the location of all 102 tide gauges. The figure to the right is a close-up of the 37 gauges located in western Russia.

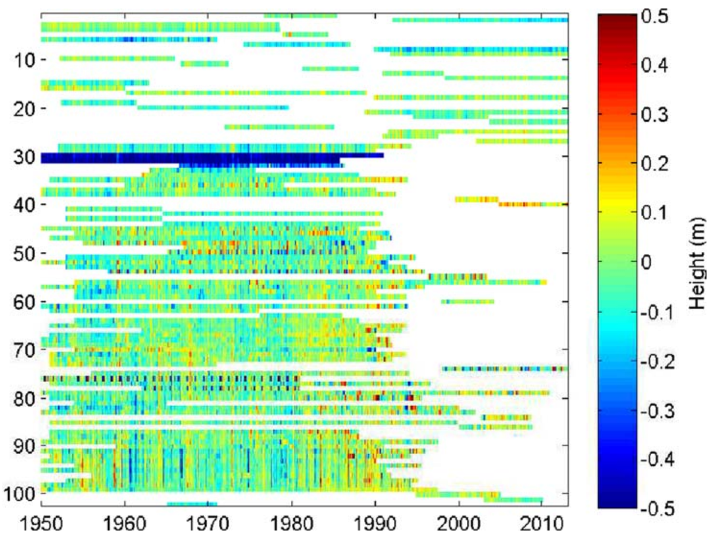

Figure 2. Monthly tide gauge observation from the 102 Arctic PSMSL gauges in meters. The labeling of the tide gauges increase with increasing PSMSL numbering (sepsmsl.org). The 19 Norwegian gauges appears with numbers (0–10 and 80–88) Canadian gauges with (95–102). Remaining gauges are Russian gauges.

Figure 2 illustrate the monthly tide gauge observations. Most tide gauges agrees on a sea level low during the late 1970s followed by higher sea level in 1980, but large differences are found. Gauges like 30–32 have offset of more than 50 cm. Gauges like 54 and 76 are typical Russian river mouth gauges dominated by annual outflow after the winter season melting. The closure of more than 80% of the Russian tide gauges after 1990 is clearly visible.

Empirical editing of the tide gauge was initially performed. Here gauges with an estimated linear trend larger than 2 cm/yr have been removed along with tide gauges with less than 5 years of data. This reduced the number of usable tide gauges from 102 to 69. This number is roughly similar to the number of gauges selected in studies by *Volkov* [2014], *Proshutinsky* [2004], and *Henry et al*. [2012].

In addition to the empirical editing an additional statistical approach based on leverage was applied. Leverage quantifies the influence of an observation/gauge on the following sea level reconstruction. It is normally important to remove tide gauges which are close in distance but different in influence. This removed an additional two stations resulting in 67 tide gauges for the reconstruction. More details on the empirical and leverage based editing and selected tide gauges can be found in *Svendsen et al.* [2015].

To make altimetry and tide-gauges comparable, in the sense of describing the same physical quantity, we need to apply inverse barometric correction for sea level pressure differences and Glacial isostatic Adjustment (GIA) corrections to the tide gauge data set. GIA is normally modeled as linear in time for the past 50 years. However, as noted by *Jevrejeva et al*. [2014], the choice of GIA model is extremely important when using Arctic gauges; they found a 17 cm difference (nearly 2 mm/yr) in accumulated sea level rise in the Arctic since 1925 simply by comparing results using the ICE-4G and ICE-5G models, respectively, with the former giving the highest increase in sea level. Similarly, the study by *Huang et al*. [2013] found variations in the GIA models in the Arctic Ocean of an order of the GIA correction itself.

We decided to use apply the GIA corrections using the recent ICE-5G model (v1.3 with the VM2 earth model [*Peltier*, 1998, 2004, 2015]). We here assume that the most recent version of the model is the most accurate version. The present-day predicted vertical rate of change for this model for each tide gauge is conveniently available from the PSMSL website.

The barometric corrections for the tide gauges were estimated using the HadSLP2 data set [*Allan and Ansell*, 2006] obtained from NOAA's Earth System Research Laboratory. The data set is a sea level pressure anomaly reconstruction on a 5° by 5° grid and interpolated to the tide gauge locations as well.

The term "virtual tide gauge records" will be used throughout the paper. These virtual tide gauges are simply the altimetry time series appearing as a "proxy" or virtual tide gauges for the period 1993–2010. These will be introduced to remedy for the fact that most Russian tide gauges in the Arctic Ocean were closed down around 1990. Our first attempts to Arctic sea level reconstruction from the few remaining tide gauges yielded very unrealistic reconstruction.

It is most logical to place the virtual gauges at the locations of the discontinued "true" tide gauges. Similarly, it is important only to replace the roughly 40 discontinued tide gauges with satellite altimetry and maintaining the rest of the tide gauges in order to control the possible datum shift that could appear if all gauges were replaced simultaneously with satellite altimetric observations.

An alternative approach is to simply augment the reduced tide gauges set after 1990 with random placed tide gauges throughout the Arctic Ocean derived from satellite altimetry after 1992. This stems from the fact that the largest long-term sea level variability in the Arctic Ocean is concentrated in areas far from the coasts like in the Beaufort Gyre and hence this would have a stabilizing effect on the reconstruction. Consequently, we investigated both the option of replacing the roughly 40 discontinued tide gauges with colocated altimetry-derived time series and adding 50, 100, or 200 randomly spaced "virtual" tide gauges from 1993 to the reduced tide gauge set after 1990.

2.2. Satellite Altimetry

While TOPEX/Poseidon and the Jason missions do not cover latitudes higher than 66°, the European Remote Sensing satellites (ERS-1, ERS-2, and Envisat) had orbital inclinations of 98.5° resulting in altimetry up to 81.5°N. Recently, Cryosat-2 has started providing satellite altimetry up to 88°N. However, the temporal record for this satellite is yet not long enough for this study.

Satellite altimetry is, e.g., available through archives like PODAAC, AVISO, and RADS. However, altimetry within these archives is generally edited using "standard" editing on various parameters [e.g., *Andersen and Scharroo*, 2011]. The lack of data in the interior of the Arctic Ocean is most likely the reason why altimetry has not previously been used for sea level reconstruction. It was found by *Cheng et al*. [2015] that in large parts of the interior of the Arctic Ocean the number of altimetric observations could increase up to several folds if these standard editing criteria were substituted with editing criteria tailored to high-latitude Arctic conditions without degrading the accuracy of the derived sea level anomalies. Hence, we decided to use this weekly data set initially creating a 1° by 1° monthly grid of sea level grids for the Arctic Ocean.

The temporal coverage of the Arctic Ocean altimetric data set is shown in Figure 3. The left figure shows the percentage of the 20 year sea level record available to the sea level reconstruction. For the interior of the Arctic Ocean (east of Nova Zemlya) the data availability is of the order of 10–40% in this reprocessed data set where it is 0–10% in standard archives like RADS and AVISO data sets. In this part of the Arctic Ocean data availability will be largely seasonal with the majority of the data in the summer. West of Nova Zemlya in the open Barents Sea and North Atlantic the data availability is generally close to 100%. Results from one of the initial sanity tests comparisons satellite altimetry with the tide gauge Izvestia Tsik located at 75.9°N, 82.9°E in the Kara Sea. Such comparisons are important to justify that historical reconstruction is possible. In this comparison there is only a few points missing in the altimeter record, and the tide gauge are highly correlated (0.79) agreeing on the trend to 0.1 mm/yr over the altimetry era.

Initially, the altimetric data set was used to compute the leading Empirical Orthogonal Functions (EOF) and spatial patterns for the Arctic Ocean. Figure 4 shows the eight leading EOFs which represent more than 50% of the variance in the altimetric sea level record and which was chosen for this study. We experimented with various numbers of EOF but in the impact of including more than eight modes were insignificant. This is partly because the altimetry sea level record is relatively noisy and it takes 80 EOF to represent

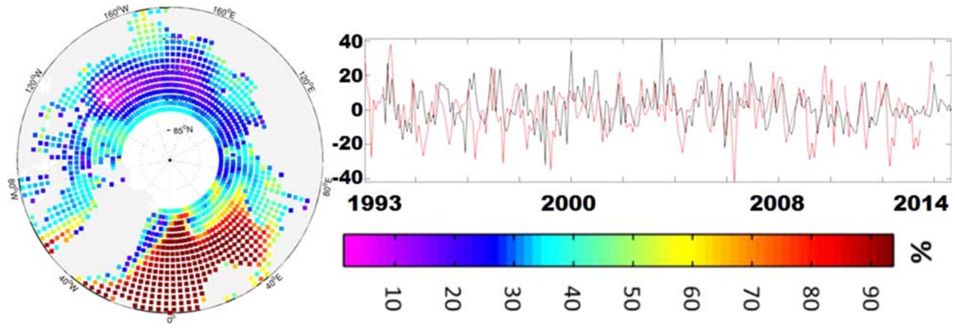

Figure 3. The figure to the left shows the percentage of the 20 year reprocessed altimetric data record available to the reconstruction on a monthly basis. The figure to the right shows the comparison between monthly satellite altimetry (red) and the IzvestiaTsik tide gauge in the Kara Sea.

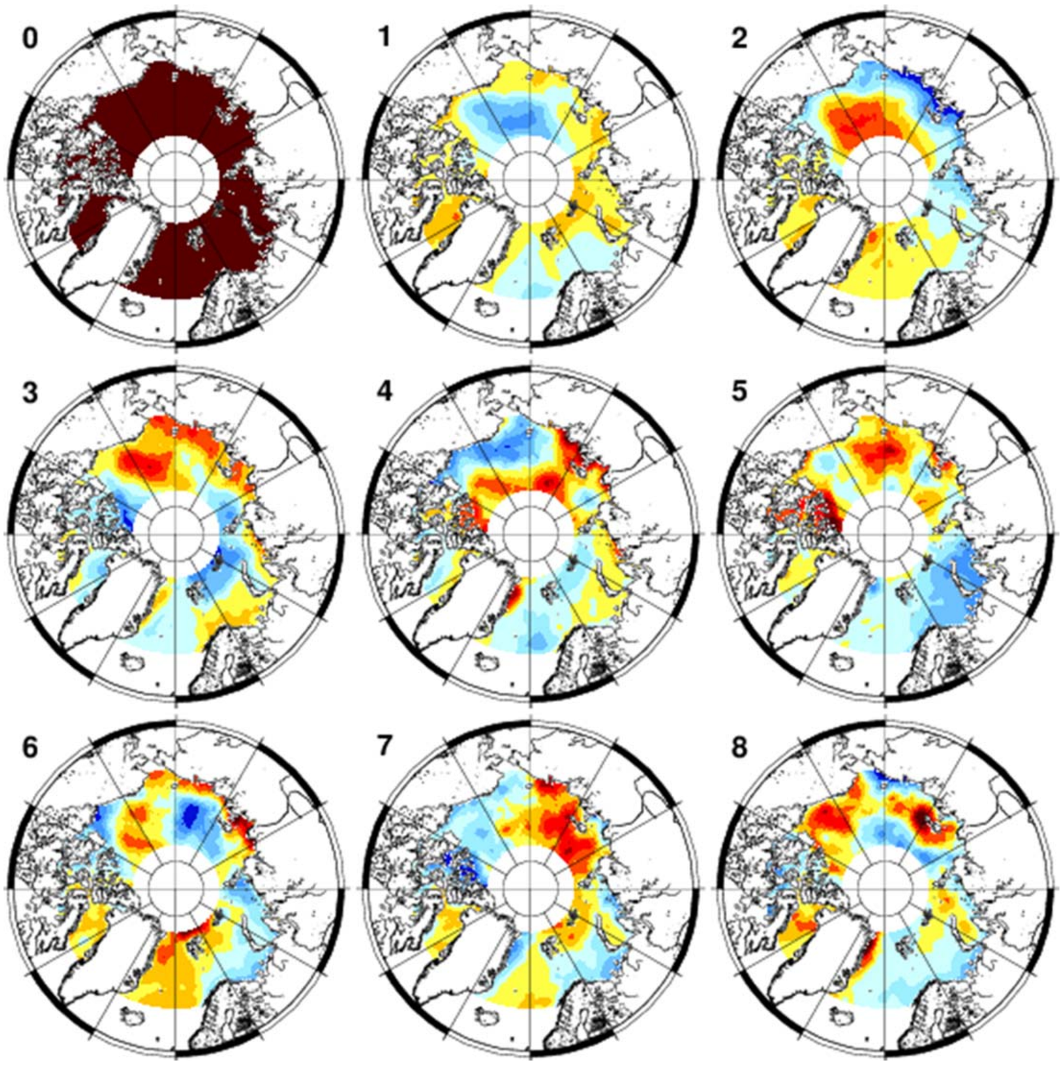

Figure 4. The leading eight EOFs (EOF1-EOF8) derived from satellite altimetry data between 68°N and 82°N. Besides these eight EOFs an additional EOF0 was introduced as a constant for the region. The scaling for the EOFs is arbitrarily.

95% of the sea level variance. The EOFs 1–3 clearly reveals the general circulation pattern in the Arctic Ocean with the North Atlantic Water entering into the Arctic and the Beaufort Gyre to the North of Canada. Furthermore, the east Siberian coastal current is seen. Particularly, EOF 2, 3, and 6 shows a strong coastal component along the East Siberian coast. It should be noted that the scaling and sign of the EOFs are arbitrary.

3. Reconstruction Strategies

Sea level reconstruction is usually carried out using an ordinary least squares regression (OLS). Assuming two data sets to be related by a linear equation, one may obtain the parameters for that linear equation through regression. Defining a response variable y (the sea level observations), a multivariate predictor X and model parameters α, the regression equation becomes

$$y = X\alpha + e, \quad (1)$$

where e are the residuals. We seek to obtain the "best" estimate for α hence minimizing e. The canonical technique for satellite and tide gauge-based sea level reconstruction was established in *Church et al*. [2004] and applied in various reconstruction studies such as *Berge-Nguyen et al*. [2008], *Calafat et al*. [2014], *Church* *and White* [2011], *Hamlington et al*. [2011], *Jevrejeva et al*. [2014], *Llovel et al*. [2009], and *Meyssignac et al*. [2012].

The EOF decomposition of 1993–2010 altimetry data (calibration grid) yields spatial patterns that are fitted to tide gauge records (the predictor X). The fit is made using an optimal interpolation (OI) technique described in *Kaplan et al*. [1997, 1998, 2000]. To capture changes in mean sea level, the set of EOFs are is augmented with a uniform pattern, i.e., a column of ones in X, called "EOF0." Globally, the inclusion of a spatially uniform pattern is crucial to an accurate reconstruction of global mean sea level [*Christiansen et al*., 2010]. For local reconstructions, the pros and cons of including the EOF0 in reconstruction was discussed by *Calafat et al*. [2014].

This leaves the issue of which corresponding "eigenvalue" to use; we have used the same value as for EOF1 similar to *Church et al*. [2004], see below.

In the canonical reconstruction we shall solve for sea level coefficients $\alpha(l \times M)$, that is, a scalar coefficient for each eigenfunction per time step or temporal points M of the (tide gauge) data set, while spatially covering the leading eigenfunctions in the data set.

Minimizing the cost function, one obtains the solution for α,

$$\alpha = P\ E^T H^T R^{-1} G, \tag{2}$$

where

$$P = (E^T H^T R^{-1} H\ E + \Lambda^{-1})^{-1}. \tag{3}$$

$R(N \times N)$ is the error covariance matrix, that is, the sum of the observation error covariance and the truncation error. For simplicity, R is set to a diagonal matrix with its nonzero elements set at 3 cm based on investigation of the data.

In *Christiansen et al*. [2010], only the truncation error contribution is considered whereas *Kaplan et al*. [1997] note that nonindependence in the observational error would increase the effective observation error but that they had no information substantially suggesting anything but independence which we also assume. $H(N \times N)$ is the indicator matrix which is zero everywhere, except at $H(j,k) = 1$ where j is the tide gauge index and k is the index of its closest pixel in the calibration grid. Λ contains the selected eigenvalues. The data matrix $X(n \times m)$ contains height at n grid points, sampled at m points in time (1993–2010). Data matrix $G(N \times M)$ contains height at N tide gauges, sampled at M points in time (1950–2010).

A detailed description of the reconstruction technique and its adaptation to the Arctic Ocean is available online from *Svendsen* [2015].

A significant adaptation of the technique from *Church et al*. [2004] is necessary when reconstructing Arctic sea level, as the tide gauge records are short and scattered compared with other tide gauges in the global ocean. In the approach by *Church et al*. [2004] they demanded continuous time series throughout the period 1950 to today. However, this is not possible in the Arctic Ocean. Consequently, the technique had to be adapted to allow for sparse and incomplete data matrices as input to the reconstruction. Similarly, the estimation of the covariance matrix R has to be adapted so that it was only computed from available (incomplete) data. To extract as much information as possible from the tide gauge data set, we solve for the α coefficients once per time step (rather than all at once), introducing the time-variable H matrix above to selects only the available tide gauges whenever these are available.

As tide gauges generally suffer from a lack of robust, absolute vertical reference, the tide gauge records are provided with individual, unknown vertical data. *Church et al*. [2004] solved this by using the differences between neighboring time steps of the tide gauge records and fitting to those, then integrating the α coefficients in time to obtain the reconstruction. In the following this method is referred to as cumulative differences.

A different reconstruction approach is discussed in *Ray and Douglas* [2011]. In their method no differencing and accumulation is used. Instead, they use the original tide gauge records and solves for the vertical datum of each individual tide gauge as part of the solution. In the following this method is referred to as the datum-fit method. This was developed to address the integration error that can accumulate as one goes back in time, as nothing forces the reconstruction back to reality when errors appear in equation (2).

Temporal outages in the tide gauges or vertical datum shifts in the time series from (e.g., replacement/repair of the tide gauge) needs careful handling in both methods. A straight forward method is to split the affected tide gauge in two, if either a temporal outage larger than a certain time is found, or if a vertical offset larger than a certain amount is encountered. Here we included a study of the effect on the sea level reconstruction accounting for vertical outages longer than 6 month and vertical jumps larger than ±25 cm.

4. Reconstruction Result

A number of parallel reconstructions were made for the Arctic to compare results using cumulated differences [as *Church et al*., 2004] and a reconstruction using the vertical datum-fit method [*Ray and Douglas*, 2011]. In total, nine different reconstructions were tested for the Arctic Ocean and compared in order to find the most stable reconstruction.

These nine reconstructions were the following: (1) reconstruction using EOF0 alone [*Calafat et al*., 2014]; (2) reconstruction using 8 EOF from altimetry and including regularization; (3) reconstruction without regularization of the EOFs [*Christiansen et al*., 2010]; (4) reconstruction using annual data instead of monthly data; (5–7) reconstructing using 50, 100, or 200 randomly spaced virtual tide gauges, respectively, and (8) splitting tide gauges for time gaps larger than 6 month and (9) splitting tide gauges for datum shifts larger than ±25 cm.

Subsequently, the reconstructed sea level were spatially integrated over the Arctic Ocean region between 68°N and 82°N to yield a monthly averaged 60 year time series as shown in Figure 5.

Figure 5 shows that reconstruction using the cumulative method by Church and White is very sensitive to the various choices in the reconstruction. For the cumulative method the reconstruction based on EOF0 gives a stable reconstruction in the Arctic Ocean. Nearly all other choices of parameters and settings lead to significant different sea level reconstruction. Particularly after the 1990 period, a lot of the Russian tide gauges ceased operation. The reconstruction is particularly sensitive to the regularization or stabilization [*Kaplan et al*., 1998] as shown in the green curve.

It is particularly interesting that the use of annual means (blue curve) gives the most stable reconstruction. This is in agreement with the investigation by *Svendsen et al*. [2015] and *Svendsen* [2015] who demonstrated that even after a careful editing some Russian shorter seasonal data outages in the winter is very critical to the cumulative method. The problem being that these outages typically happen during the same time of year. Hence, it is always the same part of the annual sea level signal that is being missed, and the cumulative integration might be biased because small thermo-steric sea level changes in the annual signal are systematically

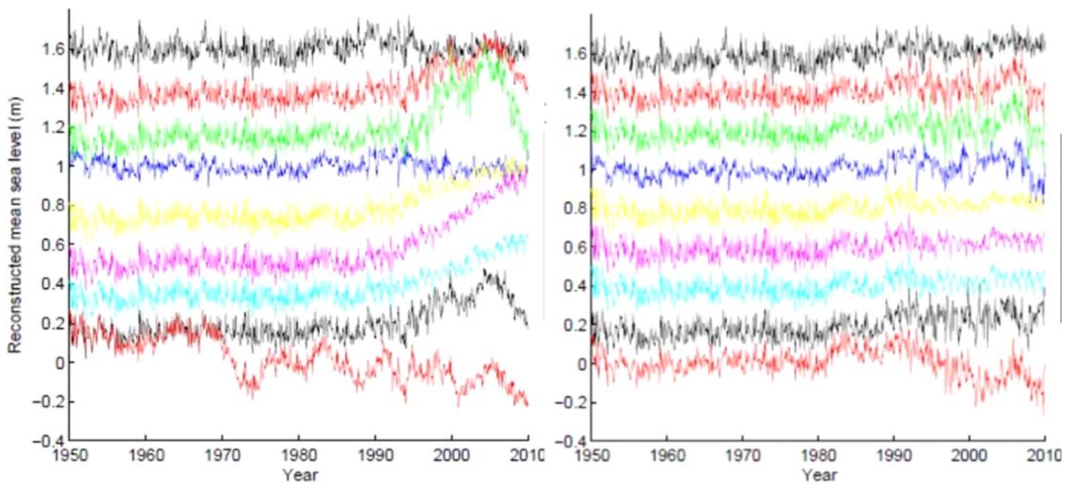

Figure 5. Spatially integrated sea level for nine parallel reconstructions for the Arctic Ocean using the cumulated difference methods by Church and White (left) and the datum-fit estimation by Ray and Douglas (right). From top to bottom the nine reconstructions are in black: reconstruction based on EOF0 only; red: based on EOF0-8; green: no regularization applied; blue: using annual tide gauge data; yellow: adding 50 virtual tide gauges; purple: adding 100 virtual tide gauges; cyan: adding 200 virtual tide gauges; dark gray; tide records split at temporal gaps and brown; tide gauge records split at vertical jumps.

Table 1. Linear Trend in Arctic Sea Level Reconstructions Using Different Methods and Number of Virtual Tide Gauges During the Altimetry Era[a]

	Nb Virtual Gauges	Linear Trend (1950–2010) mm/yr	Linear Trend (1993–2012) mm/yr
Cumulative differences (Church and White)	0	4.3 ± 0.4	3.3 ± 2.1
	50	5.3 ± 0.4	11.6 ± 0.9
	100	7.8 ± 0.4	23.6 ± 0.8
	200	5.0 ± 0.4	15.1 ± 0.8
Datum fit (Ray and Douglas)	0	1.5 ± 0.3	2.3 ± 2.4
	50	1.5 ± 0.3	2.0 ± 1.0
	100	1.5 ± 0.3	1.8 ± 1.1
	200	1.5 ± 0.3	1.8 ± 1.2

[a]The first column gives the trend for the past 60 years whereas the second column shows the trend for the altimetry era (20 year).

missed out. It is obvious that if the method by Church and White should be successfully applied in future reconstructions in latitudes, it is very important to base the reconstruction on annual means and controlling if data outages are systematic and or periodic.

The datum-estimation reconstruction by Ray and Douglas seems to give much more stable results for nearly all reconstructions tested. However, when splitting the tide gauges into independent gauges at any vertical jumps larger than ±25 cm additional degrees of freedom in the datum-fit reconstruction is introduced. This is consequently clearly seen to disrupt the reconstructed mean sea level curve, both when using cumulated time step differences and the datum-fit method. However, splitting the tide gauges in individual tide gauges at gaps in the time series longer than 6 month seem to have far less effect, but still some significant effect in the most recent part of the reconstructed sea level record.

The inclusion of a number of randomly located virtual tide gauges from 1993 onward clearly seems to have a stabilizing effect on the reconstruction. While the inclusion of the virtual gauges makes a significant difference compared to not including them, the overall trend of the reconstruction does not appear very sensitive to the number of virtual gauges used.

In order to further evaluate the effect of the inclusion of the virtual tide gauges on the various reconstructions, the linear sea level trends for 1960–2010 period and for the altimetry era (1993–2012), using the cumulative difference (Church and White) and datum-fit (Ray and Douglas) method with different numbers of virtual gauges in the altimetry era, are given in Table 1.

It is readily seen that the use of virtual gauges with the cumulative difference method yields some large trends in mean sea level indicating how these affect the sea level reconstruction in particularly the altimetry era when they are used.

The results are remarkably robust when using the datum-fit approach and this method seems to stabilize the sea level reconstruction. While the reconstruction with no virtual gauges provides MSL trend estimates consistent with those including virtual gauges, the trend uncertainty becomes much lower (approximately ±1.1 mm/yr rather than ±2.4 mm/yr). Furthermore, the altimetry-era trends are consistent with *Cheng et al.* [2015], which found a mean sea level trend of 2.1 ± 1.3 mm/yr (66°N–82°N). This is also to be expected as these data are now entering the reconstruction with larger and larger influence with increasing number of virtual tide gauges.

In the investigation above the virtual tide gauges were placed at random locations throughout the Arctic Ocean from an argument that it stabilize the reconstruction. Figure 6 shows the result of various combinations of location of virtual tide gauges in a datum-fit reconstruction for the 1990–2010 period. In Figure 6 the black curve shows the averaged altimetric data having a linear trend of 2.1 mm/yr for the Arctic Ocean for the 1993–2010 period. The red curve represents a reconstruction based on tide gauges alone and no virtual tide gauges. Hence, the discontinuation of many Russian tide gauges is seen to result in a relative noisy reconstruction. The green curve represents a reconstruction that uses 50 randomly located virtual tide gauges. The blue curve uses altimetry to represent sea level observations at the 40 discontinued Russian tide gauges. The final purple reconstruction uses 50 randomly located virtual tide gauges and replacing the 40 discontinued tide gauges with virtual altimetry gauges. In general, all the reconstruction using virtual altimetric-derived tide gauge information at 40 discontinued gauges yields a linear trend of 1.6 ± 1.0 mm/yr for the 1993–2010 period. This number should be compared with 2.0 ± 1.0 mm/yr for the reconstruction using 50 randomly placed tide gauges and 2.1 mm/yr for the altimetric averaged trend. For the 1950–2010 period the 40 gauge replacement reconstruction was 1.3 ± 0.3 mm/yr.

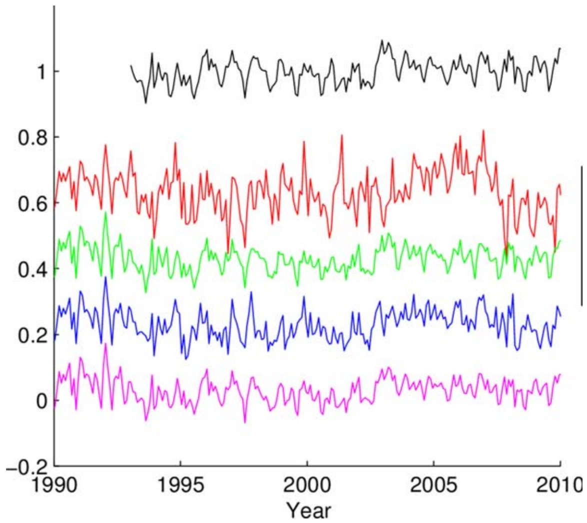

Figure 6. Averaged Arctic Sea level from several datum-fit reconstruction (axis is in meters and each curve is offset by 20 cm). Black is the averaged altimetric data; red curve represent a reconstruction based on tide gauges alone; green curve represent a reconstruction which uses 50 randomly located virtual tide gauges; blue uses altimetry at 40 discontinued Russian tide gauges and purple uses 50 random virtual tide gauges and at the 40 discontinued tide gauges.

The reconstruction appears more inaccurate when not introducing virtual tide gauges as shown with the red curve. This results in a linear trend of −0.6 mm/yr over the 1993–2010 period indicating the importance of the virtual tide gauges.

The effect of including virtual tide gauges is seen in Figure 7. Decadal sea level means relative to an arbitrarily MDT of reconstructed sea level in the Arctic Ocean using no or 50 random located virtual tide gauges is shown using the datum-fit method (Ray and Douglas). The upper row gives the decadal mean for 1950s (left) and 2000s (right) based on a reconstruction without virtual tide gauges and the lower figures based on a reconstruction using 50 virtual tide gauges. The difference between the 1950s and 2000s decadal means is much larger for the reconstruction without virtual tide gauges and in our view unrealistic indicating decadal changes at the 1 m scale for several locations. The differences for the reconstruction that uses virtual tide gauges is far smaller indicating that this is one possible way to obtain a stable Arctic sea level reconstruction and one way to circumvent the unfortunate fact that most Russian tide gauges were discontinued

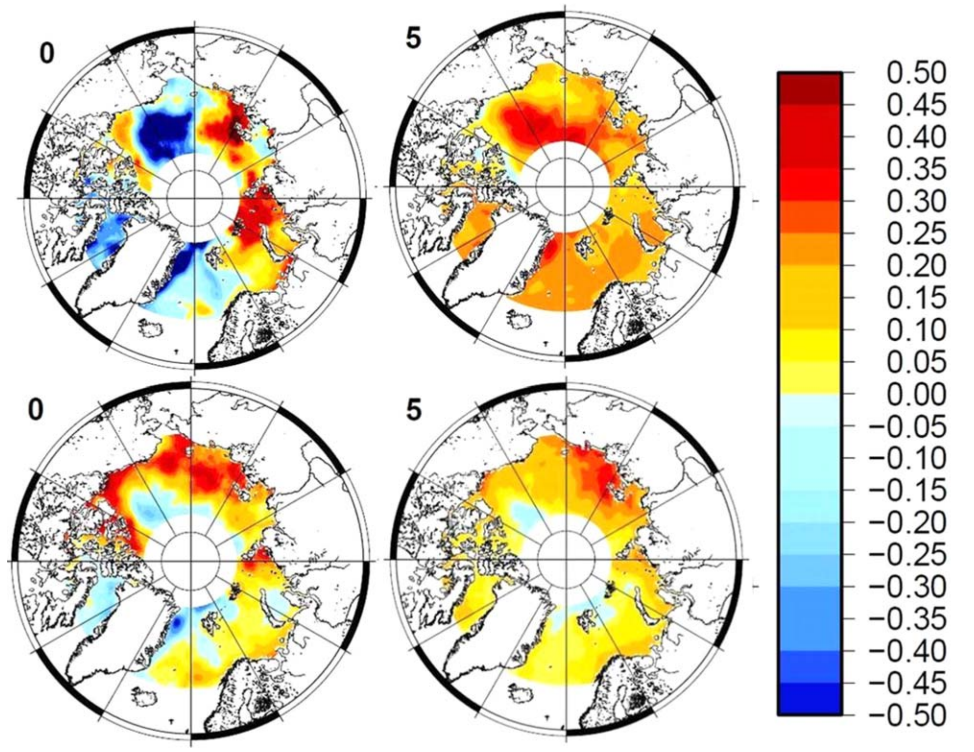

Figure 7. Decadal sea level means relative to an arbitrarily MDT of reconstructed sea level in the Arctic Ocean using the datum-fit method (Ray and Douglas). The upper row gives the decadal mean for 1950s (left) and 2000s (right) based on a reconstruction without virtual tide gauges and the lower figures based on a reconstruction using 50 randomly located virtual tide gauges. Values are given in meters.

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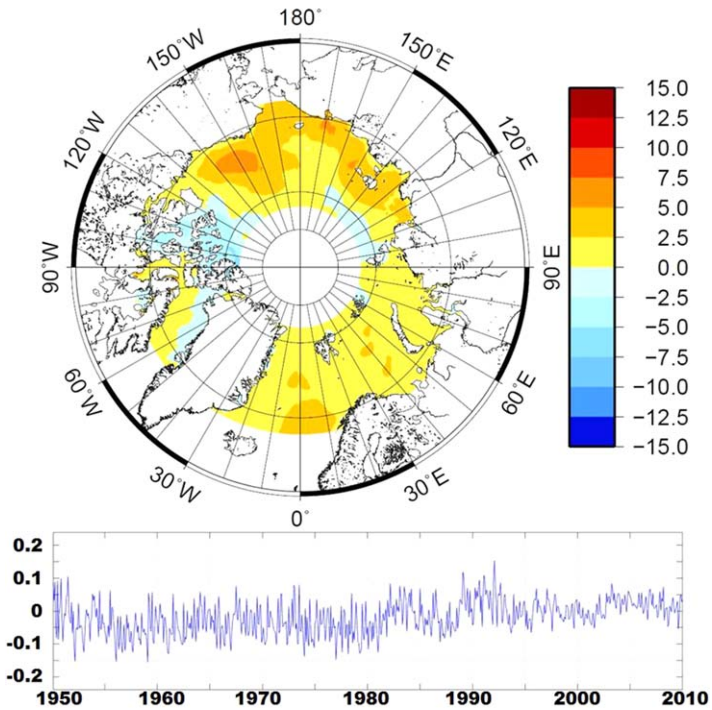

Figure 8. Spatial pattern of sea level trend for the 1950–2010 period in mm/yr based on the datum-fit estimation (Ray and Douglas) stabilized using 50 virtual tide gauges after 1993. EOF0 through EOF8 have been used. The lower monthly sea level curve corresponds to the temporal variations for the spatial sea level patterns.

in the early 1990 at the same time as satellite altimetry became available making sea level reconstruction based on a combination of these very difficult.

Combining the results shown in Figures 6 and 7 demonstrate the importance of including virtual tide gauges to stabilize the sea level reconstruction and particularly the spatial pattern throughout the Arctic Ocean up to 82°N. We are not able to judge if the reconstruction becomes more accurate if the virtual tide gauges are put at the sites of the discontinued Russian tide gauges or randomly space throughout the Arctic Ocean. A significant part of the sea level variability happens far from the coast (i.e., in the Beaufort Gyre) and our investigations also points toward a slightly more stable spatial pattern when placing the virtual tide gauges at random location throughout the Arctic Ocean. Increasing the number of virtual tide gauge to more than 50 did not have a significant effect on the reconstruction, so we decide to take the most cautious approach and only use 50 virtual tide gauges as this roughly correspond to the number of discontinued tide gauges after 1990.

The linear sea level trend from the reconstructed sea level for the 1950–2010 period is shown in Figure 8 with values given in mm/yr. This is the most reliable reconstruction we have found for the Arctic Ocean and the one we believe to be the best.

The reconstruction includes 50 random virtual tide gauges after 1993 based on satellite altimetry. In the left figure the reconstruction based on cumulated differences (Church and White) in the left figure and from the datum-fit estimation (Ray and Douglas) in the right figure. In both cases EOF0 through EOF8 have been used. The yellow averaged monthly sea level curve in Figure 5 corresponds to the temporal variation for this spatial pattern.

The spatial patterns are similar in reconstruction based on cumulative differences (Church and White) and datum-fit method (Ray and Douglas); however, the values are far more extreme in the cumulative difference approach and in the datum-fit method. The spatial pattern reveals positive anomalies corresponding to an increase in sea level in the Beaufort Gyre and along the East Siberian coast over the past 60 years. In general, the entire North Atlantic part of the Arctic Ocean is also positive as also seen in global studies like *Nerem et al*. (2010). The Baffin Bay between Greenland and Canada exhibit roughly zero trend in the datum fit reconstruction, and only the waters within the Canadian Arctic Archipelago are negative in both reconstructions. However, coastal effects and the presence of heavy sea ice in these regions mean that these results should be considered with caution.

The GIA correction is considered to be an uncertainty issue. Recently, a new GIA model called ICE-6G was released [*Peltier et al*., 2015]. We used this model to investigate the sensitivity to the choice of GIA model. It was found that correcting for GIA using the ICE-6G instead of the ICE-5G generally increases the trend during both periods with 3 mm/yr corresponding to trends of 2.3 mm/yr for the 1993–2010 period and 1.8 mm/yr for the 1950–2010 period.

5. Comparison With Other Arctic Sea Level Studies

In a study of mainly tide gauges, *Proshutinsky et al*. [2002, 2009] found that freshwater content in the Beaufort Gyre region had little interdecadal variation in the period 1950–1980. It therefore makes sense to compare reconstructed sea level for later periods with this time interval. Similar stationary pre-1980 conditions were found by *Pavlov* [2001] and *Proshutinsky et al*. [2001] and as such these conditions provide a basic reference (near-zero trend) against which to compare the trends in the reconstruction.

In order to compare with the findings by Proshutinsky and Pavlov from tide gauges, we compute the decadal means using the two reconstruction methods for the six decades (1950–1959, 1960–1969, . . .) and so forth. We subsequently computed the decadal difference with the 2000–2009 period. These are shown in Figure 9.

Indeed, the decadal means shows very little variations in the first three decades similar to the work by *Proshutinsky et al*. [2001, 2009], and *Pavlov* [2001]. This gives good faith in the sea level reconstruction. During particularly the altimetry era past 1990 large changes in the Beaufort Gyre and along the Coast of Russia is found. This is also in good agreement with the results by *Giles et al*. [2012] who presented sea level trends, derived from retracked altimetry, for the period 1995–2010. In particular, Giles et al. obtaining a 2 cm/yr trend in the Beaufort Gyre area and near-zero trends elsewhere. Through studies of satellite altimetry and wind fields, they demonstrated that this increase in the trend over the Beaufort Gyre can be explained by a wind-driven spin-up of the Beaufort Gyre from continuous satellite measurements of SSH between 1995 and 2010.

In our reconstruction as presented in Figures 6–8 we do not see such a dramatic trend as in *Giles et al*. [2012]. However, we see a clear trend in the Beaufort gyre larger than 1 cm/yr on average for the 1990–2010 period. This can also be seen in the lower figures of Figure 9 of the 2000–2009 decadal means.

The reconstruction for the Canadian Arctic Archipelago (CAA) should indeed be considered with caution and visual inspection of Figure 9 indicates that the decadal pattern behave in an opposite pattern to most other parts of the Arctic Ocean. A closer inspection of both altimetry and tide gauge data in the CAA region showed that both data sources are very scattered and noisy. Even more so than in many other parts of the Arctic Ocean. We alternatively performed a datum-fit reconstruction with 50 virtual tide gauges and blanked

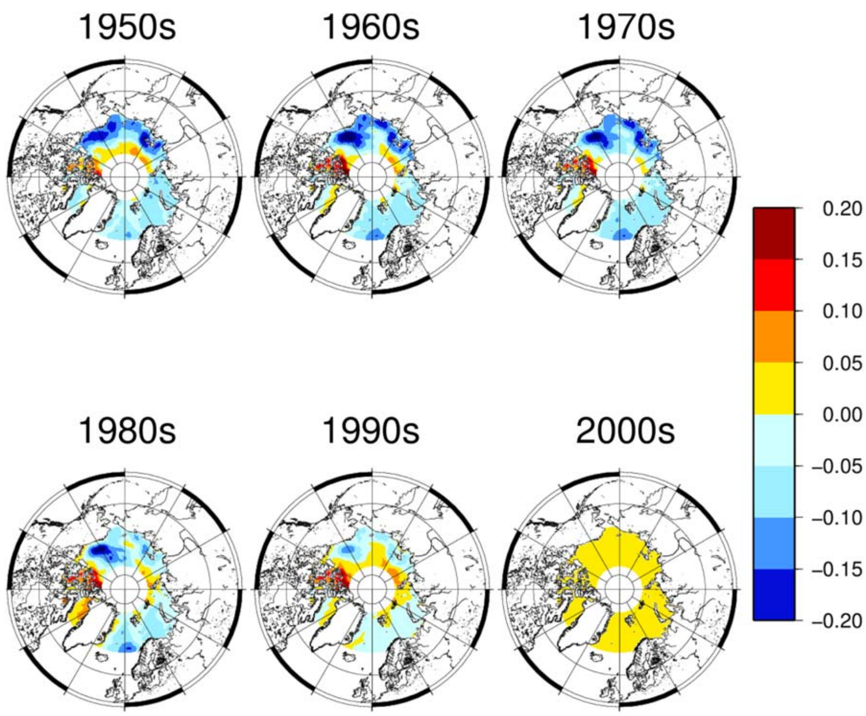

Figure 9. Decadal means of sea level variations in the Arctic Ocean from the datum-fit reconstruction method (Ray and Douglas) as described in the preceding sections. Decadal means are given in meters relative to the 2000–2009 period.

out the CAA. We obtained a slightly larger overall sea level trend which for the 1950–2010 period of 1.8 ± 0.3 or 0.3 mm/yr larger than our "best" estimate of 1.5 mm/yr. This value is actually in better agreement than the 1.5 mm/yr with the global mean trend of 1.8 ± 0.3 mm/yr for 1950–2000, as found by *Church et al*. [2004].

6. Conclusions

Reconstructing historical Arctic sea level is a considerable challenge, due to the relatively small amount of usable data. Previous analyses of Arctic sea level going back to the 1950s have dealt only with areas close to the Norwegian and/or Russian coasts. Here we attempt to extend the area coverable in such reconstructions, such that the western Arctic and the deeper areas of the Arctic Ocean can be handled with plausible results.

In attempting to screen the Arctic tide gauges it was found that empirical trend-based criteria (±2 cm/yr) provide reasonable stability in terms of reconstructed regionally averaged sea level. However, further refinement as described in *Svendsen et al*. [2015], using leverage was also suggested. GIA uncertainties are a major issue for the Arctic area. Replacing the ICE-5G with ICE-6G gives a sensitivity estimate to the choice of GIA model. We found reconstructed sea level trend differences of 0.3 mm/yr level for both the 1950–2010 period and the 1993–2010 period, but the ICE-5G model and ICE-6G are not independent. Therefore, the choice of GIA model merits further attention.

The precise number of EOFs to retain in the reconstruction may be a matter of choice; the Beaufort Gyre freshwater content will generally be expressed in EOF1. The altimetric sea level record is fairly noisy and up to 80 EOF should in principle be applied to explain 95% of the variance. However, we experienced only marginal difference in the resulting reconstruction using more than a handful of EOFs. For this project, eight spatial patterns was retained along with a constant pattern, as these explains more than 50% of the variance

Using the cumulated month-to-month sea level differences as introduced by *Church and White* [2004] can produce a reasonably stable reconstruction for the Arctic when using only the constant pattern in EOF0 or when using annual Arctic sea level values only. However, the method was shown to be prone to exaggerating the sea level trends in areas far from the tide gauges. Unrealistic trend was seen in the Beaufort Gyre and around Greenland, when using more EOFs and monthly sea level anomalies. This is likely due to shorter seasonal gaps in both satellite altimetry but also in many tide gauge records due to sea ice during winter. The fact that Arctic tide gauges are frequently located within or close to the large Siberian rivers with huge seasonal outflow will also create unrealistic accumulated sea level variations.

The datum-fit sea level reconstruction method (Ray and Douglas) produces very stable Arctic linear sea level trend of around 1.5 ± 0.3 mm/yr for the period 1950–2010, between 68°N and 82°N. This value is also in good agreement with the global mean trend of 1.8 ± 0.3 mm/yr for 1950–2000, as found by *Church et al*. [2004].

We found some suspicious behavior of the sea level reconstruction over the Canadian Arctic Archipelago in all reconstructions due to very noisy data in this region, so we suggest that this region is considered with caution.

Generally, the datum-fit method proved far more stable results considering that both altimetry and tide gauges frequently suffers from seasonal gaps in the time series. Sometimes datum shift appears within tide gauge records due to repair/change of the gauge. To remedy the effects of datum shifts in the tide gauges, we investigated different empirical criteria for detecting these, and split the record into two "tide gauge" records at these suspected datum shifts. Splitting at gaps in the time series seems to have little effect, while splitting at jumps of more than ±25 cm considerably destabilizes the reconstruction. Thus, it appears the splitting of tide gauges should be reserved for known or very strongly suspected datum shifts only.

This investigation also demonstrated the importance of intruding virtual tide gauges to stabilize the sea level reconstruction and particularly the spatial pattern throughout the Arctic Ocean up to 82°N. We are not able to judge if the reconstruction becomes more accurate if the virtual tide gauges are put at the sites of the discontinued Russian tide gauges or randomly space throughout the Arctic Ocean. However, our investigations point toward a slightly more stable spatial pattern when placing the virtual tide gauges at random location throughout the Arctic Ocean.

For future studies of Arctic sea level reconstruction, it appears reasonable to recommend the datum-fit approach in combination with altimetry EOFs. The effects of inclusion of virtual tide was proven important and seems to provide considerable extra stability for the post-1990 period for the datum-fit reconstruction method by Ray and Douglas consolidating the trend for the altimetric period (1993–2010) at 1.8 mm $\pm$ 0.3 mm. However, the use of virtual tide gauges provided little or no stability to the accumulated difference method by Church and White.

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