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Absolute sea level variability of Arctic Ocean in 1993–2018 from satellite altimetry and tide gauge observations

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Abstract

Arctic absolute sea level variations were analyzed based on multi-mission satellite altimetry data and tide gauge observations for the period of 1993–2018. The range of linear absolute sea level trends were found –2.00 mm/a to 6.88 mm/a excluding the central Arctic, positive trend rates were predominantly located in shallow water and coastal areas, and negative rates were located in high-latitude areas and Baffin Bay. Satellite-derived results show that the average secular absolute sea level trend was (2.53±0.42) mm/a in the Arctic region. Large differences were presented between satellite-derived and tide gauge results, which are mainly due to low satellite data coverage, uncertainties in tidal height processing and vertical land movement (VLM). The VLM rates at 11 global navigation satellite system stations around the Arctic Ocean were analyzed, among which 6 stations were tide gauge co-located, the results indicate that the absolute sea level trends after VLM corrected were of the same magnitude as satellite altimetry results. Accurately calculating VLM is the primary uncertainty in interpreting tide gauge measurements such that differences between tide gauge and satellite altimetry data are attributable generally to VLM.

Key words: Arctic Ocean, absolute sea level variability, sea level anomaly, satellite altimetry, tide gauge

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1 Introduction

Sea level is a naturally integrative indicator by which to understand and monitor climate change (Proshutinsky et al., 2001). Regional sea level changes are significantly different from global average sea level change (Church et al., 2013), Arctic sea level monitoring thus is very important, as the region may be particularly sensitive to climate change (Andersen and Piccioni, 2016).

The Arctic Ocean sea level changes have been studied primarily with the focus on tide gauge data. However, it is difficult to estimate the pan-arctic sea level trend from tide gauge records because of the discrete spatial distribution and tide gauges can be affected by local factors particularly vertical land movement (VLM) (Wöppelmann and Marcos, 2016). Proshutinsky et al. (2004) studied the observed sea level over the Russian sector of the Arctic Ocean and discovered a rise in sea level at the rate of 1.23 mm/a over the 1954–1989 period. Henry et al. (2012) investigated sea level change and variability by analyzing 62 long tide gauge records along the Norwegian and Russian coastlines over the 1950–2009 period and determined an increasing trend of 4 mm/a since 1995. Additionally, sea-ice extent, ice mass loss (Bamber and Riva, 2010), ocean temperature and salinity have also considered in studying the sea level change of the Arctic Ocean (Kwok et al., 2009; Polyakov et al., 2005; McPhee et al., 2009).

However, few studies of Arctic sea level are based on satellite altimetry data due to the presence of sea ice, the lack of satellites coverage, and insufficient geophysical models. Among recent publications, Proshutinsky et al. (2007) analyzed monthly sea levels from the models of Arctic Ocean Model Intercomparison Project and validated these against observations in the Arctic Ocean. Cheng et al. (2015) have reprocessed ERS-1/2 and Envisat satellite altimetry to develop an improved 20-year sea level dataset for the Arctic Ocean from September 1992 to October 2012. Cheng et al. (2015) estimated the sea level changes present a mean sea level trend of (2.10±1.3) mm/a covering the Arctic Ocean between 66°N and 82°N. Carret et al. (2017) analyzed tide gauge data to estimate coastal mean sea-level variations with (1.58±0.23) mm/a from 1950 to 2014 and compared these results with satellite observations based on the Coupled Model Intercomparison Project Phase 5 for the Arctic Ocean. Rose et al. (2019) has also studied the sea level trend of the Arctic Ocean by construct a new improved monthly sea level record based on multi-mission satellite altimetry data set, they find a sea level rise of 1.54 mm/a from September 1991 to September 2018, covering 65°–81.5°N and 180°W–179.5°E. It is additionally evident that past analyses of Arctic sea level are incomplete in terms of spatial and temporal coverage, leading to inconsistent estimates of long-

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term sea level trends (Svendsen et al., 2015). Thus, the effective coverage of satellite-derived sea level data should be firstly clearly identified, and more tide gauge observations should be combined to make up the shortage of low-coverage of satellite altimetry data in some coastal regions.

The difference between satellite altimetry (absolute sea level) and tide gauge records (relative sea level) is the comprehensive influence of many factors, such as the local geoid differences, atmospheric pressure correction, land contamination of the wet tropospheric path delay or the range in the coastal zone, but actually it is hard to quantify each one factor and the same factor always has different models with large regional differences. The largest uncertainty between them is arguably introduced by VLM (Luu et al., 2015). In the study of Arctic sea level change, the influence of VLM is rarely considered and a glacial isostatic adjustment (GIA) model is adopted instead. Furthermore, due to the vertical motion of landmass concurrent with GIA rebound, VLM is caused by regional active tectonic movement, underground water or sediment compaction. The use of the global navigation satellite system (GNSS) has demonstrated promising VLM rate at local and regional scales. However, the lack of direct GNSS near or co-location at tide gauge stations and the lack of available data and estimates, among other issues, have prevented scientists from using VLM rates in most sea level variability studies (Santamaría-Gómez et al., 2017).

In this study, the multimission satellite altimetry data were used to analyze the absolute sea level variability in the Arctic Ocean covering 66°N to 83.375°N from January 1993 to December 2018. The sea level anomaly (SLA) was compared between satellite and tide gauge records. As much GNSS observations as possible were obtained to study VLM in the Arctic Ocean.

The remainder of this paper is organized as follows. Descriptions of the data used are provided in Section 2. Section 3 presents the long-period sea level trend and compares the satellite-derived data and tide gauge results. Section 4 presents the effect of the vertical land motion to the sea level trend. Section 5 discusses the difference of the correlation coefficient between satellite altimetry and tide gauge result, and Section 6 gives the conclusions of the study.

2 Datasets

2.1 *Satellite altimetry data*

This study used the gridded maps of sea level anomalies (MSLAs) in delayed time at high resolution of 0.25°×0.25° from January 1993 to December 2018, which were produced from daily Segment Sol Multimission Altimetry and Orbitography/Developing Use of Altimetry for Climate Studies and distributed by Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO), with support from Centre National d'Etudes Spatiales (CNES) (http://www.aviso.altimetry.fr/duacs/). The dataset consists of all available satellites: ERS-1/2, T/P, EnviSat, Jason-1/2/3, Cryosat-2, HY-2A, SARAL/AltiKa, and Sentinel-3A.

Satellite altimetry observations are limited by the designed orbit of the satellite and the availability of ice-free ocean. For example, for T/P and Jason-1 have no data coverage further than north of 66°N. The satellite altimetry data coverage in different seasons is presented in Fig. 1. The irregular distribution of the data in both space and time will impact the interpretation and subsequent computation of sea level trend budget closure. In this research, the monthly averaged SLAs were used to ensure consistency with tide gauge records and GNSS observations.

2.2 *Tide gauge data*

The monthly sea level data time series for 22 tide gauges considered to be of research-quality (red circle labeled in Fig. 2) in the Arctic basin were obtained from Permanent Service for Mean Sea Level (PSMSL; https://www.psmsl.org/; Holgate et al., 2013). This study used the monthly revised local reference tide gauge records to analyze the sea level trend (Woodworth and Player, 2003). The data had more than 20 years of records from 1993 (the start of the satellite window) and at least 90% of complete valid observations. The bulk of tide gauges were located along the Russian coastline, Greenland Sea, Norwegian Sea, and Barents Sea. To increase the spatial coverage of tide gauge stations, data from two other tide gauge stations in Baffin Bay and Norwegian Sea (Nos 23 and 24 labeled in Fig. 2) with 9 and 10 years of hourly sea level tide series, respectively, were obtained from the University of Hawaii Sea Level Center (UHSLC, http://uhslc.soest.hawaii.edu/).

The inverted barometer correction, the same as used in MSLA data, was applied to the tide gauges time series by using Mean Sea Level Pressure (MSLP) from the monthly National Centers for Environmental Prediction/National Center for Atmospheric Research (NECP/NCAR) reanalysis data (Kalnay et al., 1996), which provided by National Oceanic and Atmospheric Administration (NOAA, https://www.esrl.noaa.gov/psd/data/reanalysis/reanalysis.shtml) with a spatial resolution of 2.5°×2.5°. The quality checks of tide gauge records mainly contained detection and processing of missing values and abnormal values. Interpolation calculation by polynomial fitting is adopted at the locations with less than five consecutive missing values. When there are more than five missing values, no processing is performed in order to reduce the accumulation of errors. To reduce the impact of abnormal values to long-term sea level trend, the three-fold median error is taken as the threshold to remove outliers. Finally, SLA at each tide gauge stations is described as sea level departure values obtained from subtracting the mean value of the whole period, to analyze the relative sea level trend.

2.3 *VLM corrections*

Local sea-level observations are susceptible to VLM, which arguably introduce the greatest uncertainties in the assessment of long-term sea level trends. Thus, tide gauge data should be corrected for VLM to obtain the absolute sea level trend. Since the vertical landmass related to the post-glacial rebound is only one component of VLM, the GIA model results are not considered in this study. Rather, this study examine data from 11 GNSS stations, among them 6 stations located near to the tide gauge stations, provided by System d'Observation du Niveau des Eaux Littorales (SONEL, http://www.sonel.org/; Santamaría-Gómez et al., 2012).

The GNSS vertical velocity fields produced at the University of La Rochelle (ULR) are intended to correct the VLM from tide gauge observations (Santamaría-Gómez et al., 2017). The ULR6b GNSS solution is aligned in the ITRF2014 reference frame, instead of ITRF2008 for ULR6a. Both ULR6 solutions result from the reanalysis of 19 years of GNSS data from 1995 to 2014, carried out within the framework of the 2nd data reprocessing campaign of the International GNSS Service (IGS). The VLM data used in this paper have time series ranged from 9 years to 19 years with gaps less than 10% of observations. The locations of tide gauge stations and GNSS stations are shown in Fig. 2.

3 Comparison between satellite-derived and tide gauge data

The sea level fluctuates considerably at time scales ranging

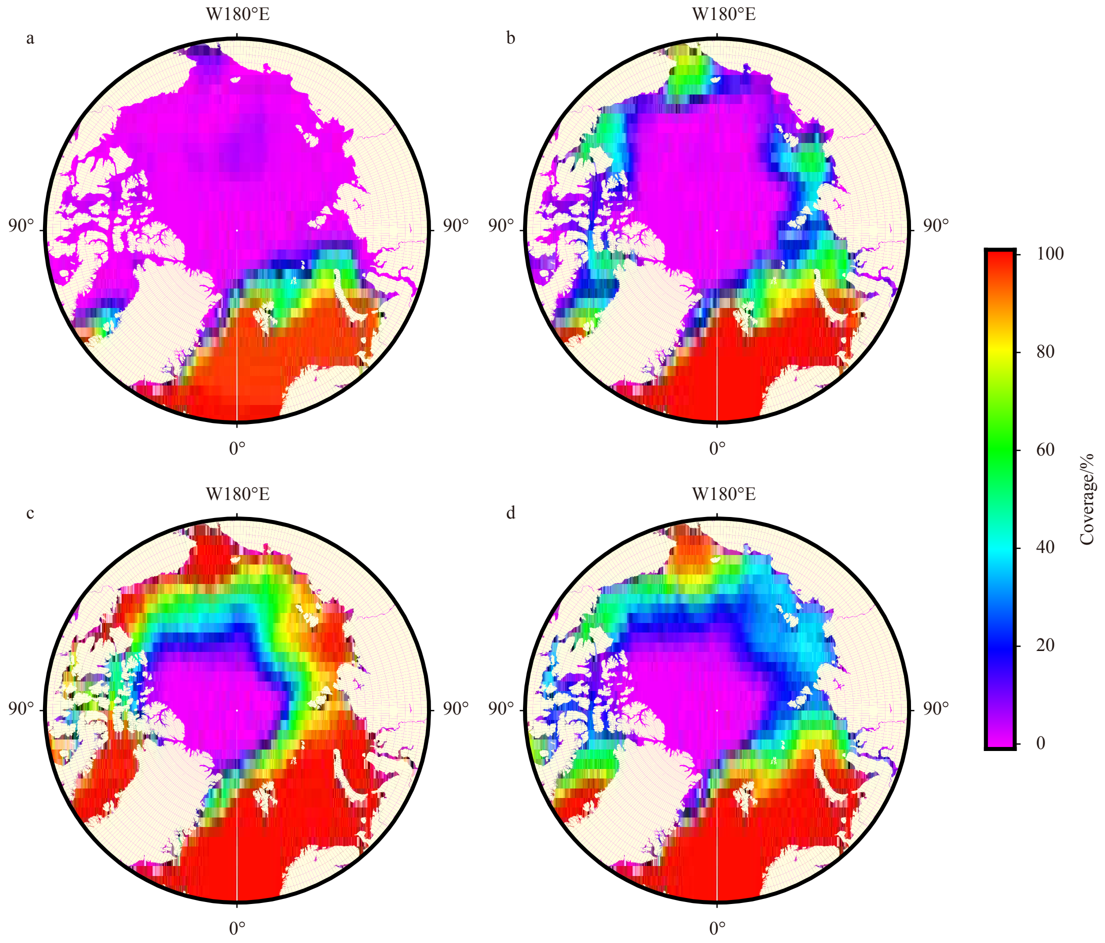

Fig. 1. Fraction of satellite-derived SLA data coverage in the Arctic Ocean of spring (January–March, a), summer (April–June, b), autumn (July–September, c), and winter (October–December, d) over the 1993–2018 period.

from intraseasonal to interdecadal (Feng et al., 2015; Fu et al., 2019). Figure 3 shows the spectral structure for satellite-derived data, in which the SLA (top panel) and amplitudes as a function of extraction period (bottom panel) are shown. These amplitudes represent the energies associated with sea level oscillations at a given periodicity. The periods of A–H are 0.50 a, 1.00 a, 1.24 a, 1.73 a, 3.71 a, 5.20 a, 6.50 a and 13.00 a, respectively.

Sea-level variability in the Arctic Ocean (from 66°N to 83.375°N) was estimated for the time period of 1993–2018. The averaged SLA time series is displayed in Fig. 3a. The regional sea level trend computed over the whole period indicates a rising linear trend of (2.53±0.42) mm/a. From Fig. 3a, it can be seen that the increase in sea level is not a straightforward up or down change, but is divided into periods. The sea level rises occurred during two periods: 1993–2004 and 2012–2018. In the period of 2005–2009, the sea level slightly decreased. The minimum SLA occurred in 1995 and the maximum occurred in 2003 and 2017. The rate of sea level rise is estimated to be (4.46±1.35) mm/a for 1993–2004, (11.02±1.39) mm/a for 2012–2018 (the fastest rise). In contrast, the rate of sea level decline was (−1.71±2.77) mm/a for 2005–2009.

A detailed view of the spatial pattern of the linear sea level trend for period of 1993–2018 is presented in Fig. 4 with a resolution of 0.25°×0.25°. The sea level linear trend is defined using basic statistics as the regression coefficient estimated using the least squares method. The sea level trend is given by following formula:

$$\text{trend} = \frac{\sum\limits_{i=1}^{N}[(x_i-\bar{x})(y_i-\bar{y})]}{\sum\limits_{i=1}^{N}(x_i-\bar{x})^2} \pm \frac{\sqrt{\sum\limits_{i=1}^{N}\frac{1}{N-2}(y_i-\hat{y}_1)^2}}{\sqrt{\sum\limits_{i=1}^{N}(x_i-\bar{x})^2}}\,t_p,$$
$$i = 1,\ 2,\ \cdots,\ N, \tag{1}$$

where N is the number of sea level records considered, y_i is the actual sea level measure at the time x_i and $\hat{y}_1$ is the estimated value. Futher, $\bar{x}$ is the average of the x_i, $\bar{y}$ is the average of the sea level measurement, and t_p is the selected 95% confidence level, of the t-distribution with N-2 degrees of freedom.

The sea level trend in the Arctic Ocean ranges from −2.00 mm/a to 6.88 mm/a, with positive rates primarily calculated for shallow water and coastal areas and, negative rates were in high-latitude areas and Baffin Bay. In order to validate the altimetry observations, a comparison with tide gauge results was performed. For each tide gauge the sea level trend was evaluated by comparing with the nearest satellite altimetry grid point located within 20 km of the tide gauge position except the THULE station is 39.29 km. As shown in Fig. 4, the spatial distribution of long-term trends exhibits distinct spatial variations. More details of comparison results are listed in Table 1. Column 6 represents the correlation coefficient between tide gauge records and the nearest satellite altimetry grid point data.

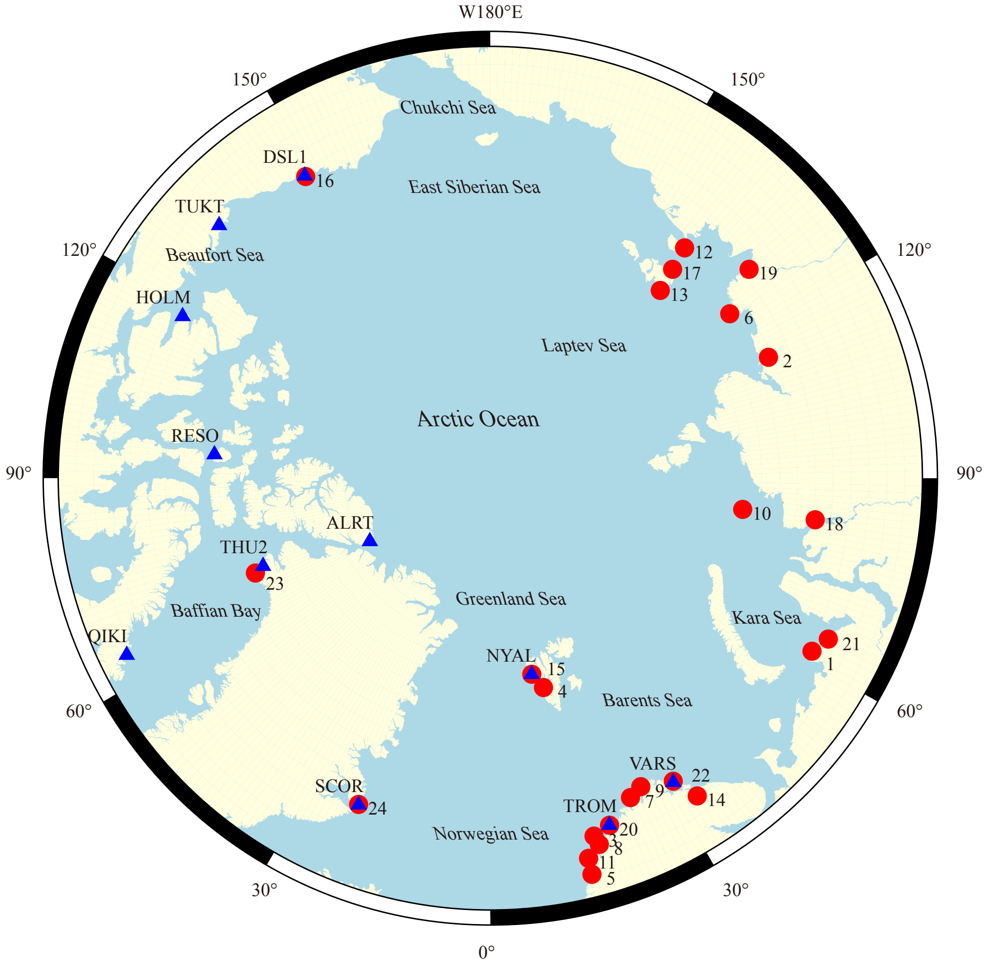

Fig. 2. Geographic locations of tide gauge stations (red circles) and global navigation satellite system stations (blue triangles).

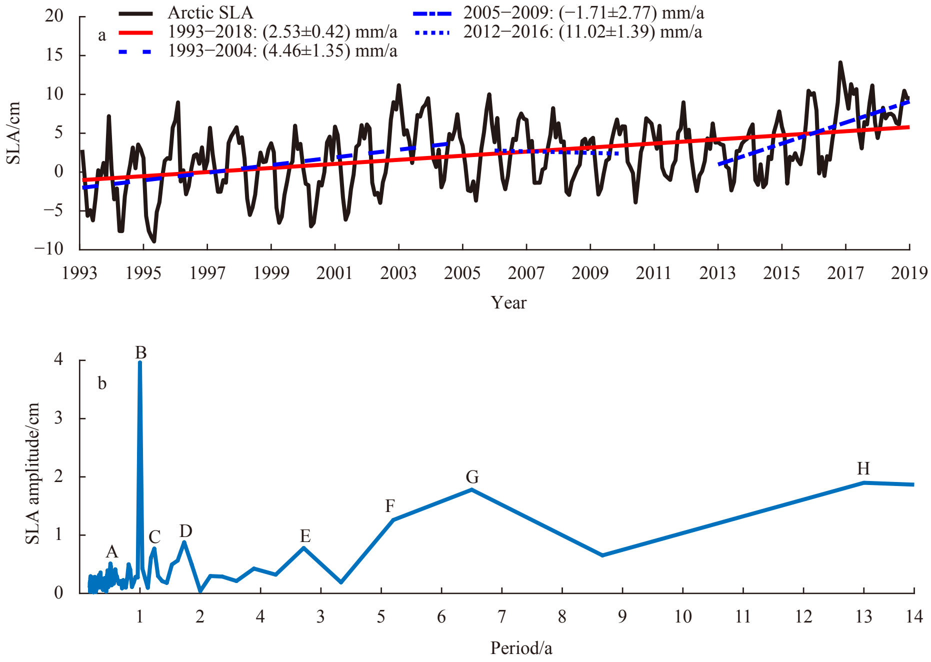

Fig. 3. Time series of satellite-derived SLA for the period from January 1993 to December 2018 (a), and the spectral structure of SLA (b). The identified peaks corresponding to the principal components are labelled A–H.

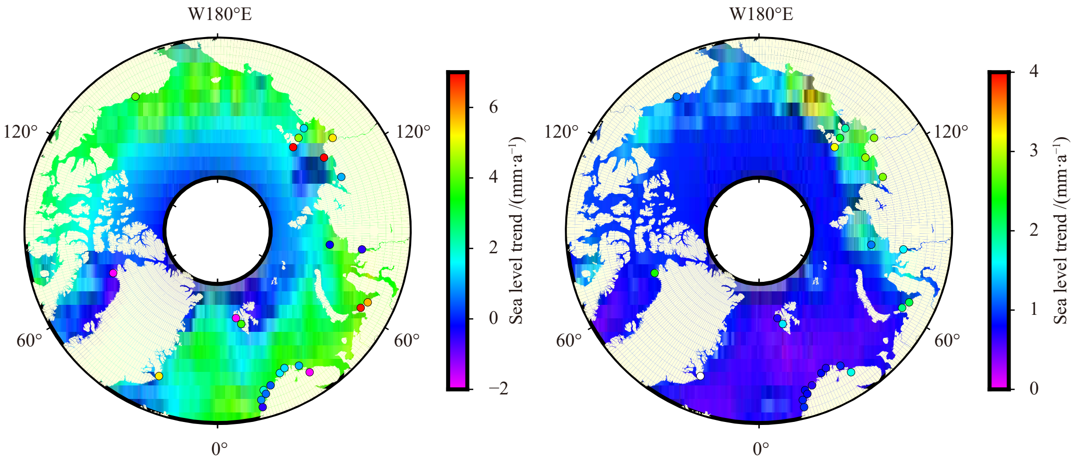

Fig. 4. Spatial trend pattern (left) and uncertainties of trend (right) from satellite altimetry over the 1993–2018 period.

Table 1. Comparison between tide gauge measurements and the nearest satellite grid results

No.	Tide gauge station	North latitude /(°)	East longitude /(°)	Period	Correcoef	Satellite /(mm·a^{-1})	Tide gauge /(mm·a^{-1})	Difference /(mm·a^{-1})	Distance /km
1	AMDERMA	69.75	61.70	1993–2013	0.62	2.12±0.71	6.84±1.99	−4.72	5.55
2	ANABAR	73.22	113.50	1993–2013	0.10	2.27±1.88	1.05±2.79	1.22	3.66
3	ANDENES	69.33	16.14	1993–2018	0.65	3.46±0.44	1.89±0.80	1.57	15.32
4	BARENTSBURG	78.07	14.25	1995–2017	0.65	1.19±0.48	3.77±1.53	−2.58	7.44
5	BODO	67.29	14.39	1993–2018	0.25	3.51±0.45	−0.53±0.93	4.04	12.77
6	DUNAI	73.93	124.50	1993–2010	0.41	4.94±2.20	7.34±2.90	−2.40	7.44
7	HAMMERFEST	70.67	23.68	1993–2018	0.70	3.93±0.50	1.47±0.81	2.46	11.99
8	HARSTAD	68.80	16.55	1993–2018	0.36	3.29±0.39	0.57±0.78	2.72	7.77
9	HONNINGSVAG	70.98	25.97	1993–2018	0.66	4.20±0.51	1.37±0.72	2.83	3.77
10	IZVESTIA TSIK	75.95	82.95	1993–2013	0.25	2.61±1.36	−0.17±1.18	2.78	7.88
11	KABELVAG	68.21	14.48	1993–2018	0.47	3.94±0.52	0.84±0.88	3.10	4.55
12	KIGILIAH	73.33	139.87	1993–2013	0.38	2.73±4.24	1.35±1.86	1.38	15.87
13	KOTELNYI	76.00	137.87	1993–2013	0.39	2.27±1.94	9.36±3.17	−7.09	12.99
14	MURMANSK	68.97	33.05	1993–2017	−0.15	4.13±0.54	−3.86±1.67	7.99	6.66
15	NY-ALESUND	78.93	11.94	1993–2018	−0.30	1.34±0.38	−7.25±0.71	8.59	10.43
16	PRUDHOE BAY, ALASKA	70.40	211.47	1995–2018	0.83	2.90±1.16	4.16±1.24	−1.26	11.54
17	SANNIKOVA	74.67	138.90	1993–2013	0.54	2.60±2.60	4.39±2.32	−1.79	14.43
18	SOPOCHNAIA KARGA	71.87	82.70	1993–2013	0.20	3.20±1.67	−0.54±1.57	3.74	15.76
19	TIKSI	71.58	128.92	1993–2009	0.78	7.30±3.91	5.36±2.84	1.94	12.99
20	TROMSO	69.65	18.96	1993–2018	0.45	3.57±0.41	0.43±0.67	3.14	12.21
21	UST KARA	69.25	64.52	1993–2013	0.44	3.29±1.45	5.74±2.17	−2.45	1.89
22	VARDO	70.38	31.10	1993–2018	0.58	4.68±0.58	1.08±0.92	3.60	18.09
23	THULE	76.00	292.00	2007–2018	0.58	−3.20±1.96	−17.47±2.47	14.27	39.29
24	SCORESBY	70.50	338.02	2008–2018	0.34	2.33±1.54	5.33±6.92	−3.00	1.89

Note: Column 6 represents the correlation coefficient between tide gauge records and the nearest satellite altimetry grid point data. Columns 7 and 8 represent the satellite-derived and tide gauge result, respectively, and column 9 represents the difference between them.

It is worth noting that tide gauge observations reflect a relative sea level change and satellite altimetry capture the absolute sea level change. Results of the two methods present large differences at most stations. There are two tide gauge stations with large differences, namely NY-ALESUND and THULE, the sea level trend for satellite-derived and tide gauge result was (1.34±0.38) mm/a and (−7.25±0.71) mm/a, and (−3.20±1.96) mm/a and (−17.47±2.47) mm/a, respectively. For the all tide gauge stations, the differences between satellite and tide gauge results in 75% of stations are in the range of ±4 mm/a. The relationship of correlation coefficient between tide gauge records and the nearest satellite altimetry grid point data was discussed in Section 5.

Many factors can result in the large difference of sea level trend between satellite-derived and tide gauge result. For example, the low precision of satellite data in the coastal zone and the influence of effective data coverage of satellite altimetry, i.e., THULE station is located in the Baffin Bay, which has narrow passages and complex terrain. This research compare the sea level trend between tide gauge station and the nearest grid satellite-derived result. Theoretically, the large distance between them can also bring errors. Therefore, the influence of the distance should not be ignored, especially the largest distance was up to 39.29 km in THULE station. More details about the relationship between correlation coefficient and distance were deeply discussed in Section 5. Last but not least is the fact that sea level data obtained by tide gauge station includes the influence of meteorological factors such as atmospheric pressure and wind as well as VLM. Thus, the quantitative impact of VLM on sea level variability needs to be clarified.

4 Effect of the vertical land motion to the sea level trend

In order to evaluate the impact of VLM on sea level change, the VLM observations collected from 11 GNSS stations were analyzed in this study. Of these 11 stations, 6 of them are located near the tide gauge stations. The daily VLM time series of the 6 GNSS observation stations are presented in Fig. 5. It can be seen that the magnitude of the range of VLM at most stations for the whole period is in the range of ±10 cm, most of the GNSS station had long-term VLM data, i.e., >10 years, except the SCOR station, which has 9 years of data from 2005 to 2013. From Fig. 5, it can be seen that the long-term VLM data presents a continuous linear positive or negative trend with a periodic fluctuation.

Without considering the influence of wind, atmospheric pressure and other meteorological factors, the absolute sea level variability can be divided into the VLM component and the change of sea level relative to the crust. Therefore, it can be considered that the absolute sea level trend is equal to the linear addition of the VLM rate obtained by GNSS station and the relative sea level rate obtained by tide gauge, as shown in the following equation: $V(\varphi, \lambda)=V_{\rm VLM}(\varphi, \lambda)+V_{\rm tide}(\varphi, \lambda)$, where φ and λ are the station geodetic latitude and longitude, $V(\varphi, \lambda)$ is the absolute sea level trend, $V_{\rm VLM}(\varphi, \lambda)$ is the VLM rate, and $V_{\rm tide}(\varphi, \lambda)$ is the relative sea level trend.

The statistical results are shown in Table 2. Column 9 represents the sea level trend after the VLM correction, namely the absolute sea level trend. Column 10 represents the difference between the absolute sea level trend after VLM correction and the satellite sea level rate. Although the time scale of VLM data is different, most stations exhibit an positive trend of crustal changes in the Arctic Ocean, among which NYAL station shows the biggest change with a VLM rate of (8.09±0.15) mm/a, and a negative value of VLM rate in DSL1 and TUKT stations, indicating a crustal subsidence of (−4.49±0.22) mm/a to (−0.95±1.09) mm/a in the Beaufort Gyre area region. It is worth noting the tide gauge + VLM result in Table 2 is corresponding the time period for VLM and tide gauge data have effective observations, which is differ-

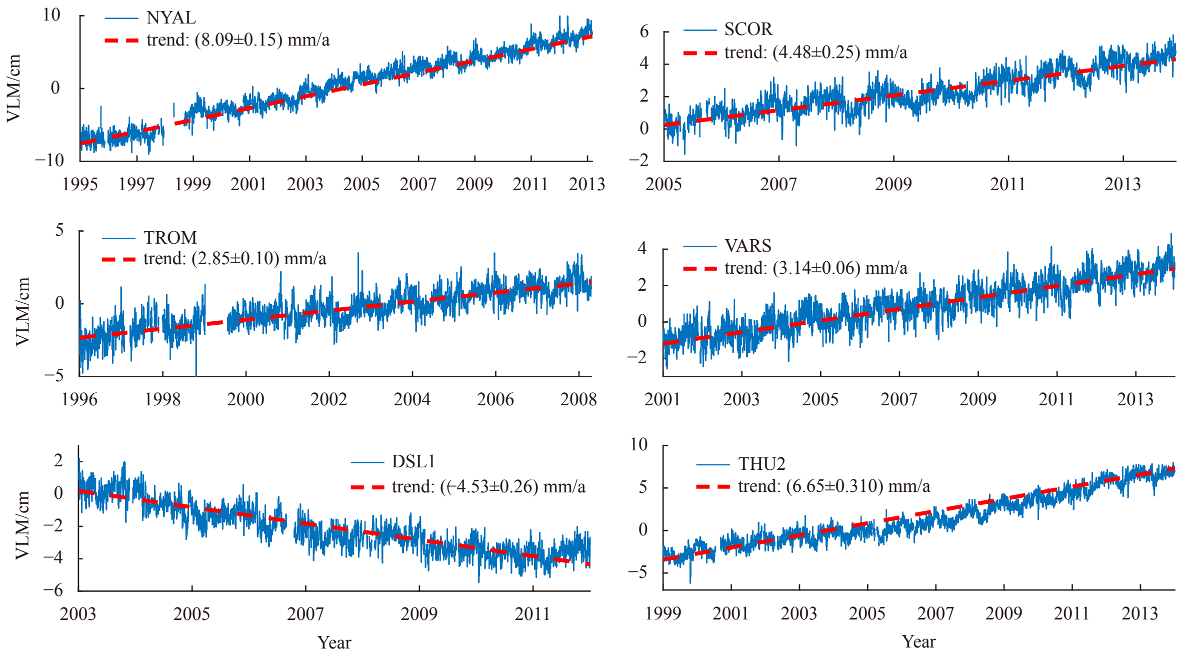

Fig. 5. Daily vertical land movement time series at GNSS stations.

Table 2. Rate of vertical land movement rate over the selected period within the Arctic Ocean

No.	GNSS station	North latitude /(°)	East longitude /(°)	Period	VLM rate /(mm·a^{-1})	Satellite /(mm·a^{-1})	Tide gauge /(mm·a^{-1})	Tide gauge + VLM/(mm·a^{-1})	Difference /(mm·a^{-1})
1	NYAL	78.93	11.87	1995–2013	8.09±0.15	1.11±0.67	−6.65±1.14	1.44±1.17	0.33
2	SCOR	70.49	338.05	2008–2013	5.35±0.29	2.17±3.32	−1.16±12.87	4.19±13.05	2.02
3	TROM	69.66	18.94	1996–2008	2.85±0.10	4.50±1.33	3.37±1.56	6.22±1.53	1.72
4	VARS	70.34	31.03	2001–2013	3.14±0.06	0.87±1.27	−3.29±1.86	−0.14±1.85	−1.01
5	DSL1	70.33	211.53	2003–2013	−4.49±0.22	−6.20±2.99	1.27±5.74	−2.82±4.67	3.38
6	THU2	76.54	291.17	2007–2013	8.90±0.28	3.12±3.42	−18.78±6.34	−9.88±6.29	−13.00
7	QIKI	67.56	295.97	2004–2013	4.25±0.83	–	–	–	–
8	RESO	74.69	265.11	2001–2013	6.31±0.57	–	–	–	–
9	TUKT	69.44	227.01	2003–2013	−0.95±1.09	–	–	–	–
10	HOLM	70.74	242.24	2001–2013	3.22±0.58	–	–	–	–
11	ALRT	82.49	297.66	2002–2013	6.61±1.91	–	–	–	–

ent with the tide gauge records in Table 1. Thus, the absolute sea level trend obtained by tide gauge after VLM correction is different from the sum of the relative sea level trend in Table 1 and VLM rate in Table 2.

It is clearly indicated that the absolute sea level trends after VLM correction are of the same magnitude as those obtained by satellite altimetry, the differences between them are in the range of −1.01 mm/a to 3.38 mm/a, except for the THU2 station. For THU2 station, the satellite-derived sea level trend is (3.12±3.42) mm/a for the period of 2007–2013 (Table 2), but is (−3.20±1.96) mm/a for 2003–2018 (Table 1). Thus, it is inaccurate by using the short time period to calculate the sea level trend. Nevertheless, from Table 2 it can be seen that the absolute sea level trend obtained from the tide gauge + VLM decreased the difference between satellite-derived result. Among the stations, the uncertainties associated with data from NYAL station are the smallest. Thus, the differences between tide gauge and satellite altimetry data were generally attributed to VLM.

5 Discussion

The absolute sea level variability of Arctic Ocean was analyzed by using multi-mission satellite altimetry data, which showed a positive sea level trend of (2.53±0.42) mm/a with time spanning from January 1993 to December 2018. Rose et al. (2019) used a combination of altimeter data and obtained about 1.54 mm/a over the period of September 1991 to September 2018, when ignoring the troublesome ERS-1 satellite data the SLA trend becomes 2.22 mm/a, which is quite similar with this paper.

Actually, the satellite altimetry data used, geographical coverage and SLA grid size result in the quite difference between Rose et al. (2019) and this paper. Rose et al. (2019) used data from four radar altimeter satellites: ERS-1, ERS-2, Envisat and CryoSat-2. The SLA data records were finally given in monthly grids of 0.25° latitude by 0.5° longitude, covering 65°–81.5°N and 180°W–179.5°E. Compared with Rose et al. (2019), HY-2A, SARAL/AltiKa and Sentinel-3A satellite data are further adopted in cells of 0.25°×0.25° SLA grid product. The last but not least, the sea level trend was calculated in this paper corresponding to the spatial coverage of 66°–83.375°N and 180°W–180°E, which was the most important factor to bring quite huge difference with other studies.

The relationship of correlation coefficient between tide gauge records and the nearest satellite altimetry grid point data, as shown in Table 1, are not prominent relevant with their distance. Figure 6a black line presents the function relationship between correlation coefficient and the distance. The largest distance is 39.29 km (THULE station), and others are all in the range of 20 km. Combined with Table 2, it can be seen that there are just two stations, namely MURMANSK and NY-ALESUND station, presented negative correlation coefficient of −0.15 and −0.30, respectively. Actually, this phenomenon was mainly caused by the effect of the VLM. The correlation coefficient between tide gauge after VLM corrected and satellite altimetry data was up to 0.58 and 0.72, respectively, as shown in Fig. 6a red line.

Low satellite data coverage affect the quality of SLA, which make contribution to the difference between tide gauge and satellite-derived result. For the ANABAR station, the nearest grid satellite point (73.125°N, 113.625°E) show the satellite altimetry data coverage of 0, 5.13%, 74.36% and 25.64% in different seasons (Fig. 1), respectively, almost no effective data in surrounding grid point. Although the ANABAR station present the minimum distance of 3.66 km, as the anticipate, they presented the low correlation coefficient value of 0.10.

In the data processing, the uncertainties in tidal height determination were found that can also aggravate the difference. For example, in the IZVESTIA TSIK station as shown in Fig. 6b, the average sea level data of tide gauge and the nearest satellite grid point in 1993 is 43.10 cm and −84.42 cm, respectively. When abandoning this value, the correlation coefficient increased from 0.25 to 0.46.

6 Conclusions

The Arctic sea level requires detailed monitoring, as this region is particularly sensitive to global warming. This study estimated Arctic Ocean sea-level variability for the region 66°–83.375°N covering the period of January 1993 to December 2018. Delayed time satellite grid data were used to analyze long-term trends in the Arctic sea level, which were validated against 24 tide gauge observations. Difference of sea level trend between the two meth-

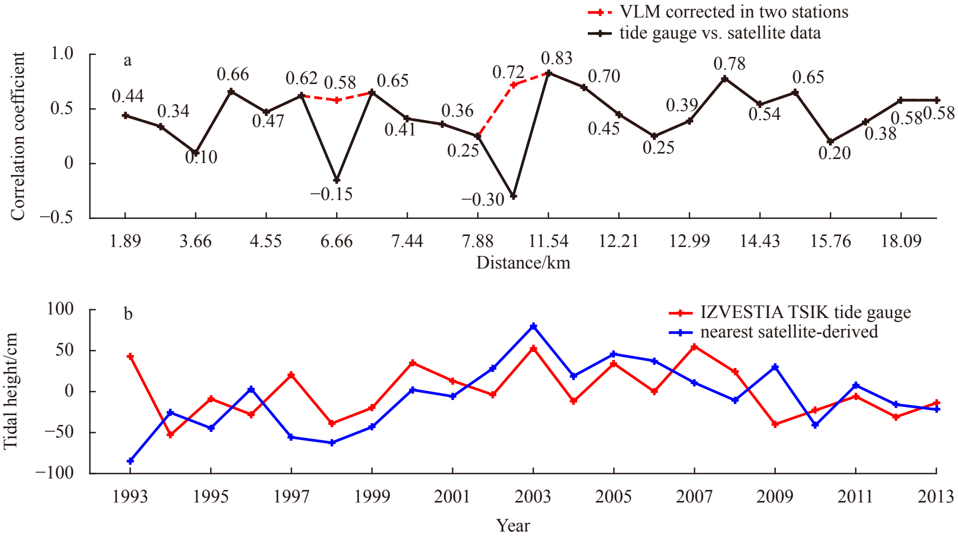

Fig. 6. Relationship between tide gauge observation and satellite-derived result. a. Function of correlation coefficient and distance. Black line present correcoef between tide gauge and the nearest satellite data, red line are the VLM corrected in two stations. b. Tidal height series in IZVESTIA TSIK tide gauge station and satellite-derived result.

ods was limited to ±4 mm/a at 75% of stations. The Arctic sea level trend estimated over the whole period indicates a rising linear trend of (2.05±0.46) mm/a. The fastest rate of sea level rise occurred during the most recent sub-period of 2012–2018, which exhibits rates of (11.02±1.39) mm/a. Analyses of the spatial distribution of the linear sea level trends for the period of 1993–2018 indicate that the sea level trend in the Arctic Ocean is between –2.00 mm/a to 6.88 mm/a, with positive rates predominantly distributed in shallow water and coastal areas and negative rates were in high-latitude regions and in the Baffin Bay.

The correlation between tide gauge and satellite-derived data was deeply analyzed. VLM time series obtained from 11 GNSS stations indicate that most stations show a positive trend of crustal changes in the Arctic region. Absolute sea level trends obtained from tide gauge data after VLM corrected are of the same magnitude as the satellite altimetry, which is almost in the range of –1.01 mm/a to 3.38 mm/a, the differences between tide gauge and satellite altimetry data may attributable generally to low satellite data coverage, uncertainties in tidal height processing and VLM.

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