Estimation of Surface Freshwater Fluxes in the Arctic Ocean Using Satellite-Derived Salinity

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Abstract

The temporal and spatial distribution of sea surface salinity (SSS) is not well known in the Arctic region, and only recent satellite-derived measurements and models have allowed for potential enhancement, though their accuracy remains uncertain. We use NASA's Soil Moisture Active Passive (SMAP) and the European Space Agency's Soil Moisture Ocean Salinity (SMOS) to investigate the variability of SSS in the Arctic from 2015 to 2017, as well as to calculate surface advective freshwater fluxes. These data sets are compared with Argo and European Center for Medium-Range Weather Forecasts Ocean Reanalysis version 4 (ORAS) to assess the ability of satellites in detecting freshwater fluxes. Salinity and surface freshwater fluxes are estimated for the Bering Strait and Barents Sea Opening (BSO). In this study, we have compared the Jet Propulsion Laboratory's (JPL) SMAP salinity to the remote sensing system's (RSS) SMAP salinity product, as well as the The Centre Aval de Traitement des données SMOS salinity product. There is disagreement between the reanalysis product and satellites on the mean and variability of surface freshwater fluxes in the BSO; however, the meridional fluxes of the satellites and reanalysis product were significantly correlated within the Bering Strait. This shows the capability of using satellites to measure surface freshwater fluxes in this pathway. However, the discrepancies between satellite-derived SSS and fluxes in other regions of the Arctic Ocean emphasizes the need to increase in situ monitoring to help validate satellites in the higher latitudes.

Keywords Arctic Ocean · Salinity · Freshwater fluxes

1 Introduction

The Arctic Ocean plays a very important role in the Earth's freshwater cycle, essential to both the oceanic and atmospheric components in the Northern Hemisphere. The Arctic Ocean acts as a gateway connecting the North Pacific waters to the North Atlantic and is a key region in the deep-water formation of the meridional overturning circulation. High salinity water from the Atlantic cools as it enters the Arctic, causing overturning circulation. Some studies suggest an addition of freshwater into the Arctic could have an effect on this overturning (e.g., [16, 28]). Monitoring freshwater fluxes in the Arctic is therefore crucial to see the effects of freshwater input on circulation and climate. However, Arctic Ocean processes are difficult to study due to perennial ice and the remoteness of the region. Freshwater fluxes and content can be affected by circulation (e.g., [15]) and salinity, which are in turn impacted by precipitation, evaporation, rivers, and ice [6]. Changes in circulation can impact the strength of the freshwater fluxes as well as where the freshwater is stored or released. The seasonal release of brine and freshwater from ice melting and formation drives changes in near-ice salinity [30].

In order to determine the surface advective freshwater fluxes into the Arctic Ocean, we analyze two major Arctic pathways, the Bering Strait and Barents Sea Opening (BSO), as shown in Fig. 1. The Bering Strait transports low salinity water from the Pacific Ocean into the Arctic. The BSO is a region of inflow of salty Atlantic water to the Arctic region between Svalbard and Norway. There have been many previous studies estimating freshwater fluxes in the Arctic Ocean (e.g., [5, 15, 34]); however, none have estimated these fluxes using satellite-derived sea surface salinity (SSS). There is disagreement between different models as to the strength of freshwater fluxes from different regions [3], emphasizing the need to improve estimates using remote sensing techniques. Previous literature has found Bering

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Strait freshwater contributions to the Arctic have increased since the 1990s [5, 15]. Most studies do not specifically look at the BSO, but instead include it in "miscellaneous" categories combined with other regions, due to the uncertainty, again emphasizing the need to improve estimates.

Comparisons between satellite-derived SSS, reanalysis products, and in-situ observations will help assess the capability of using satellites to study surface freshwater processes in the Arctic region. SSS in the polar regions is difficult to monitor from satellites due to the cold-water reducing the sensitivity of L-band instruments to SSS [18, 19], high winds and strong waves affecting surface roughness and the accuracy of SSS [9, 10], and the lack of in-situ measurements for validation [14, 35, 36]. Nevertheless, NASA's Jet Propulsion Laboratory's Soil Moisture Active Passive (JPL SMAP) salinity data version 4 utilizes a new correction strategy in the Arctic region to account for the large uncertainties and errors near land and sea ice. It was found to have a root mean square difference less than ~ 1 psu and a correlation coefficient of ~ 0.82 psu with in-situ data north of 50° N [37]. The remote sensing system's SMAP (RSS SMAP) salinity data version 3 product also provides SSS measurements in the Arctic Ocean; however, more data is removed using their algorithm due to ice bias and land contamination, as shown by the extent of the product into the Arctic and along coasts (Fig. 3). This removes bias associated with the SSS measurements near ice or land; however, important measurements along the sea ice edge are removed. The LOCEAN CATDS SMOS version 3 product also improved high latitudinal biases in SSS as well as land-sea biases close to coasts. With these uncertainties in mind, we examine the Arctic region using a variety of remote sensing datasets, JPL SMAP, RSS SMAP, and SMOS salinity, as well as surface salinity from the ECMWF's Ocean Reanalysis version 4 (ORAS).

## 2 Materials and Methods

2.1 Observational Data

SMAP was launched on January 31, 2015, with data availability beginning in April 2015. JPL SMAP version 4 level 3 monthly product (DOI: https://doi.org/10.5067/SMP40-3TMCS) [13, 17] is used to analyze SSS and derive surface freshwater fluxes within the Arctic. The SMAP product has a 60 km feature resolution and provides SSS at $0.25° × 0.25°$ gridded spatial resolution. We also use RSS SMAP version 3 level 3 monthly product (DOI: https://doi.org/10.5067/SMP3A-3SPCS) [23, 24, 29]. The feature resolution of this product is 70 km and it is provided in $0.25° × 0.25°$ gridded spatial resolution. We also use version 3 of debiased SMOS level 3 18-day product generated by LOCEAN CATDS [7, 8]. This product is available from January 2010 through December 2017.

In order to calculate the surface freshwater fluxes, meridional and zonal geostrophic currents from Copernicus Marine Environment Monitoring Service (CMEMS) sea surface height (SSH) level 4 products are used for the components of velocity. The product identifier for the SSH from Copernicus is SEALEVEL_GLO_PHY_L4_REP_OBSERVATION-S_008_047 (reprocessed product). These near real-time and reprocessed products allow for quality control checks and cross-calibration processes to remove residual orbit error. This dataset runs from January 1993 to present in $0.25° × 0.25°$ resolution.

We also use the Global Ocean Argo gridded data set (version 2018), generated by China Argo Real-time Data Center using the Barnes objective analysis [21], in order to validate the satellite-derived SSS and reanalysis SSS. It covers the global ocean from 79.5° S to 79.5° N from 2004 to 2017 in $1° × 1°$ spatial resolution. It has 58 vertical levels; however, we will be using the first layer at 0 dbar, or sea surface. When comparing the satellite products to Argo, we regridded the satellites to $1° × 1°$ spatial resolution.

2.2 Reanalysis Product

To compare to satellite-derived freshwater fluxes and Argo salinity, we use ECMWF's ORAS (version 4) [4, 25]. The product is in $1° × 1°$ horizontal resolution from 1959 to present and uses the Nucleus for European Modeling of the Ocean v3.0 ocean model with direct surface forcing from ERA40 and
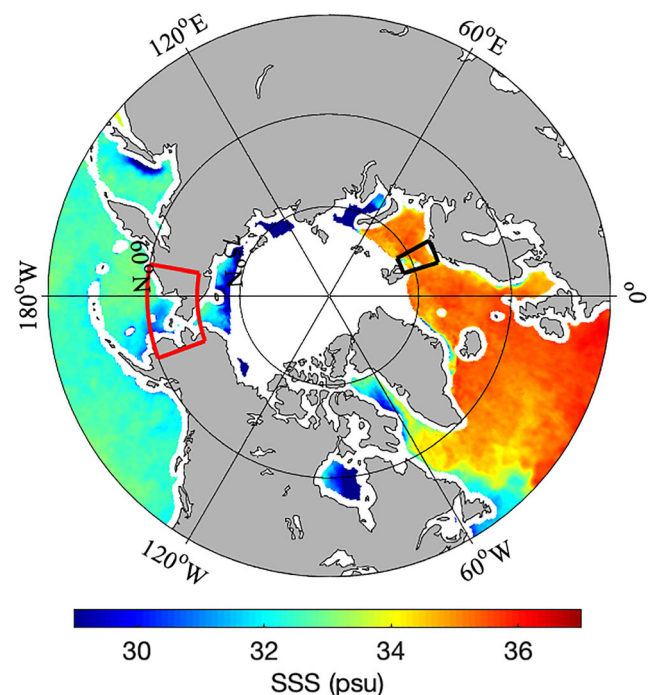
Fig. 1 Projection of Arctic pathways on RSS SMAP SSS for September 2015. Red box represents the Bering Strait and the black the Barents Sea Opening

ERA-Interim as well as observational data from Olv2 SST, EN3 in-situ, and AVISO SLA.

2.3 Surface Advective Freshwater Fluxes

The surface advective freshwater flux (hereby referred to as freshwater flux) is an important component in salinity variability and the movement of freshwater across the different Arctic regions. First, we estimate the freshwater anomaly (S_{fw}) from salinity [22]:

$$S_{fw} = (S_R - SSS)/S_R \qquad (1)$$

S_R is the reference salinity, 34.8 psu. This is approximately the mean salinity of the Arctic region and used in previous studies [1, 12, 15, 20, 34]. SSS are the salinity values. Freshwater fluxes (FW), in units of m^2 s^{-1}, are estimated as:

$$FW_{zonal} = U \cdot S_{fw} \cdot lat_{dist} \qquad (2)$$
$$FW_{meridional} = V \cdot S_{fw} \cdot lon_{dist} \qquad (3)$$

U and V are the zonal and meridional geostrophic current components respectively (m s^{-1}), S_{fw} is the standardized (unitless) freshwater anomaly value from Eq. (1), and lon_{dist} and lat_{dist} are the horizontal expanse of the grid cell (m). This is a similar process to [26, 27]; however, we are only calculating surface fluxes. The relationships between the fluxes are compared through Pearson's correlation coefficient. The correlations are tested with an alpha of 0.05, resulting in values of 95% confidence level.

2.4 Arctic Pathways

The Arctic pathways considered throughout the analysis are the Bering Strait and BSO. The Bering Strait is important as freshwater is transported through this opening from the Pacific to the Arctic. The BSO is important as water moves between the Atlantic and Arctic in this region. The pathways are defined as:

Bering Strait: 60° N–68° N and 160° W–170° E
BSO: 71° N–77° N and 17° E–29° E

The projections of the two pathways can be seen in Fig. 1 overlaid on RSS SMAP SSS for September 2015 and are similar coordinates to Tang et al. [37].

3 Results and Discussion

3.1 Comparison of SSS Products

In order to assess the capability of satellites in calculating freshwater fluxes in the Arctic and subarctic, we compare the SSS values of the various products to Argo. ORAS shows low differences to Argo in both the Pacific and Atlantic (Fig. 2). The satellites, JPL SMAP particularly, show higher salinity in the Pacific basin. SMOS has a lower SSS in much of the Atlantic, whereas JPL SMAP is higher in most of the Atlantic as well. All satellites show higher deviation to Argo along the coasts and in the Greenland and Norwegian Seas. ORAS shows very low deviation from Argo across most of the subarctic. While Argo does not measure SSS in the regions of this study, we see agreement between ORAS and Argo in the regions just outside of the Bering Strait and BSO, suggesting that this product can capture SSS well in the pathways defined by our study and may be used as a comparison for the satellites.

The greater similarities between Argo and ORAS may be due in part to sampling depth. The reanalysis product and Argo provide data at approximately 5 m, whereas satellite-derived salinity is measured in the top millimeters of the water column. The reanalysis product is also likely more similar to Argo because it incorporates in-situ observations in the creation of their datasets.

3.2 Salinity Variability

JPL SMAP, RSS SMAP, SMOS, and ORAS display similar SSS patterns in the subarctic, with high salinity in the Atlantic, lower salinity in the Pacific, and very low salinity in the Arctic (Fig. 3). This is due to higher precipitation in the North Pacific than the North Atlantic and moisture transport from the Atlantic across Central America to the Pacific [32, 38]. This causes the Pacific Ocean to act as a freshwater input to the Arctic, while the Atlantic input increases the SSS of the Arctic. ORAS covers the entire Arctic region, including below the sea ice, whereas the sea ice contaminated measurements are removed from the satellites. However, JPL SMAP and SMOS algorithms retrieve and retain SSS measurements at higher latitudes in the Arctic than RSS SMAP. All the satellites, especially JPL SMAP, exhibit higher variability along coasts and the sea ice edge. ORAS shows much lower variability than the satellites in the central Pacific and Atlantic but show similar patterns of increased variability in many other regions. The variability in the satellite SSS for these products may be due to seasonal and interannual changes in SSS as well as residual ice and land contamination. It is important in the future to separate the effects of natural variability and sea ice contamination in order to improve satellite-derived salinity.

The SSS along the two pathways for JPL SMAP, RSS SMAP, SMOS, and ORAS are shown in Fig. 4. JPL SMAP shows higher variability of SSS during this time period. This high variability occurs mainly during winter months when sea ice is greater in these regions, thus leading to more sea ice contamination. From December 2015 to April 2016, RSS SMAP has no measurements in this region because they were removed likely due to ice contamination, whereas JPL SMAP

Fig. 2 Mean (**a**–**d**) and standard deviations (**e**–**h**) of the JPL SMAP (**a**, **e**), RSS SMAP (**b**, **f**), SMOS (**c**, **g**), and ORAS (**d**, **h**) salinity (psu) minus Argo salinity during April 2015 to December 2017
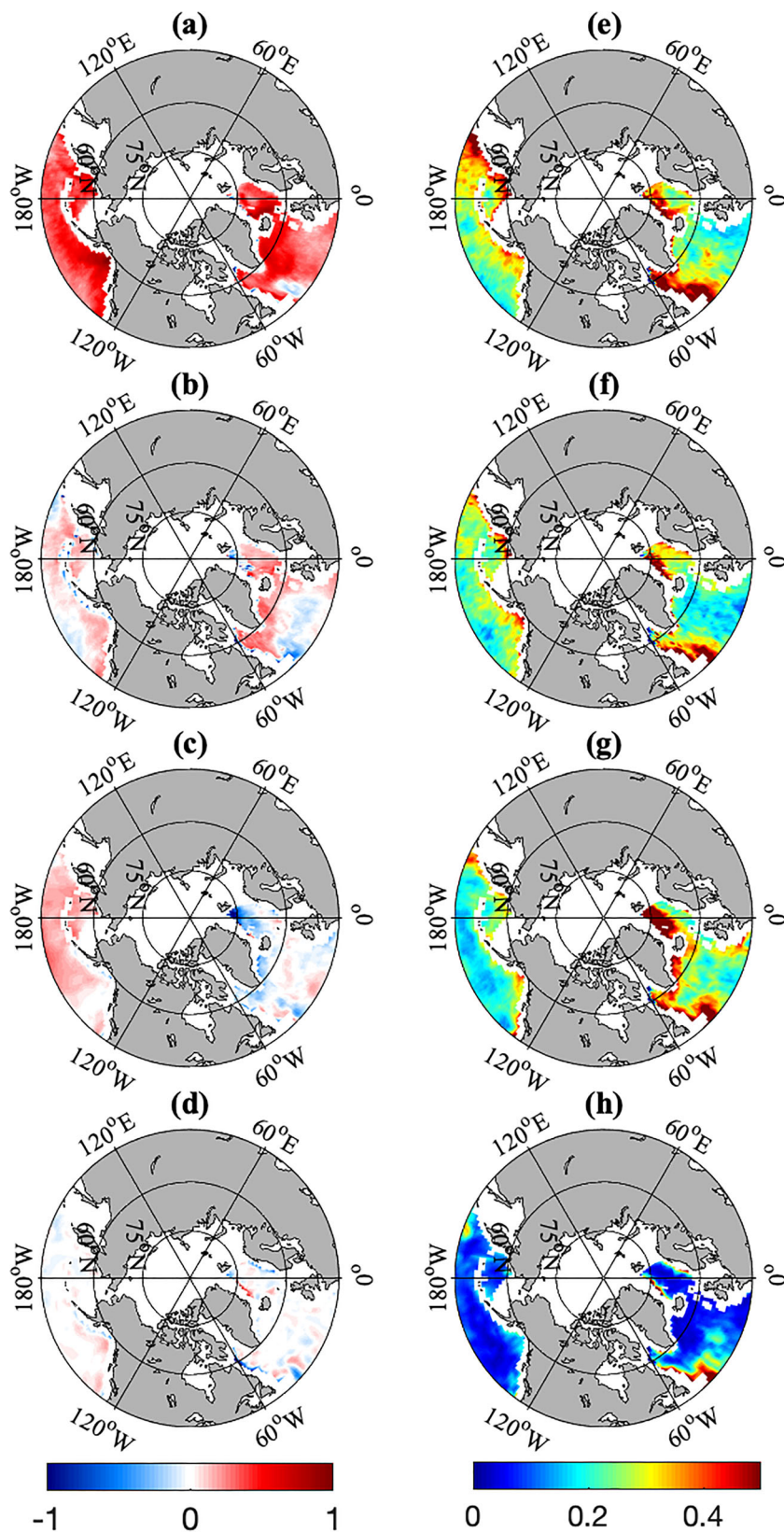
shows significantly lower SSS. In the Bering Strait, the mean and 95% confidence interval are 31.99 ± 0.2090 psu for RSS SMAP, 30.73 ± 0.5469 psu for JPL SMAP, and 32.50 ± 0.0561 psu for SMOS. In the BSO, the mean and 95%

Fig. 3 Mean (**a**–**d**) SSS (psu) and standard deviation (**e**–**h**) from April 2015 to December 2017 for JPL SMAP (**a**, **e**), RSS SMAP (**b**, **f**), CATDS SMOS (**c**, **g**), and ORAS (**d**, **h**)
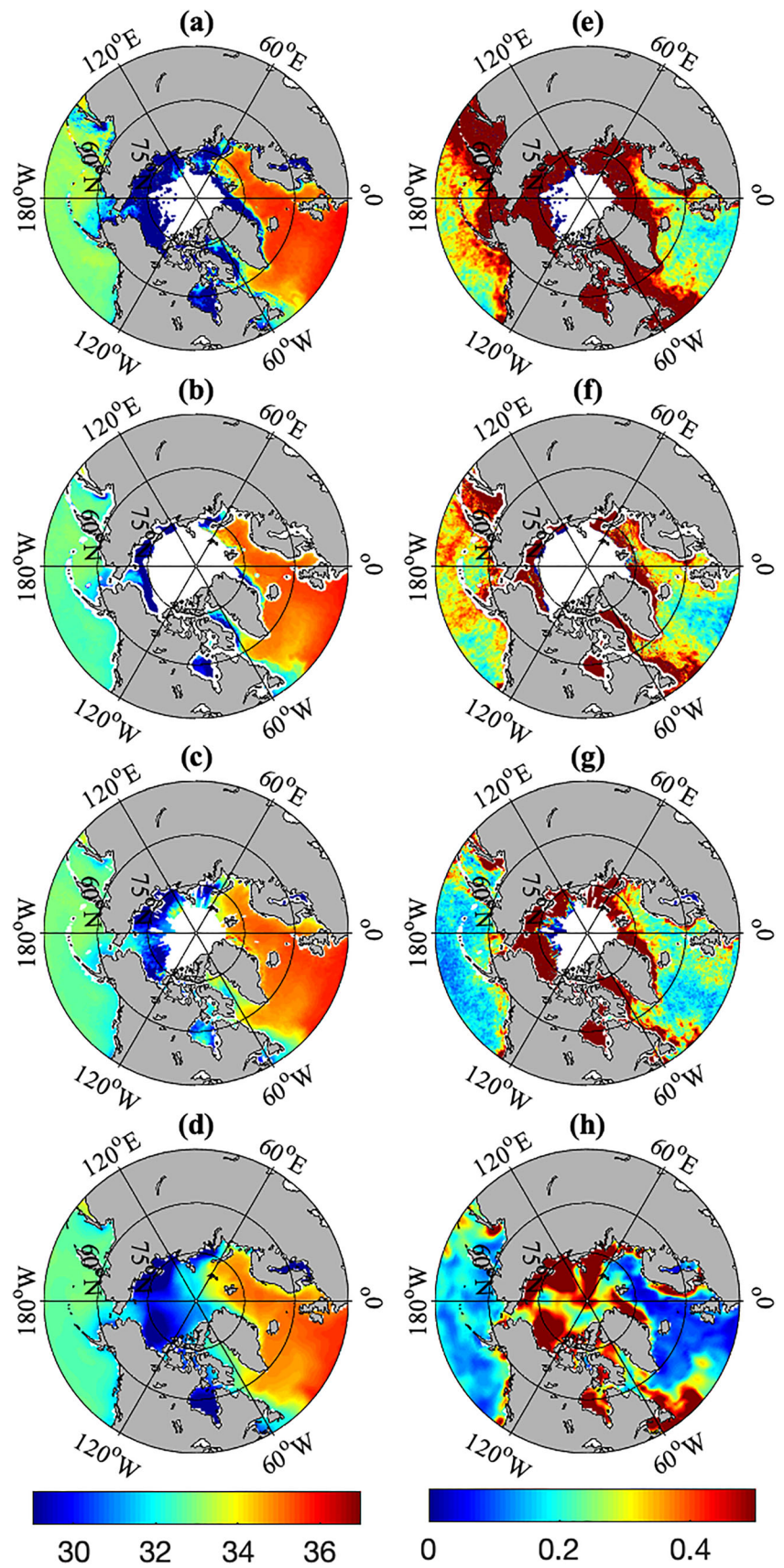
confidence interval are 34.76 ± 0.1450 psu for RSS SMAP, 34.71 ± 0.2829 psu for JPL SMAP, and 34.76 ± 0.0707 psu for SMOS. These SSS values are similar to previous studies for these regions (e.g., [2, 31, 37, 39]). JPL SMAP has a lower salinity in the Bering Strait than RSS SMAP or SMOS due to significantly lower salinity during the winter months. BSO has higher SSS than the Bering Strait because most of the water in this region is from the Atlantic, which has a higher SSS overall compared to the Pacific and the Arctic Oceans [33].

The variations between the SMAP products are due to the screening for sea ice and land contamination. However, the differences between the SMAP and SMOS products also come from differences in the satellite's measurements. Sea ice can have a large impact on satellite sensors. More areas were removed from the RSS SMAP product due to sea ice contamination compared to the JPL SMAP. While this removes measurements close to the ice edge, which is an area of importance for freshwater flux measurements, it allows for less bias or error. This is why the Bering Strait and BSO were focused on in this study. Compared with other gateways in the Arctic, like the Davis Strait or Fram Strait, the BSO and Bering Strait have less error due to lower sea ice concentrations, higher water temperatures, and a greater distance from the land.

3.3 Surface Advective Freshwater Fluxes

These surface advective freshwater fluxes are calculated using geostrophic currents from blended altimetry. The zonal and meridional geostrophic currents are shown in Fig. 5. These figures show the direction and strength of the currents used to calculate the fluxes. The red (blue) currents represent northward/eastward (southward/westward) propagation. As expected, we can see water entering the Arctic through the Bering Strait as well as the BSO. We can also see that the deviation of these currents within the Bering Strait and BSO range from near 0 up to approximately 0.08 m s^{-1}. This variability can be due to changes in the flow of the water which can be impacted by many factors, most notably wind.

The circulation and strength of surface advective freshwater fluxes between the Arctic and subarctic seas can be seen in Figs. 6 and 7, along with the standard deviation of these fluxes. Red represents freshwater moving northward (eastward) for the meridional (zonal) fluxes. The high standard deviations depict the large seasonal and interannual variability in the freshwater fluxes, as well as error associated with the measurements. The North Atlantic fluxes show lower deviations except along Greenland; however, the central Atlantic shows greater variability. Along Greenland, especially in the Fram Strait and Davis Strait, there is a high seasonal
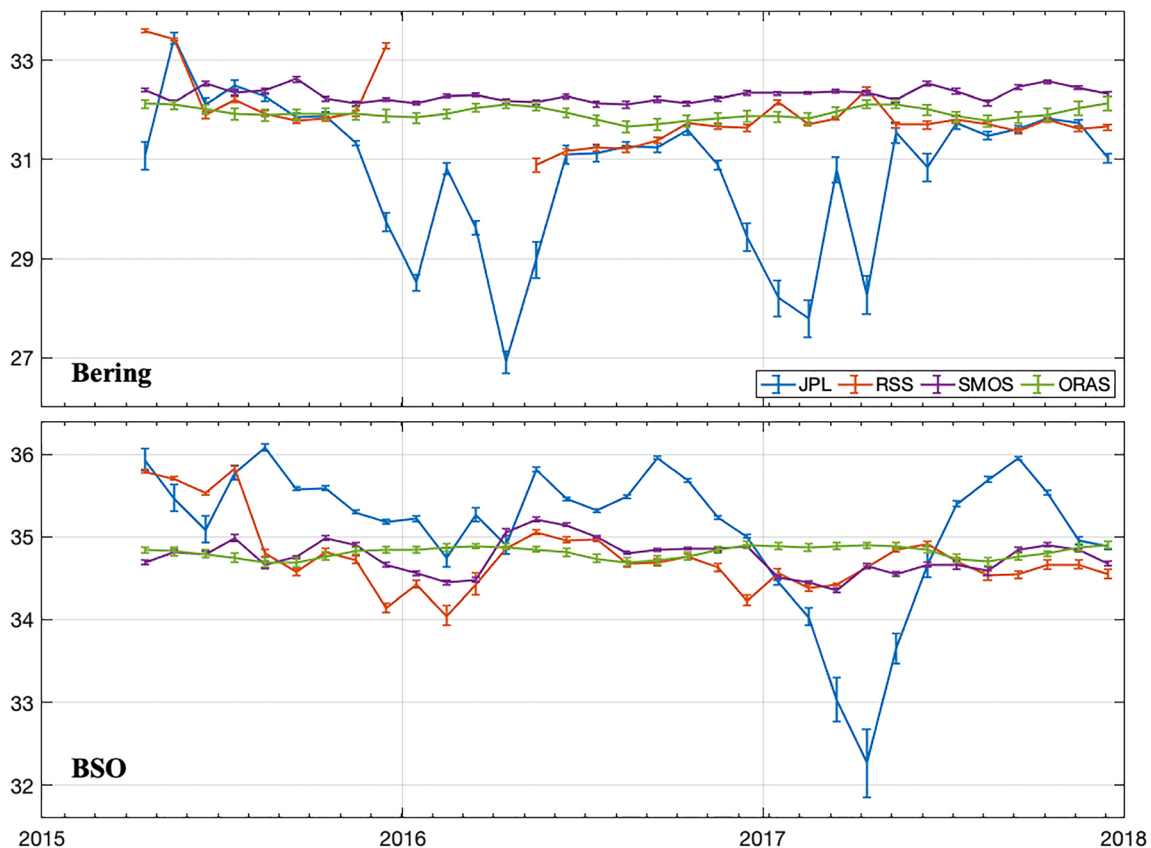
Fig. 4 SSS (psu) time series, with standard error bars, in the Bering Strait and BSO from April 2015 to December 2017 using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green)

cycle of salinity due to the melting and formation of ice. In the central Atlantic, the high variability may be due to variation in the strength and location of the North Atlantic Drift. The fluxes have standard deviations that are as large or higher than the mean fluxes in localized regions. These figures show the regions where freshwater is moving into the Arctic, like the Bering Strait, and regions where freshwater is leaving the Arctic, like much of the subarctic Atlantic. The direction of these fluxes is what we would expect to see based on surface currents in these regions. For example, in most of the subarctic Pacific, the fluxes are northward propagating because Pacific waters move into the Arctic. However, in the subarctic Atlantic, the freshwater fluxes are generally southward propagating as there is high freshwater export out of the Arctic.

The satellite-derived zonal and meridional surface advective freshwater fluxes are compared to ORAS in the Bering Strait and BSO (Figs. 8 and 9). Some satellite products were able to detect similar mean flux and variability to ORAS in the Bering Strait; however, in the BSO, they were very different (Table 1). ORAS can also be a used as an external reference for the satellites, as it covers the same time period and shows similar SSS to Argo in the subarctic. However, there were no significant correlations between the zonal freshwater fluxes of ORAS and any of the satellites. For meridional fluxes, ORAS was significantly correlated to JPL SMAP (0.4017), SMOS (0.5358), and RSS SMAP (0.4560) in the Bering Strait. While SMOS meridional freshwater flux had the highest correlation to ORAS in the Bering Strait, JPL SMAP was most similar in mean flux to ORAS (1642.40 $\pm$ 996.72 m^2 s^{-1} for JPL SMAP and 1501.4 $\pm$ 1324.5 m^2 s^{-1} for ORAS). The only significant correlations with satellite products and ORAS in the BSO were negative, indicating the satellites do not capture an accurate representation of the fluxes in this region. The Bering

Fig. 5 Mean (**a**, **b**) and standard deviation (**c**, **d**) of the zonal (**a**, **c**) and meridional (**b**, **d**) geostrophic currents (m s^{-1}) from April 2015 to December 2017
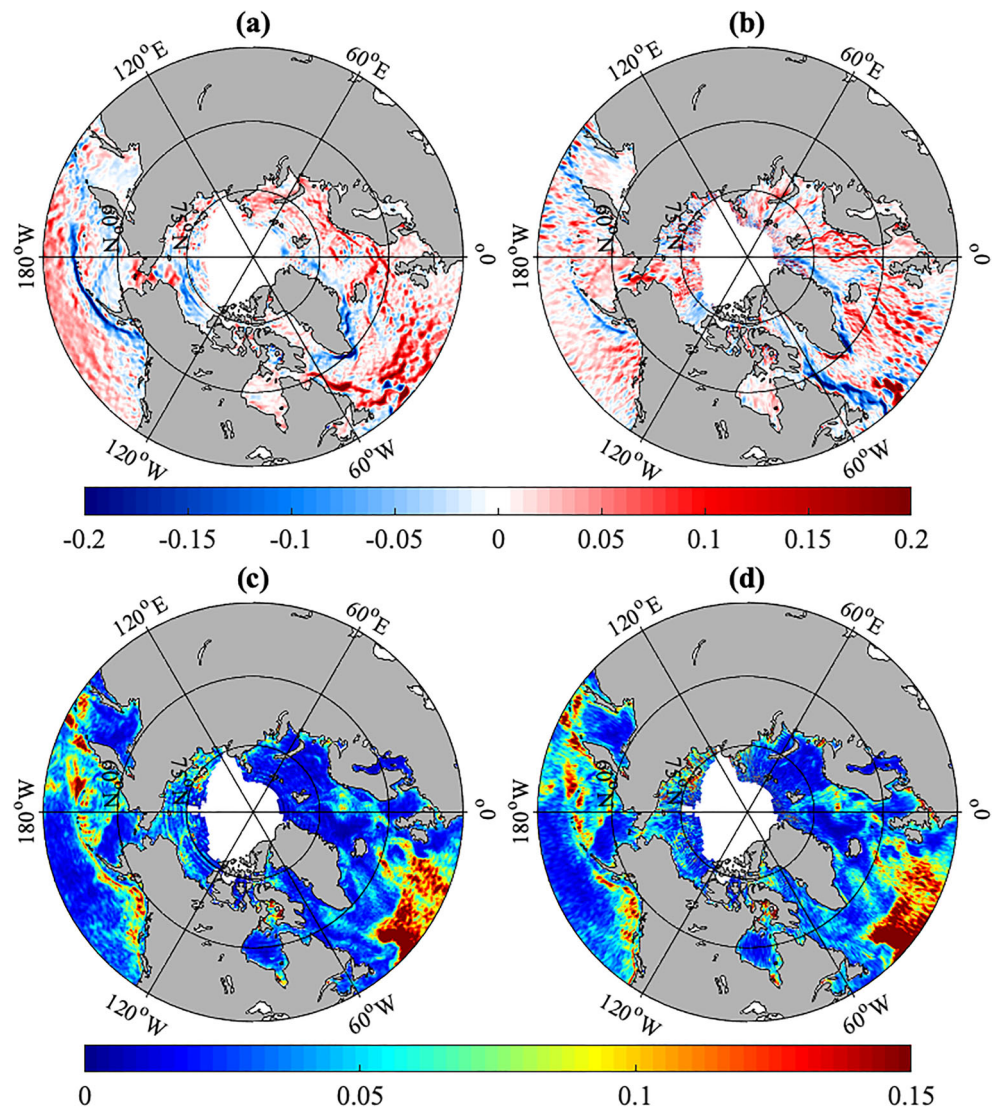
Fig. 6 Mean (**a–d**) and standard deviation (**e–h**) of the zonal freshwater fluxes (m² s⁻¹) from April 2015 to December 2017 for JPL SMAP (**a**, **e**), RSS SMAP (**b**, **f**), SMOS (**c**, **g**), and ORAS (**d**, **h**)
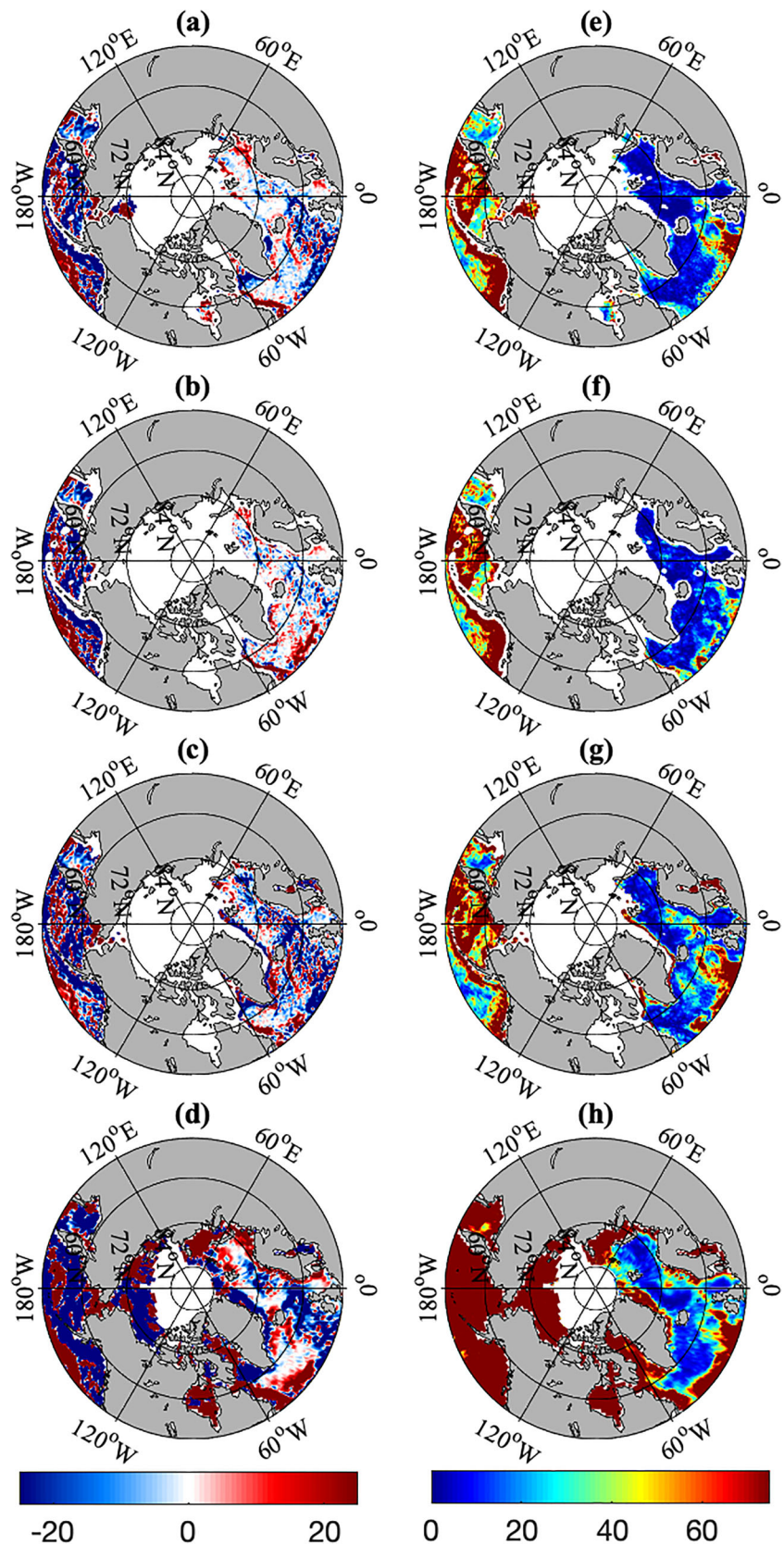

Strait is at a lower latitude than the BSO which could decrease errors associated with SSS retrieval in the higher latitudes. The

means and standard deviations for each product's freshwater fluxes are shown in Table 1. These values show very different

Fig. 7 Mean (**a**–**d**) and standard deviation (**e**–**h**) of the meridional freshwater fluxes (m^2 s^{-1}) from April 2015 to December 2017 for JPL SMAP (**a**, **e**), RSS SMAP (**b**, **f**), SMOS (**c**, **g**), and ORAS (**d**, **h**)
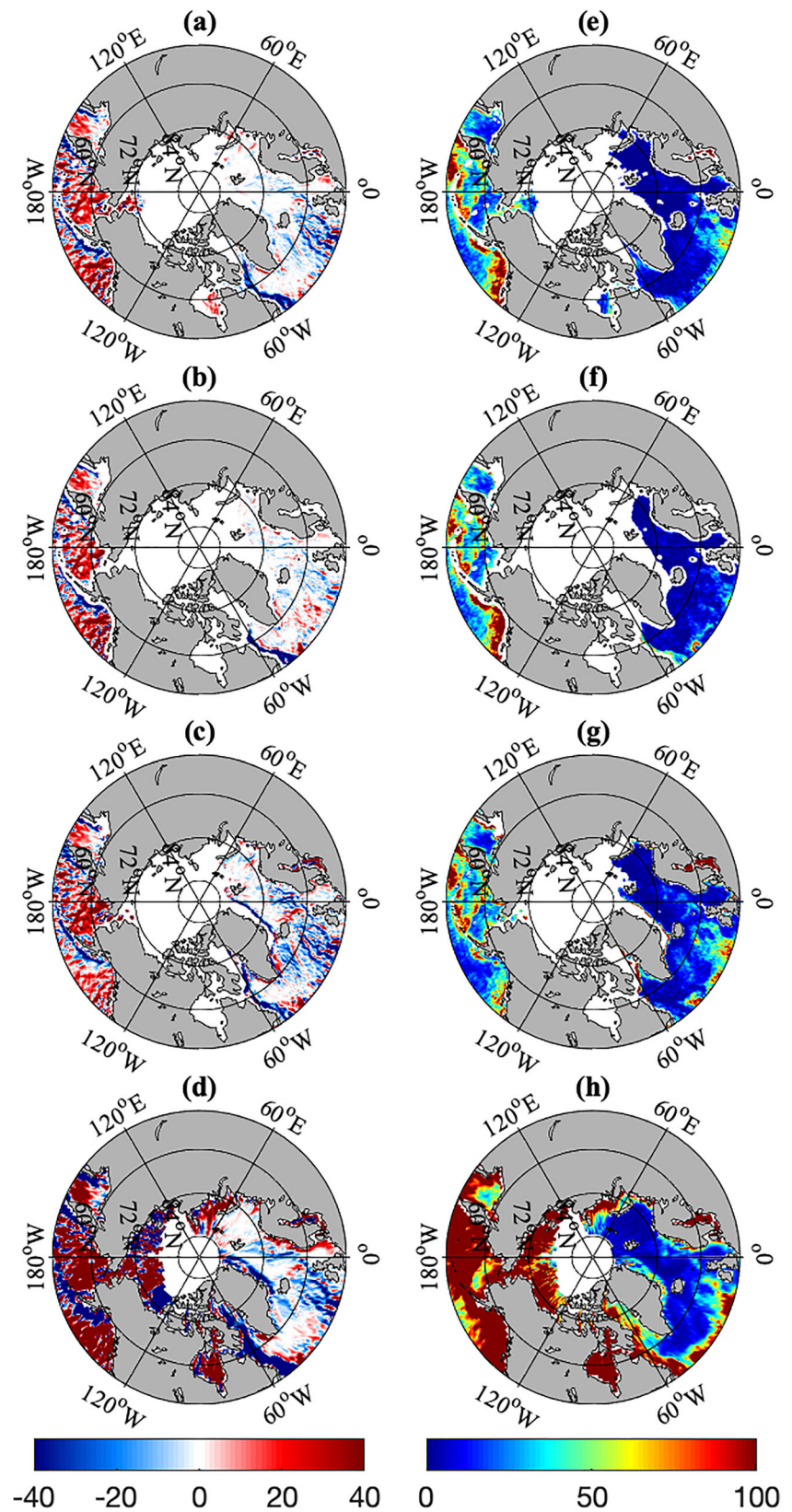
means and standard deviations in the BSO. In the Bering Strait, the meridional flux values are more similar, hence why we see significant correlations between meridional fluxes in this region.
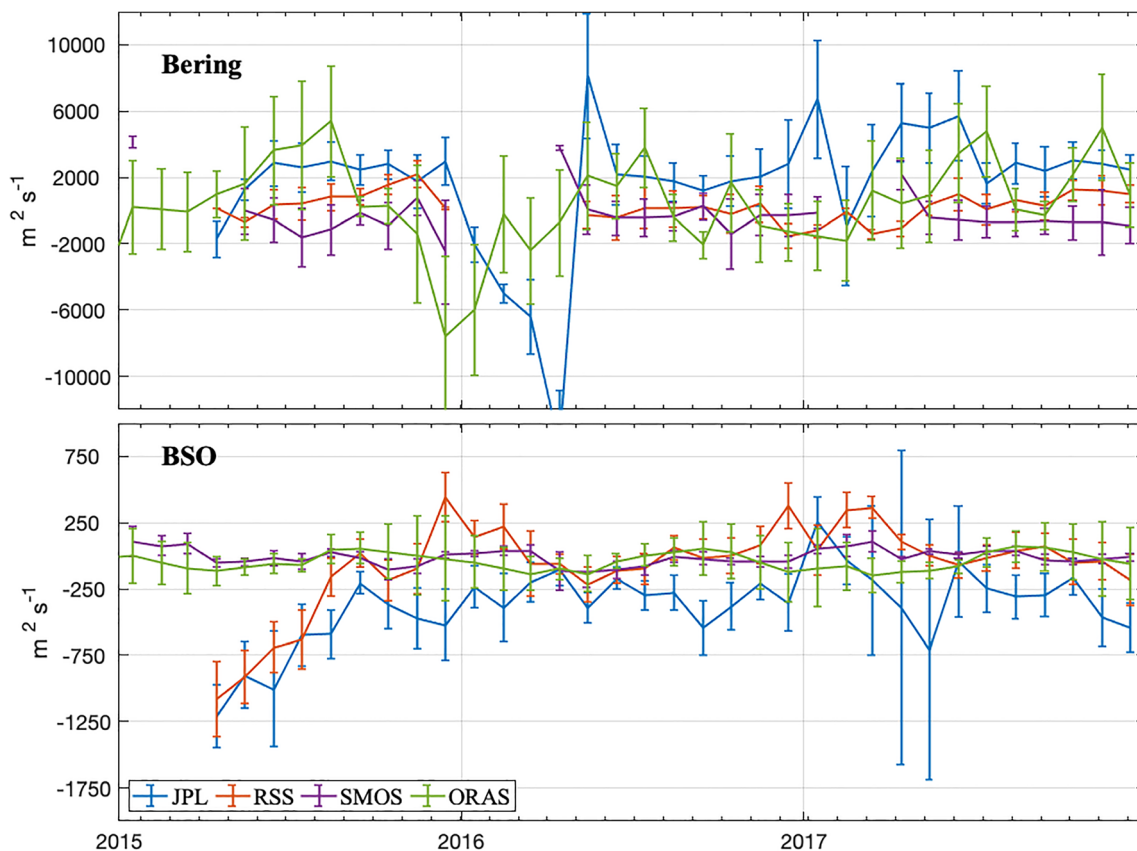
Fig. 8 Zonal freshwater flux time series, with standard error bars, using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green) for the Bering Strait and Barents Sea Opening (BSO) from January 2015 to December 2017

These results indicate that these satellites may be capable of measuring the variability of surface freshwater fluxes in the Bering Strait. The BSO, due to its higher latitude and proximity to many land masses, does not show the same capability of satellites in measuring surface freshwater fluxes. The Bering Strait has a much larger amplitude than BSO (Figs. 8 and 9) which is able to be captured by the satellites and ORAS. This large variability is due to changes in local winds (e.g., [11]) and substantial interannual salinity variability [39].

Variability in the surface freshwater fluxes are driven by multiple different factors, including SSS and geostrophic currents. These surface advective freshwater fluxes are estimated as the freshwater anomaly compared to SSS of 34.8 psu. Larger freshwater fluxes indicate SSS values lower than this reference. The long-term trends of surface freshwater fluxes are not calculated as we were calculating fluxes during the SMAP time period and investigating the ability of satellites in measuring surface freshwater fluxes. However, a longer SSS trend will prove the utmost importance in monitoring the Arctic climate. The freshwater fluxes from all these datasets are calculated with geostrophic currents from altimetry based on SSH. While this is not an overall measure of the currents, there is a lack of full coverage currents in the Arctic region. This is a very difficult region to get accurate, year-round measurements due to the sea ice and harsh winter

conditions. Error associated with geostrophic currents may also affect the freshwater flux calculations.

4 Conclusions

Satellite-derived SSS can capture overall patterns, like a higher SSS in the Atlantic, a low SSS in the Pacific, and a lower SSS in the Arctic. The satellites and ORAS are similar to Argo SSS in the subarctic seas. However, these satellites have more difficulty accounting for surface freshwater fluxes in smaller regions close to land and sea, like the Arctic gateways. The satellites can detect fluxes in similar magnitude and variability to ORAS in the Bering Strait; however, they have more difficulty in the BSO.

There is large variability, both from seasonal variability and product bias, in the SSS and resulting horizontal advective freshwater fluxes in the Arctic. The lack of consistency between products in these regions emphasizes the need to improve satellite-derived measurements and uncertainties in the Arctic. This can be done by increasing in-situ observations on consistent, broad scales in order to validate the satellite data. As sea ice declines, impacting freshwater distribution in the Arctic, it is important to continue and improve in-situ and satellite monitoring of this area because we do not yet fully
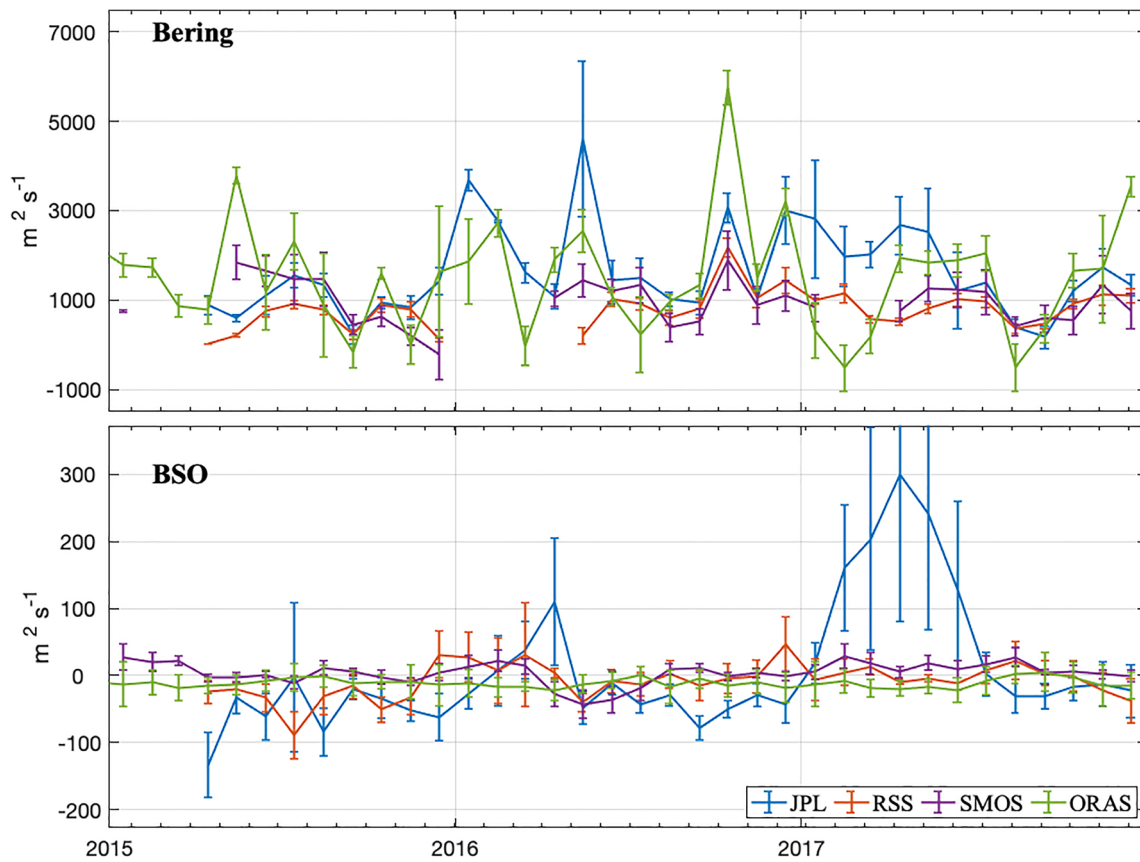
Fig. 9 Meridional freshwater flux time series, with standard error bars, using JPL SMAP (blue), RSS SMAP (orange), SMOS (purple), and ORAS (green) for the Bering Strait and Barents Sea Opening (BSO) from January 2015 to December 2017

know the broader impacts from climate change. While this study focuses on the surface region, it is also important to study potential changes with depth, which is why the accuracy of models and reanalysis products is crucial as well.

This work provides a way to study horizontal advective freshwater fluxes using satellite-derived SSS in the Arctic region. As far as we are aware, there has not been work on surface advective freshwater fluxes derived from remote sensing SSS in the Arctic region due to previous data gaps and

high latitude satellite uncertainties. The JPL SMAP product provides SSS measurements closer to the coasts and sea ice than previous sensors, which allows for better coverage of processes, but possesses large uncertainties in these regions. RSS SMAP and SMOS therefore have less uncertainty in the high latitudes due to sea ice contamination but miss critical processes along the sea ice in the Arctic. Satellite-derived salinity may also prove to better account for surface freshwater than ocean or ocean-atmosphere coupled models and can

Table 1 Zonal and meridional horizontal advective freshwater flux estimates ($m^2 \, s^{-1}$) from April 2015–December 2017 in the Bering Strait and BSO for JPL SMAP, RSS SMAP, SMOS, and ORAS

	Product	Zonal mean	Standard deviation	Meridional mean	Standard deviation
Bering ($m^2 \, s^{-1}$)	JPL SMAP	1563.7	3954.8	1642.4	996.72
	RSS SMAP	222.23	854.25	788.49	436.02
	SMOS	− 154.12	1388.5	963.23	503.48
	ORAS	530.11	2799	1501.4	1324.5
BSO ($m^2 \, s^{-1}$)	JPL SMAP	− 381.17	282.74	7.75	95.84
	RSS SMAP	− 71.72	329.97	− 8.25	26.15
	SMOS	9.15	60.38	4.15	16.3
	ORAS	− 41.1	67.39	− 11.16	6.79

be used to improve future model simulations by assimilating these satellite-derived salinity products.

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