



Sea surface salinity variability from satellite and in situ observations around Greenland

Gilles Reverdin, Fabrice Bonjean, Louise Kilian, Jacqueline Boutin, Sébastien Guimbard, Jean-Luc Vergely, Nicolas Foukal, M. Femke de Jong, Elodie Duyck, Colin Stedmon, et al.

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Sea surface salinity variability from satellite and in situ observations around Greenland --Manuscript Draft--

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Abstract:	Sea Surface Salinity (SSS) is investigated south of Greenland using products derived from satellite radiometric data at pixel resolution: the weekly CCI SSS+ V4.4 dataset from the Climate Change Initiative (CCI) for 2010-2022 and a higher temporal resolution dataset, CATDS-HR, for 2015-2022. These are compared to quality assured in situ measurements. Both satellite data products reveal large positive biases on the shelves. The CCI product removes more data on the Greenland shelves and underestimates variability in this region by almost twice as much as CATDS-HR. In contrast, in regions with low SSS variability in the central North Atlantic subpolar gyre, satellite salinity products overestimate variability by 40% (0.17 instead of 0.12 pss, Practical Salinity Scale), due to uncertainties of about 0.14 pss in SSS retrievals. Nevertheless, there, CATDS-HR is 10% closer to in situ data than CCI-V4. In regions with high SSS variance, farther than 100 km from the Greenland coast, the two products capture significant seasonal and interannual SSS variability of salinity, resolving variability at 50 km length scales. Both satellite products and in situ data from 2010-2022 indicate that the freshest water in the eastern Labrador Sea occurred in September-October 2021. Then, the satellite products show a larger than 2 pss drop in SSS over the slope, and still over 1 pss 300 km further offshore, lagging behind the variability near the shelf break. This suggests that satellite SSS products contribute to resolve freshwater exchange from the shelves to the ocean interior, albeit adjustments are needed on the shelves closer to Greenland to adequately correct for systematic biases.
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Paris, July 20 2024

Dear Editor,

Please find attached the manuscript entitled:

‘Sea surface salinity variability from satellite and in situ observations around Greenland’

by G. Reverdin et al., that we would like to publish in *J. Atmosph. Ocean. Technol.*.

In this paper, we investigate to which extent recent sea surface variability of surface salinity near Greenland can be inferred from in situ and satellite observations since 2010. The overall motivation is the influence of large fresh water input from Greenland shelves as well as from the Labrador shelves on the surface salinity of the Labrador Sea and the North Atlantic subpolar gyre. This region is the site of intermediate water formation which freshening can influence, as well as ultimately the deep branch of the Atlantic overturning circulation. The more immediate motivation was a large freshening observed in in situ and satellite data in the eastern Labrador Sea in September-October 2021, but with conflicting information closer to Greenland.

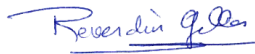
To pursue this investigation, we compiled an extensive set of in situ salinity data with unprecedented coverage over the Greenland shelves, and used collocation methods of in situ and satellite data to investigate ‘collocated’ variability. The investigation indicated that, away from shore, recent satellite products produced at CATDS and by CCI SSS perform rather well, in accordance to the uncertainty estimates provided, with still some room for improvement, as suggested by a prototype high resolution time product. However, salinity variability is underestimated on the shelves in these satellite products. Also, we found that the filtering of near-shore data is not done in the same way in the different products, and that, in this region, it would be beneficiary to retain data closer to the coast than in the standard CCI SSS V4.4 Product. We also identified strong average biases of these satellite products in coastal waters, which are related to the ISAS product based mostly on Argo profile data that is used to adjust the satellite products long-time average. These biases can be corrected in this region, revealing the spatio-temporal variability of the freshening in September-October 2021 in the Labrador Sea, and its origin from the SW Greenland shelves.

We confirm that neither the manuscript nor any parts of its content are currently under consideration or published in another journal.

All authors have approved the manuscript and agree with its submission to J. Atmosph. Ocean. Technol..

Sincerely yours,

Reverdin Gilles

A handwritten signature in blue ink that reads "Reverdin Gilles". The signature is written in a cursive style with a horizontal line underneath the name.

Sea surface salinity variability from satellite and in situ observations around Greenland

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Keywords: Band-L radiometry; SSS; North Atlantic subpolar gyre; Labrador Sea; Greenland shelves

Significance statement: Low salinity water originating from the Arctic and Greenland is present over the shelves off Greenland, which at times is exported to the Labrador Sea, where it can influence its surface salinity and density. We explore surface salinity variability from an unprecedented in situ surface data set as well as surface salinity products from band-L radiometry retaining the satellite data spatial resolution. These products often present large average biases over the Greenland shelves, which originate from the adjustment of their long-time average to a biased climatology which can be regionally improved. The variability in the satellite products satisfactorily reproduces the variability observed in in situ data, with underestimated variance on the shelves, and larger variance associated with the uncertainties in the less variable central North Atlantic subpolar gyre. We identify a major export of freshwater from the southwest Greenland shelf into the eastern Labrador Sea in September-October 2021, with unprecedented spatial resolution.

Abstract

Sea Surface Salinity (SSS) is investigated south of Greenland using products derived from satellite radiometric data at pixel resolution: the weekly CCI SSS+ V4.4 dataset from the Climate Change Initiative (CCI) for 2010-2022 and a higher temporal resolution dataset, CATDS-HR, for 2015-2022. These are compared to quality assured *in situ* measurements. Both satellite data products reveal large positive biases on the shelves. The CCI product removes more data on the Greenland shelves and underestimates variability in this region by almost twice as much as CATDS-HR. In contrast, in regions with low SSS variability in the central North Atlantic subpolar gyre, satellite salinity products overestimate variability by 40% (0.17 instead of 0.12 pss, Practical Salinity Scale), due to uncertainties of about 0.14 pss in SSS retrievals. Nevertheless, there, CATDS-HR is 10% closer to *in situ* data than CCI-V4. In regions with high SSS variance, farther than 100 km from the Greenland coast, the two products capture significant seasonal and interannual SSS variability of salinity, resolving variability at 50 km length scales. Both satellite products and *in situ* data from 2010-2022 indicate that the freshest water in the eastern Labrador Sea occurred in September-October 2021. Then, the satellite products show a larger than 2 pss drop in SSS over the slope, and still over 1 pss 300 km further offshore, lagging behind the variability near the shelf break. This suggests that satellite SSS products contribute to resolve freshwater exchange from the shelves to the ocean interior, albeit adjustments are needed on the shelves closer to Greenland to adequately correct for systematic biases.

1. Introduction

Parts of the interior Labrador Sea and Irminger Sea in the North Atlantic subpolar gyre (NASPG) are sites of intermediate water formation by convection, reaching depths greater than 1500 m during certain years due to strong atmospheric forcing and heat loss (de Yong et al., 2012; Kieke and Yashayaev, 2016; Yashayaev, 2024). The occurrence of convection is sensitive to salinity (Clément et al., 2023), which has been decreasing in recent years (Yashayaev, 2024; Biló et al., 2022; Fried and de Jong, 2022). Large freshwater transport from the Arctic and from continental inputs, particularly from Greenland, occurs on the shelves around Greenland and the Labrador Sea (Bacon et al., 2014; Carmack et al., 2016; Foukal et al., 2020; Duyck et al., 2022). This freshwater is largely trapped near the sea surface, although in winter it spreads deeper and into the slope currents, as seen in the East Greenland Current (Le Bras et al., 2018). The shelf water is strongly stratified, with minimum surface salinity in late summer due to lighter winds, which is not well monitored by subsurface moored arrays (Le Bras et al., 2018), leading to an underestimation of summer freshwater transport. On the shelves of west Greenland, south of Davis Strait, surface salinity is well documented from *in situ* data (Reverdin et al., 2018), indicating coastal freshening due to summer Greenland melt in some years (Castelao and Medeiros, 2022).

Exchanges between the fresh shelf surface water and the ocean interior occur across the shelf break during short-lived episodes associated with wind driven upwelling at the coast, as shown in studies of the East Greenland Current (Håvik and Våge, 2018; Duyck and de Jong, 2023) and the West Greenland Current near Cape Farewell (Pacini and Pickart, 2023). These processes are spatially and temporally very variable, and are likely uncommon along southeast Greenland until reaching Cape Farewell (Holliday et al, 2007; Foukal et al., 2020; Duyck and de Jong, 2023).

A large part of the freshwater found east of Cape Farewell is transported to southwest Greenland by currents, particularly by the continuation of the East Greenland Coastal Current or by currents along the shelf break (Foukal and Pickart, 2023). Along southwest Greenland, off-shelf transport due to wind variability is compounded by eddies shed from slope currents towards the interior Labrador Sea (Böning et al., 2016). Freshwater transport along the Greenland shelf is expected to increase in the long term due to excess Arctic freshwater and increased continental ice melt (Bamber et al., 2018). Changes in wind regimes could also modify the shelf to ocean exchanges of freshwater (Castelao et al, 2023). Whether these

changes are already affecting convection and ocean circulation remains debated (Böning et al., 2016; Yang et al., 2016).

This study focuses on salinity variability retrieved from *in situ* data and satellite radiometry since 2010, particularly in the seas around South Greenland (south of 70°N). *In situ* data are sparse, providing incomplete coverage of the salinity fields on time scales of a few days to weeks, which are relevant for variability both on the shelves and across the shelf-break. L-Band radiometric satellite measurements collected since 2010 offer the potential to measure finer spatial and temporal variability. However, this region is challenging for L-Band radiometry salinity measurements due to the low sensitivity of the radiometric signal to salinity at low temperatures encountered in particular in winter-spring, coverage by sea ice and icebergs, and occasional intense winds, making satellite salinity retrievals less accurate (particularly near Cape Farewell, Moore and Renfrew, 2005). Radiometric measurements were further influenced by radiometric frequency interferences (RFIs), especially south of Greenland in 2011 and east of Greenland until 2015, with challenges in removing or mitigating these RFIs from L-Band radiometric data, particularly for interferometric satellite mission (Bonjean et al., 2024). An earlier analysis suggests that some satellite salinity products identified significant near-coastal freshening events off west Greenland, although there were annual average or seasonal biases depending on data products used (Castelao and Medeiros, 2022).

Recently, efforts have increased to retrieve salinity variability at smaller spatial and temporal scales by combining data from different L-Band radiometric satellite missions (CCI SSS+ L4 products; Boutin et al., 2021). Additionally, enhanced *in situ* data coverage over the past decade, particularly from 2017-2022, provides *in situ* surface salinity measurements of the south Greenland shelves and nearby seas, that motivates a dedicated validation of satellite salinity products in this region. This will contribute to more confidence in the performance of derived products that combine satellite salinity data with *in situ* observations (Melnichenko et al., 2016; 2021, Kolodziejczyk et al., 2021).

2. Data

a. The satellite salinity products

We use a selection of salinity products with high spatial resolution, featuring minimal spatial smoothing. Salinity in this paper is reported as a practical salinity in the 1978 scale (pss).

Effective resolution is primarily determined by the satellite measurement footprint, approximately 45 km for SMOS and SMAP.

The Climate Change Initiative (CCI) SSS V4.4 (referred to as CCI V4.4) gridded salinity product for the period 01/2010 to 11/2022 combines data from all satellite microwave radiometers operating at 1.4 GHz since 2010 (Boutin et al, 2024). This includes level 2 SSS from Soil Moisture and Ocean Salinity (SMOS) mission (processed by ESA Data Processing Ground Segment version 7) from 01/2010 to 11/2022, Aquarius (version 5) from 08/2011 to 06/2015, and Soil Moisture Active Passive (SMAP) mission data processed by Remote Sensing System (version 5.0) from 04/2015 to 11/2022. The overlap in temporal coverage helps reduce random uncertainties during the SMOS and SMAP period compared to the SMOS-only period and reduce blurring compared to the Aquarius period, owing to the better spatial resolution of SMOS and SMAP. Compared with earlier SMOS ESA versions and Centre Aval de Traitement des Données SMOS (CATDS) processing, the masks around land and ice were extended further, leading to less CCI data near coasts.

The CCI processing involves three main aspects (Boutin et al. 2021). Systematic biases depending on satellites geometry acquisitions are estimated based on SSS auto-consistency criteria during optimal interpolation in the time domain, with no further spatial smoothing applied. The optimal interpolation in time considers both random and systematic errors for the different satellite missions and maps of SSS variability at various spatio-temporal scales to derive monthly and weekly fields of SSS and estimates of its uncertainties. A final adjustment is made by aligning in each pixel the median value of the produced SSS time series (or an upper quantile in highly variable regions) to that of the In Situ Analysis System (ISAS) product based on *in situ* data (Gaillard et al., 2016).

With respect to earlier CCI versions, CCI v4.4 has been extended in time to 10/2022. Ice filtering has been significantly improved (it was too strong in earlier versions), and the SMOS SSS measurements have been adjusted using improved models for the wind dependence, dielectric constant and rain impact. Furthermore, latitudinal seasonal corrections have been applied to all satellite missions, reducing latitudinal seasonal biases at high latitudes, though a positive bias remains in 2015 from April to October due to an issue in SMAP v5.0. Further details on CCI v4.4 algorithms can be found in the Algorithm Theoretical Baseline Document (ATBD), End-to-End ECV Uncertainty Budget (E3UB), and Product Validation and

Algorithm Selection Report (PVASR) available on <https://climate.esa.int/en/projects/sea-surface-salinity/>.

The random uncertainties for CCI v4.4 provided as ‘uncertainty’ fields are larger near the coasts and sea ice border due 1) to the higher representativity error in these highly variable regions and 2) to land-sea and ice-sea contaminations on satellite brightness temperatures (Tb), which degrade the SSS retrieval quality. They are also larger in regions with RFI, as identified in the north-east Atlantic in 2010-2014, and near South Greenland in 2011, due to a reduced number of Tb, filtered to avoid RFI contamination, or insufficient Tb filtering. Furthermore, the ISAS product results from spatial objective mapping of *in situ* data, mostly from Argo floats, and resolves variability scales larger than 300 km. Thus, it cannot resolve the narrow freshwater tongue on the southeastern Greenland shelf or the strong salinity contrast near the shelf break. Since the fresh tongue is present most of the year, this high quantile of multi-year ISAS SSS can bias the final calibration of the CCI data. Also, ISAS benefits from very little sampling in shelf areas, except occasionally in southwestern Greenland from September 2021 to the end of 2022. Similar issues are present in products combining *in situ* and satellite data, such as in Melnichenko et al (2016) and Kolodzieczyk et al. (2021).

We also use the global SMOS SSS product ‘debiased-SSS 09days v8’ from the Center of Expertise of CATDS - Ocean Salinity, later referred to as CATDS CEC V8. These fields are used to compare performance when using only SMOS data. The CATDS SMOS processing involves less filtering than the ESA v7 processing and uses nearest neighbor median smoothing, resulting in more data on the Greenland shelves than in the CCI v4.4 product. The spatial smoothing results in a 70 km effective resolution of the CATDS CEC v8 product.

Finally, we use a test CATDS-HR product processed specifically for the Greenland region from 2015-2022. It uses a similar processing method as the earlier CATDS-HR fields in eight regions available at CATDS (documentation available online at https://data.catds.fr/cecos-locean/Ocean_products/HIGH_RESOLUTION_8_REGIONS/documentation/Doc_High_Resolution_8_Regions.pdf). The HR SSS product results from an optimal interpolation in the time domain, grid node per grid node, estimating SSS biases based on the satellite measurement geometry (Boutin et al. 2018). The optimal interpolation uses a more tapered smoothing function than for global CATDS CEC products to maintain high temporal

SMOS and SMAP SSS variability in highly variable regions while filtering outliers in low variability regions. For this Greenland CATDS-HR product, no spatial smoothing was applied. It incorporates the same SMOS data as in the CATDS CEC V8 product, as well as an updated version of the SMAP data (version 5.3) from the CCI V4.4 product, mitigating the large 2015 SMAP bias in version v5.0.

b. in situ data

The bulk of the *in situ* data originates from the Salinity Pilot Mission Exploitation Platform (Pi-MEP) (Guimbard et al., 2021), which validates salinity from satellite missions. These data, sourced from public archives after a quality control, mostly include upper-level data from Argo floats (quality flagged as good or probably good), conductivity temperature depth (CTD) casts during cruises and from pinnipeds, and thermosalinograph (TSG) data from research vessels and ships of opportunity. This includes delayed mode data from the French Surface Salinity observing System (SNO SSS) (Alory et al., 2015), other delayed-mode sailing and research ship files from the Global Ocean Surface Underway Data (GOSUD), and US-based Shipboard Automated Meteorological and Oceanographic system (SAMOS).

We further checked the SAMOS TSG data, identifying biased salinity data based on comparisons with nearby Argo float profiles, and either removed or adjusted these by a constant value when possible. We also replaced some SNO SSS data at Pi-MEP with the latest adjusted version. Additionally, we updated this archive with complementary data from the Coriolis site (dataselection.coriolis.eu.org), including CTD tags on hooded seals from 2018-2019 (also in the Marine Mammals Exploring the Oceans Pole to Pole (MEOP) Archive) and real-time transmitted TSG data from German Research vessels Maria S Merian and Meteor in 2020-2022. We extracted validated delayed-mode TSG data from CCGS Amundsen (Canadian Cryospheric Information Network (CCIN) 12715) from 2010-2021. We also accessed and quality-controlled TSG data from HDMS Lauge Koch of the Royal Danish Navy from 2017-2021, as well as from RV Armstrong in August-September 2021.

A-XCTD and CTD data from the Oceans Melting Greenland (OMG) NASA-supported surveys from 2016-2021 were also added, along with data from NOC glider deployments in December 2019 (Clément et al., 2023). We included salinity data from drifters deployed on the east Greenland shelf or near Cape Farewell from 2019-2021 (Duyck et al., 2022; Duyck and de Jong, 2023) and in 2021-2022 near Cape Farewell (Coquereau and Foukal, 2023; from

the Global Drifter Program at NOAA’s Atlantic Oceanographic and Meteorological Laboratory), after checking them against nearby Argo float near-surface data. Data from a few public-accessible CTD cruises, such as the 2017 profiles in Carlson et al. (2021), were also included.

Most of the data in the archive have an accuracy better than 0.05 pss. However, some data, particularly from HDMS Lauge Koch in late 2020 and 2021, have an accuracy not better than 0.1 pss. The data are usually collected in the top 5 m of the water column, but salinity stratification, especially over the shelves in spring and summer, results in a degree of heterogeneity in the data, with measurements closest to the surface, such as from drifters, usually being fresher than deeper data (often near 4 or 5-m depth). This was not compensated for in this study.

The *in situ* data were reduced onto a 25 km x 25 km grid at daily resolution, referred to as *in situ* pixels. This is important in order to reduce the weight of high temporal resolution measurements from drifters or thermosalinographs on vessels, compared to data from CTD profiles (research cruises, Argo floats or sea mammals). The 25-km resolution is smaller than the effective footprint of the satellite data used to retrieve salinity, ensuring that the spatial resolution of the satellite products is not downgraded when collocating *in situ* pixel data to the satellite product. The daily resolution is the shortest time span that the satellite data can resolve, and among the satellite salinity products we used, this time resolution is only approached by the CATDS-HR product.

We then checked the in-situ pixel data set for outliers and removed twenty-three pixel data from 2015-2022 in the central or eastern parts of the North Atlantic subpolar gyre with very low values (less than 33 pss and even less than 30-31pss in some cases, in regions where salinity is usually above 34.5 pss). These data, out of more than 25,000 pixel data in this central region of low variability, originate from the Pi-MEP archive (mostly TSGs or the uppermost point of ARGO floats) and not from the data we added or from qualified SNO SSS data. Such low values are not reproduced in the satellite products, either because the temporal or spatial scales of the phenomena are too small for the satellites to resolve or because they are artefacts. In this very low variability region, they contributed 20% of the total *in situ* variance in 2015-2022. Outliers may also occur in regions of greater variability, where they are challenging to detect. In any case, based on what was found in this region, we expect that

this should remain a small subset through the whole domain, which contains nearly 120,000 pixel data from 2010-2022.

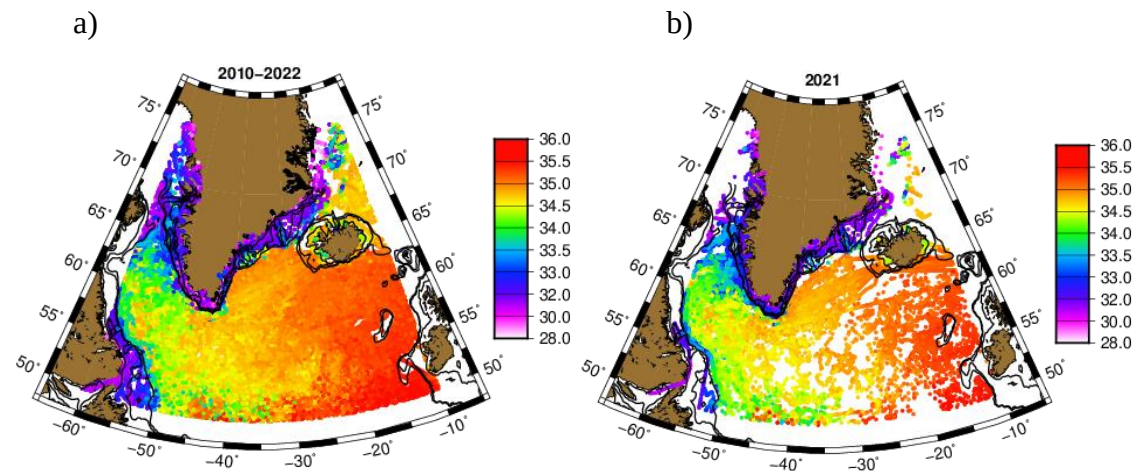


Figure 1: The *in situ* pixel data used for the analysis color-coded as a function of mean salinity for 2010-2022 (a) and for the year 2021 as an example (b). The 100, 300 and 500 m bathymetric contours are shown in black.

In individual years, such as 2021 (Fig. 1b), there are large regions with little or no sampling, but over the whole period (2010-2022) (Fig. 1a), data can be found almost everywhere south of 70°N, at least once, with small data gaps northwest of Iceland or north of 72°N east of Greenland, as well as off western Ireland. The most noticeable large-scale features of Fig. 1 are the low SSS waters present on the shelves around Greenland, originating from the Arctic through Fram Strait and local freshwater inputs, as well as on the Labrador shelf (Fig. 1b), which primarily originate from Baffin Bay and the Arctic through Davis Strait, as well as from Hudson Bay. Near the southern boundary at 50°N, and west of 33°W, more saline waters of the North Atlantic Current (NAC) are occasionally observed with very fresh surface water to its north. In the eastern part of the North Atlantic subpolar gyre (NASPG), the saltier NAC water spreads northward and then cyclonically around the NASPG and the bathymetric features, such as the Reykjanes Ridge, southwest of Iceland.

3. Results

a. Mean fields

The average differences between satellite products and in-situ pixel data are shown in Fig. 2a, and show a similar bias for both satellite products and ISAS data. However, it should be

noted that in the processing chain the mean field of these different satellite products is adjusted to ISAS. The most striking difference is greater coverage of near shore CATDS-HR compared to CCI (Fig. 2a, c). Differences in spatial resolution between the datasets are also clear with CCI V4.4 resolving smaller spatial scales (40-50 km) compared to ISAS (300-500 km in the open ocean), but with residual errors/noise on the smaller scales, increasing the standard deviation of the difference to *in situ* data.

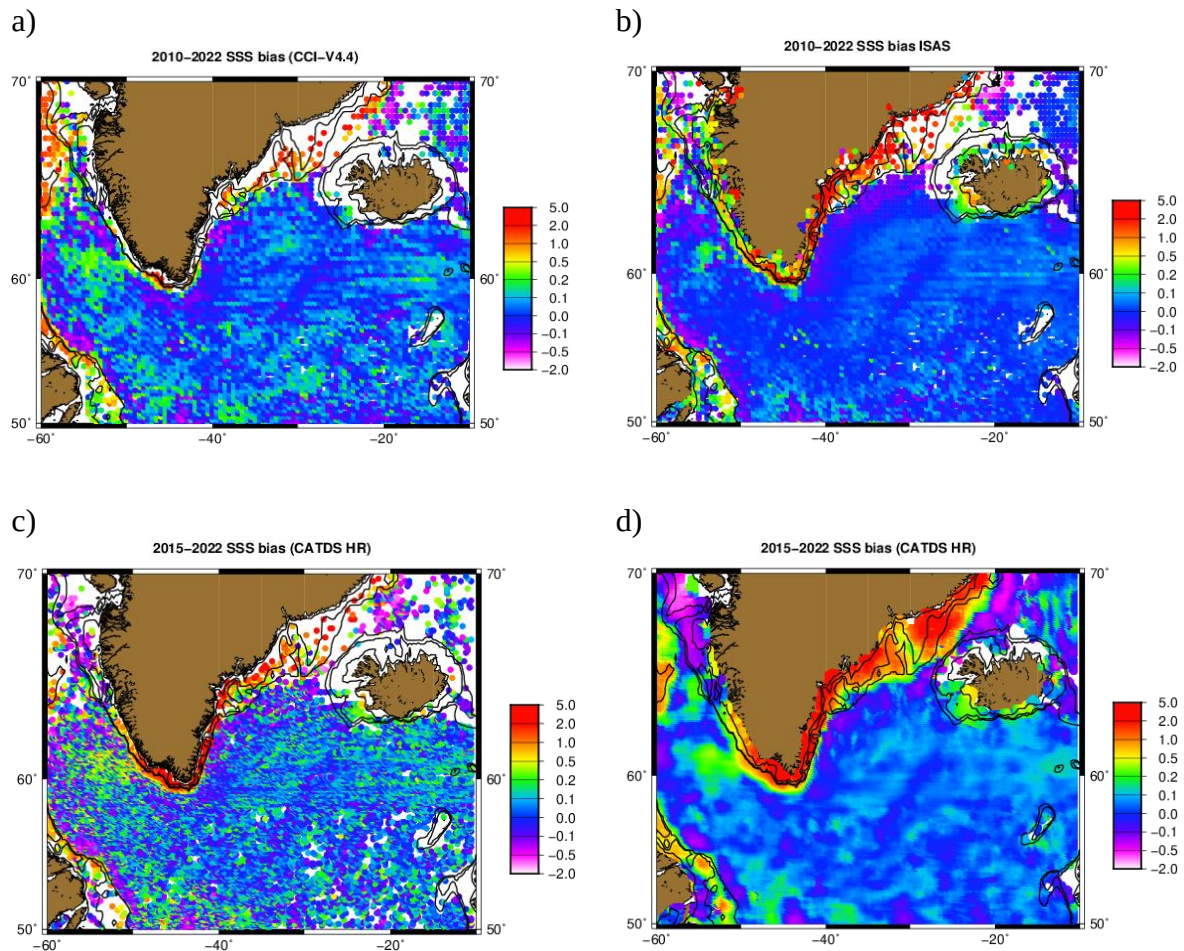


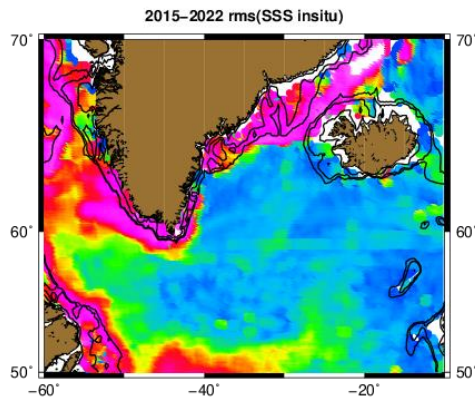
Figure 2: Mapped average SSS difference between different products and the gridded data pixels (a) for CCI V4.4 in 2010-2022, (b) for the ISAS product in 2010-2022, (c) for CATDS-HR in 2015-2022 d), same as c) but with additional spatial smoothing (40 km) applied to the maps. The 100, 300 and 500 m bathymetric contours are plotted.

Figure 2 indicates large positive biases of the different products on most shelves, where the low salinity is not well represented in the gridded ISAS product used to provide a mean reference for these different satellite products. With the exception of western Greenland north

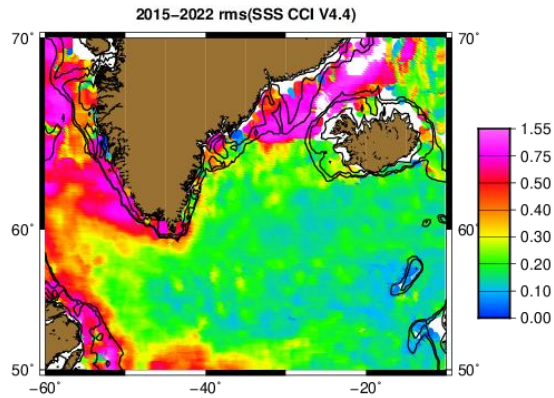
of 65°N, the shelves show positive deviations from *in situ* data, reaching more than 2 pss south or east of Greenland, as previously noted by Castelao and Medeiros (2022) for an earlier product of gridded SMOS data also using ISAS for setting a mean reference. East of Greenland, smaller biases appear just north of two deep troughs on the shelf (the Sermilik Trough south of 65°N, and the Kangerdlussuaq Trough near 67°N), better visualized in the smooth version of Fig.2d. These East Greenland features correspond to saltier *in situ* data than nearby (Fig. 1) that are not reproduced in ISAS and thus in the time mean of the different satellite products we examine. Additionally, there are slightly negative anomalies just offshore of the shelf break, and a patch of slightly positive anomalies in the central Labrador Sea near 58-62°N (Fig. 2). This last patch largely originates from many drifter data in fall 2021, which measured very low SSS but were not incorporated in ISAS. Except for that patch, the ISAS average bias pattern is expected to result from the spatial smoothing of the product (300 to 500 km), with largest differences to *in situ* data corresponding to regions of salinity extrema in the mean fields (Fig. 2b).

b. Root mean square (rms) variability

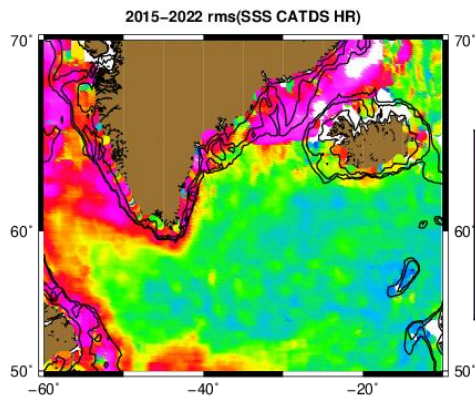
a)



b)



c)



d)

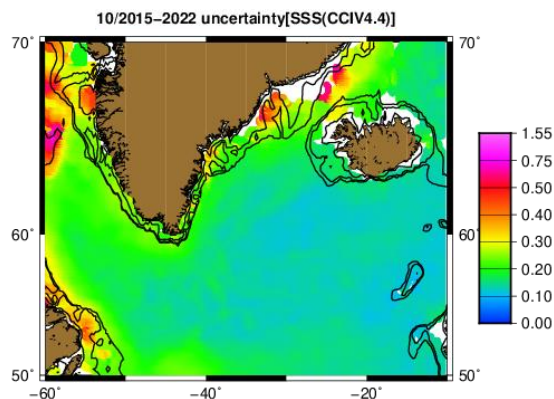
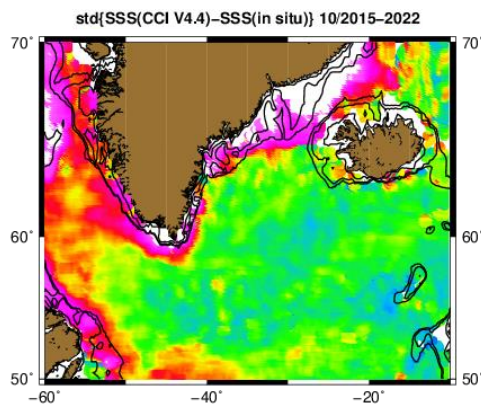


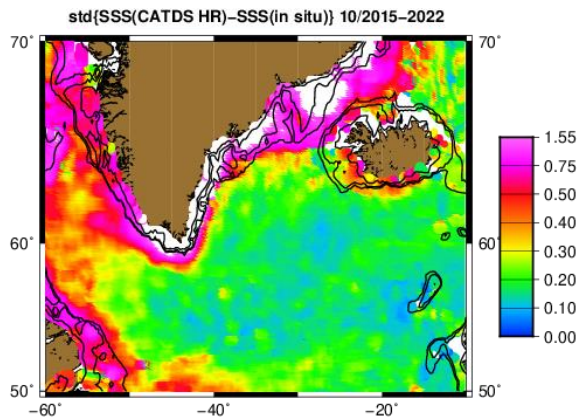
Figure 3: Spatial variability in the root mean square (rms) variability of the *in situ* pixel data in 10/2015-10/2022 (3a), and in the collocated CCI SSS V4.4 fields (3b) and CATD-HR fields (3c); (3d), the uncertainty estimate on the CCIV4.4 product averaged for 10/2015-10/2022. The 100, 300 and 500 m bathymetric contours are plotted.

The large-scale pattern of the root mean square (rms) of the time variability is similarly depicted in the in-situ data and the satellite products, with a large area of low rms centered near 53°N, west of 24°W, but also east of 20°W. There are also large areas of weak rms in *in situ* data near 24°W/60°N in central Iceland Basin, and near 35°W/62°N in the central Irminger Sea. This last one is less pronounced in the satellite products, consistent with the larger estimated uncertainty in the CCI V4.4 product in this area (Fig. 3d). Higher rms values are found on the shelves, in the northern Labrador Sea, and near 50°N between 35°W and 48°W. There is in general a fair agreement between the spatial patterns of rms variability for the different datasets, although the satellite products tend to present less spatial contrasts of rms variability than the *in situ* data, with the bias often more pronounced for the CCI (Fig. 3b) than with the CATDS-HR product (Fig. 3c).

a)



b)



c)



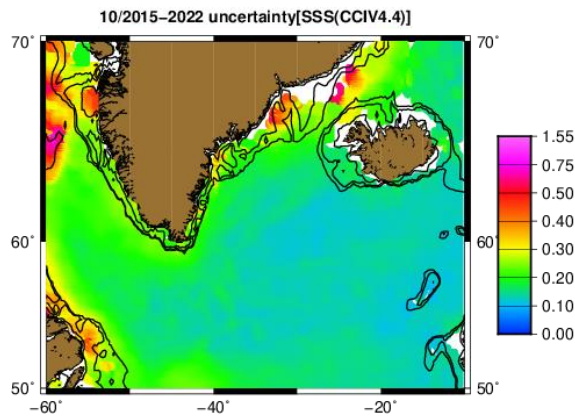


Figure 4: standard deviation of the bias between data products and the *in situ* pixel data for the period 10/2015-10/2022: a) CCI V4.4; and b) CATDS-HR. c) shows the uncertainty estimate on the CCIV4.4 product averaged for 10/2015-10/2022. The 100, 300 and 500 m bathymetric contours are plotted.

These patterns are also observed in the standard deviation (std) of the bias between the collocated CCI V4.4 satellite and *in situ* pixel data (Fig. 4). In areas of the subpolar gyre with low rms variability in the *in situ* data (Fig. 3a), these std differences (0.19 pss) tend to be larger than the rms variability in *in situ* data in the open ocean (0.115 pss), but close in magnitude to the rms variability in the satellite product (0.17 pss). This suggests that a significant part of the variability of the satellite products is uncorrelated with *in situ* data. In this region, the uncertainty in the CCI V4.4 satellite products (fig. 4c) has a magnitude (0.14 pss) close to the rms variability (0.17 pss) in the satellite product. Thus, this uncorrelated variability likely contributes significantly to the std of the bias, which is also roughly 10% smaller in these regions for CATDS-HR than for CCI V4.4. The results are more variable over the shelves, with larger std in the differences of CATDS-HR with *in situ* data in some regions of SW and SE Greenland or near Iceland, but larger for CCI V4.4 in others.

This structure of variability in magnitude and variance of the bias from *in situ* pixel data generally holds for the earlier part of the record of the satellite CCI V4.4 product (not shown). However, it is more difficult to interpret, as this includes a long period incorporating Aquarius data, which have a much larger satellite footprint (100 to 150 km), resulting in smoother spatial CCI V4.4 fields in the open ocean. There are also remaining influences of RFIs, in particular for the SMOS data in the northeastern Atlantic until early 2015 and around 2011 near South Greenland. Furthermore, data processing/sorting near the coast or ice-covered

areas creates differences between the different products. For that reason, we will now investigate them as a function of distance to the Greenland coasts and shelf break.

c. Time series of variability as a function of distance to Greenland coast.

We sort the comparisons of *in situ* pixel data and the satellite products as a function of distance to the coast, grouping the data regionally based on shelf width and average distance to the coast (Fig. 5). This was done as we expect large coastally trapped signals and a strong dependency of the errors in the satellite products on distance to the coast and sea ice. The distance to the coast is estimated based on the closest land-boundary contour at a resolution of 0.04° . Thus, because of the presence of many fjords, islands and bays, salty sea surface water often penetrates much further inshore than the not-shown 0-distance contour. The domain we investigate extends to the middle of the nearby seas, where Greenland is the nearest coast. Region W includes the west Greenland shelf from 63.5°N to south of Disko Bay (68°N) and the associated coastal current and West Greenland current near the shelf break. The shelf there is wider than 100 km and can be seasonally covered by sea ice. Region SW along southwest Greenland, has a 50-km wide shelf and almost no seasonal sea ice. Region S extends far to the south of Greenland. The transient and varying shelf circulation around Cape Farewell implies that it is a heterogeneous shelf region (Foukal and Pickart, 2023), albeit there is often continuity of circulation near the shelf break and offshore (Duyck and de Jong, 2023). In spring, sea ice intermittently arrives from East Greenland. Regions SE and E up to 68°N north of Denmark Strait is seasonally covered by sea ice on the shelf, and the shelf is 50-km wide in SE but much wider in region E, extending 100 to 150 km from the coast and cut by deep troughs. The currents in these boxes include the southwestward flowing very fresh and cold East Greenland Coastal Current and the East Greenland Current near the shelf break. The saltier Irminger Current is found further offshore in the Irminger sea.

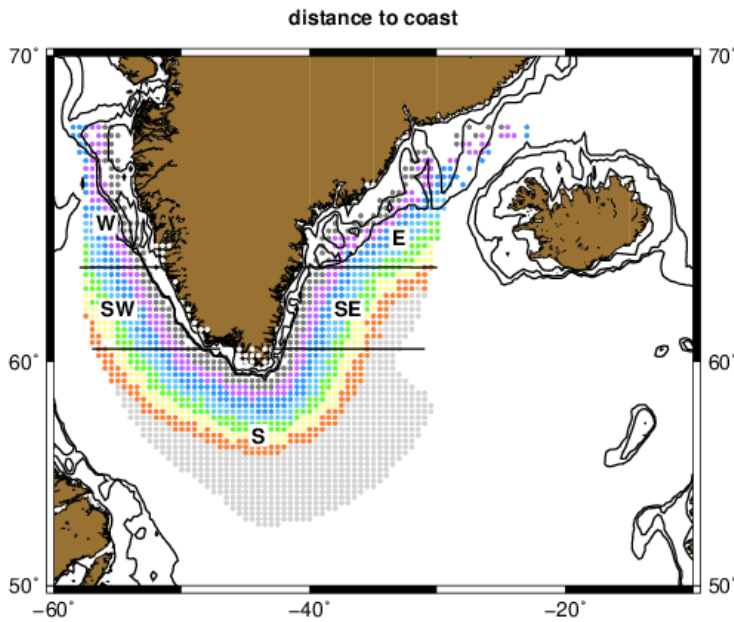
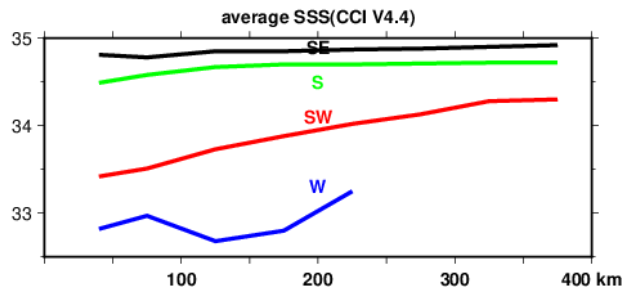


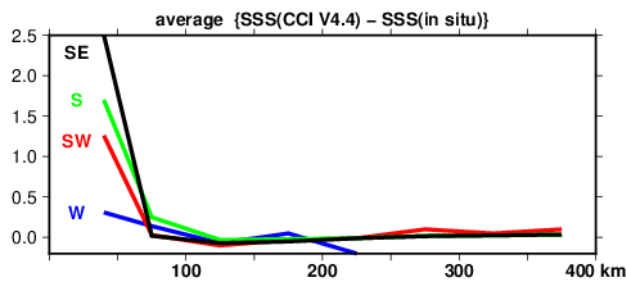
Figure 5: grid points with at least 3 pixels of data, color-coded as a function of distance to shore (one colour for 50 km band-range; light grey corresponding to distance larger than 400 km). The strait lines separate the different sub-regions south of 68°N (W, SW, S, SE, and E). The 100, 300 and 500 m bathymetric contours are plotted.

To gather enough comparison data and reduce large sampling uncertainties, we binned collocated data in bands of 50-km distance from the coast in each domain and each month. In each bin, all the *in situ* pixel data were averaged and aligned with collocated satellite data to create two time series, retaining a value if there are at least two pixels averaged in the bin. The distribution of the pixels is often spatially heterogeneous, but the circulation is often rather swift with less than one-month transit time from region E to southwest Greenland (region SW) (Duyck and de Jong, 2023). Variability in west Greenland on the shelf was also found to be rather meridionally homogeneous on seasonal time scales from TSG data (Reverdin et al., 2018) and from SMAP or SMOS monthly fields (Castelao and Medeiros, 2022), except for the northernmost Disko Bay region. Thus, except possibly for regions E and W or within 50 km of the coast, major seasonal signals extend throughout the region in each 50-km distance band to the coast. There is still a large noise remaining in the monthly binned comparisons due to limited sampling, which needs further assessment. Even with data and satellite products collocated at the same time and space, there are differences related to representativeness differences in comparing the daily pixel data with products based on satellite data with a larger spatial footprint and with longer time scales.

a)



b)



c)

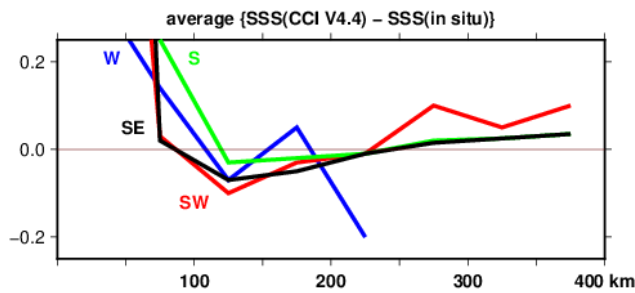
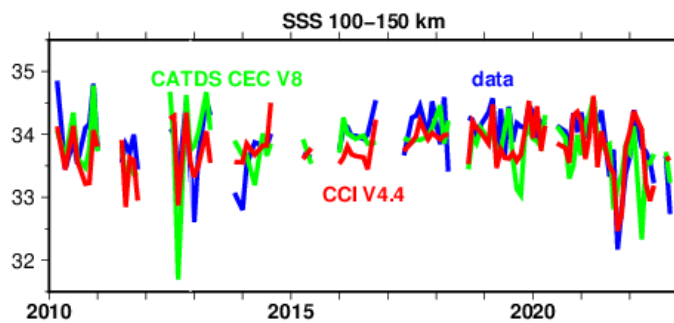


Figure 6: (a) Average CCI salinity, (b) and (c) average differences between CCI and the in-situ data as a function of distance to Greenland by region (c is a zoom of b) (vertical scales in pss)

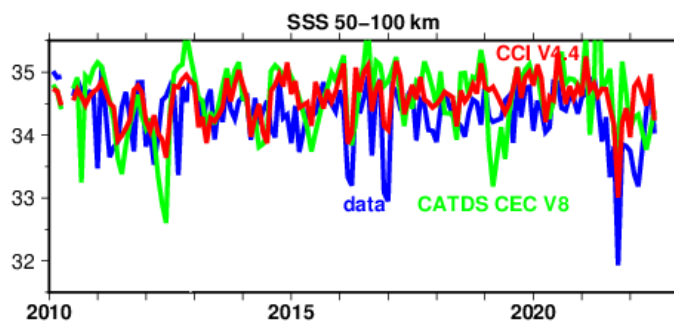
The average differences (Fig. 6) confirm the spatially mapped averages of figure 2. The uncertainties on these averages (not shown) are usually smaller (~ 0.01 - 0.03 pss) than the mean portrayed, except very close to the coast and for region W, where uncertainty on the average differences is on the order of 0.15 pss at distances 150 to 250 km from Greenland. In the four regions of Figure 6, the bias changes between positive values within 50 km of the coast (and very large in all regions except W) to negative differences compared to *in situ* data at 100-225 km from the coast, followed by slightly positive biases further offshore. The results are similar for CATDS-HR (not shown) or the CATDS CEC V8 product, as they all adjust to the ISAS average objective-analyzed gridded fields. The satellite products in region E present large and positive biases (greater than 1 pss) but with large uncertainties extending

to 150 km from the coast near the shelf break. In E, the season sampled in the pixel data is short with large interannual variability in data coverage, and thus would require further investigation to be certain on the bias.

a) SW



b) S



c) S

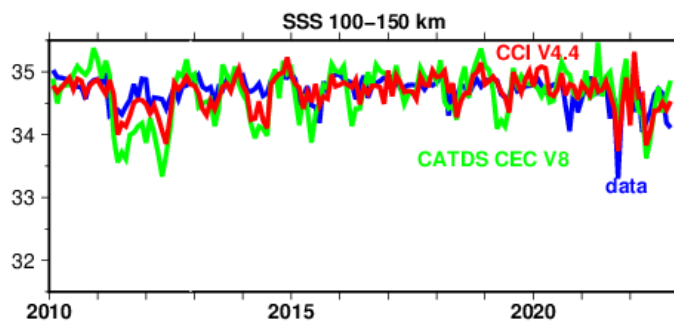


Figure 7: examples of monthly time series in SW and S regions, just off the shelf break (data only shown if at least two pixels in a monthly average). The red curve is for the V4.4 data, retained even if they flag ‘bad’, the blue curve for in-situ data, and the green curve for the CATDS CEC V8 product.

Within 50km of the coast, gridded data are often missing in the CCI V4.4 product. However, more data are retained in this coastal band in the CATDS CEC V8 and CATDS-HR products.

For distance bands slightly further from the coast (examples on Fig. 7), CCI V4.4 captures much of the seasonal and interannual variability seen in *in situ* data, particularly since 2015 (for example, see the September-October 2021 low salinity event on Fig. 7a, b). It also appears to perform better than the CATDS CEC V8 product, even in the early years. For example, the 2011 low salinity in CATDS CEC V8 for region S at a distance of 100-150 km (Fig. 7c), likely due to RFIs, is much less present in CCI V4.4 and CATDS-HR, which are closer to the in-situ data (CATDS-HR not shown, but usually close to CCI V4.4).

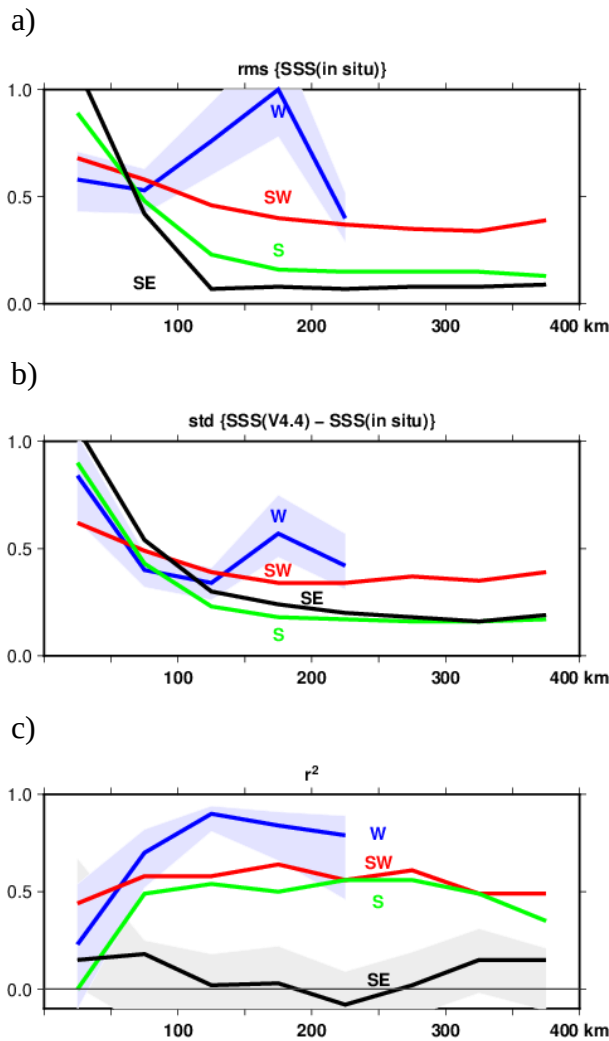


Figure 8: Variability in the time series as a function of distance to coast in 4 regions (cf Fig. 5). (a) root mean square variability of the in-situ SSS time series; (b) standard deviation of the differences $SSS(V4.4) - SSS(in situ)$; (c) correlation coefficients between in-situ and CCI V4.4 time series. The 5-95% confidence intervals are shown (light coloring) for the W time series on all plots, as well as for the SE time series for panel c, and have comparable ranges for S and SW time series, albeit a little smaller.

These comparisons can be characterized by the statistics on standard deviation and correlation (Fig. 8). The number of months sampled is less in regions W and E, leading to larger uncertainties there (illustrated for region W), as well as in the less sampled near-shore band. Except for region W, the largest in-situ variability (Fig. 8a) is found on the shelf, decreasing across the slope and offshore. In region W, the largest variability found further offshore is likely due to fronts in the northern Labrador Sea and Davis Strait. Offshore standard deviation decreases from region W to region SE, with intermediate values in regions SW and S. In the interior Irminger Sea (region SE), a 0.070 pss minimum *in situ* variability std is found between 100-150 km. CCI V4.4 standard deviation (not shown) follows a similar pattern to the *in situ* standard deviation, but is less for the closest to shore band and slightly larger at greater offshore distance (particularly for regions S and SE). Standard deviation of the differences between V4.4 and *in situ* (Fig. 8b) is never smaller than 0.15 pss and is smallest in the 200-350 km range from shore, with the lowest values for series in S and SE. Nonetheless, in SE for the 100-200 km range, the rms of the differences remains larger than the in-situ rms. It is mostly near the shelf break that standard deviation in the differences is less than the rms variability the in-situ time series, but this also extends up to 250 km from the coast in region SW. The correlation coefficients are low (often not significant) at the coast and throughout SE. Elsewhere, they tend to be significantly non-zero in other regions (5-95% percentile ranges for all curves of similar magnitude to the one plotted for SW).

4. Discussion

a. Average biases

Large average biases are present between in-situ data and satellite-based V4.4 product along the Greenland shelves, in some places exceeding 2 pss, similar to findings for an earlier SMOS product (Castelao and Medeiros, 2022). This discrepancy arises from the limitation of the ISAS fields used to adjust the mean fields, which only reproduce scales larger than 300 km and are designed for analyzing off-shelf Argo float data. As expected, due to the near-shore to off-shelf negative salinity contrast, the ISAS mean and thus the V4.4 mean are typically too salty on the shelves compared to *in situ* data. With the substantial amount of *in situ* data collected on the shelves, a pattern emerges in these average biases, which are smaller north of 62°N along west Greenland than further south or along southeast Greenland. The areas with large coastal biases are related to the narrowness of the shelf and strong frontal salinity gradients with the much larger offshore salinity along the continental slope (Fig. 1).

Slightly low values are also found in the satellite products further offshore along the continental slope (Fig. 6), likely resulting from the spatial smoothing in the ISAS climatological fields to which the satellite products are adjusted (Figure 2). The maps for the average differences (Fig. 2), albeit rather noisy, suggest that the mean fields of the CCI SSS V4.4 product could be improved, as there are sufficient data at the L-band radiometric resolution close to 50 km. Ad hoc corrections of the mean can be attempted for this region based on *in situ* data, although issues related to inhomogeneous seasonal sampling near Greenland and differences in the accuracy of the products over time (for example, larger for CCI V4.4 during the early SMOS-only period) have not been addressed.

b. SSS variability close to Greenland

In CCI SSS V4.4, most data within 50 km of Greenland and on the shelves at higher latitudes are removed due to possibly contamination by land or proximity to sea ice. Conversely, in the CATDS CEC V8 and CATDS-HR products, more data are retained close to shore, capturing SSS variability off west and southwest Greenland, as suggested by Castelao and Medeiros (2022), in particular for the summer of 2012, with an earlier SMOS product of CATDS.

Beyond 50 km from the shore, the CCI V4.4 product is clearly improved over the CATDS CEC V8 and earlier CCI SSS products (not shown). This improvement is evident in all sub-regions and might result from better correction of systematic biases across all satellite products, improved filtering of RFIs, and sea ice contamination in the satellite data, and a more optimal combination of SMOS and SMAP data since 2015. However, in some regions, such as SE in the Irminger Sea, away from the slope region, the standard deviation in the differences with in-situ time series remains larger compared rms variability in the in-situ data (Table 1), consistent with the uncertainty estimates of the CCI V4.4 product. Therefore, in this region, the correlation between *in situ* and satellite derived time series is reduced.

Table 1: Average Pearson correlation coefficients between the binned time series of *in situ* data and CCI V4.4 satellite product. Values are reported when there are more than 20 months of data in each distance band, for two distance ranges. For the second range (100-250 km; right columns), which includes 3 individual distance bands, we report the averaged correlation coefficients for the three bands

50-100 km

100-250 km

		W	SW	S	SE	E	W	SW	S	SE	E
488											
489	2010-2022	0.70	0.58	0.47	0.19		0.82	0.59	0.57	0.03	0.78
490	Months 6-11	0.69	0.50	0.58	0.18		0.82	0.73	0.72	0.52*	0.86
491	5/2015-2022	0.86	0.73	0.69	0.30		0.86	0.70	0.66	0.38	0.82
492	5/2015-2022	0.76	0.75	0.83			0.88	0.79	0.79	0.60**	0.91
493	(only months 6-11)										

* Standard deviation of difference is 0.17, compared to only 0.077 in *in situ* data, and there are less than 30 months sampled

** Standard deviation of difference is 0.16, compared to only 0.07 in *in situ* data, and there are less than 17 months sampled

Table 1 also indicates that the statistics are not homogeneous throughout the record. This is illustrated for the correlation coefficients, but similar conclusions are reached when considering the standard deviation of the differences between *in situ* and CCI V4.4 time series or by comparing rms variability in the CCI V4.4 and *in situ* time series. The correlations are usually higher if only data since May 2015 are considered, when both SMOS and SMAP data are combined, and are also better in summer-fall (months 6-11). The improvement is significant up to 250 km from shore almost everywhere, but not necessarily significant in any specific region, for example in region 4, as indicated by the asterisk in table 1. Seasonal variability in performance could result from larger uncertainties in winter-spring associated with low SST, stronger winds, and in some regions, ice contamination. Statistics are poor before 05/2015 or often for the winter season, but suggest that the product marginally captures variability during winter or the earlier period, although there are signs of improvement in CCI V4.4 relative to earlier products or the CATDS CEC V8, such as in 2011, south of Greenland (Fig. 5c).

Table 2: Average Pearson correlation coefficients between the binned time series of *in situ* data and satellite products for 10/2015-2022. Values are reported when there are more than 20 months of data in each distance band, for two distance ranges. For the second range (100-250 km; right columns), the averaged correlation coefficient of the three bands is reported.

		50-100 km					100-250 km				
		W	SW	S	SE	E	W	SW	S	SE	E
518											
519											
520	CCI V4.4	0.83	0.86	0.72	-0.03		0.82	0.69	0.68	0.28	0.84
521	CATDS-HR	0.84	0.74	0.68	0.35		0.88	0.69	0.67	0.43	0.84

It was found (Fig. 3 and 4) that CATDS-HR often shows closer rms variability to that depicted in the in-situ data than was found with CCI V4.4, as well as smaller std differences to *in situ* data. While in some areas this also translates to higher correlation for the time series, it does not in others. Table 2, for example, indicates cases where the correlation with *in situ* time series is actually lower for CATDS-HR, such as near the shelf-break of regions SW and S, but CATDS-HR correlation with *in situ* data tends to be higher further offshore. Additionally, the CATDS-HR correlation coefficient is relatively high in the 0-50 km band from shore, (0.72, 0.75 and 0.55 for regions W, SW, and S respectively), where more data are retained and fewer are flagged in CATDS-HR than in the CCI V4.4 product. These correlations are significantly larger than 0.50 at the 99% confidence level for regions W and SW. For this nearest to shore band, this, along with a larger rms variability of the time series in CATDS-HR compared to CCI SSS V4.4; thus, closer to the variability in the in-situ time series, suggests that the data selection used for CCI SSS V4.4 has removed a large number of relevant data in the southern to western parts of the shelf. However, this is still different from what is depicted in *in situ* data with a smaller rms variability, in particular in the southern and south-eastern shelf regions (as suggested in Fig. 4b)

c. An event of freshwater export from the shelf (09-10/2021)

The new *in situ* dataset allows us to improve the correction of bias in the satellite datasets and better resolve cross shelf export of freshwater. The collocated time series (Figure 7) reported the largest fresh anomaly in September and October 2021 offshore of the Southwest Greenland shelf. We illustrate this event in the satellite data with a few snapshots from 09-10/2021 (Fig. 9) for CATDS-HR and CATDS-HR corrected from the average bias presented on Figure 2d.

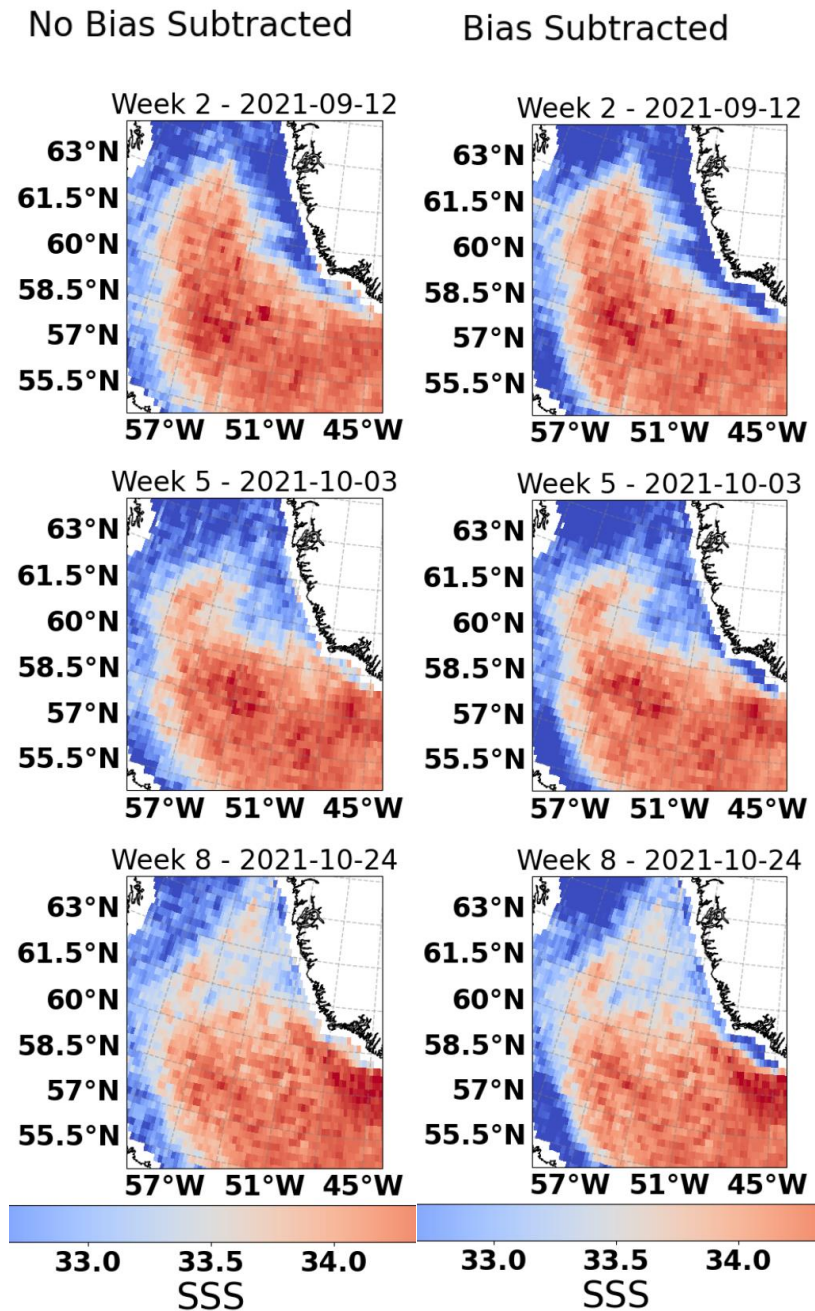


Figure 9: daily snapshots every three weeks of the CATDS-HR product without (left) and with (right) subtracting the average smoothed bias presented on Figure 2d.

On September 12, 2021, a fresh filament emerges off the southwest Greenland shelf near 61-61.5°N. Three weeks later, this expands into a blob of fresher surface water in the interior of the Labrador Sea near 61-61.5°N. This is still noticeable three weeks later in late October, for example near 61°N/57°W, despite a strong weakening of surface stratification due to fall cooling, as observed from Argo float profiles. These features are best identified in the right panels after attempting to correct the average bias. The right panels also indicate that despite

the low salinity in this blob, salinity is not lower there than on the Greenland shelves further southeast near Cape Farewell. The CCI V4.4 fields (and the CATDS CEC V8) show similar features but with less intensity and granularity. The main difference seems to be that the CATDS-HR product results in less smoothing over time than the Gaussian function used in the CCI V4.4 optimal interpolation. This is clearly noticeable when plotting time series of the products (Figure 10) along a nearly zonal section from shelf break at 61.5°N and 57°W/61°N, near the average core of the largest fresh anomalies.

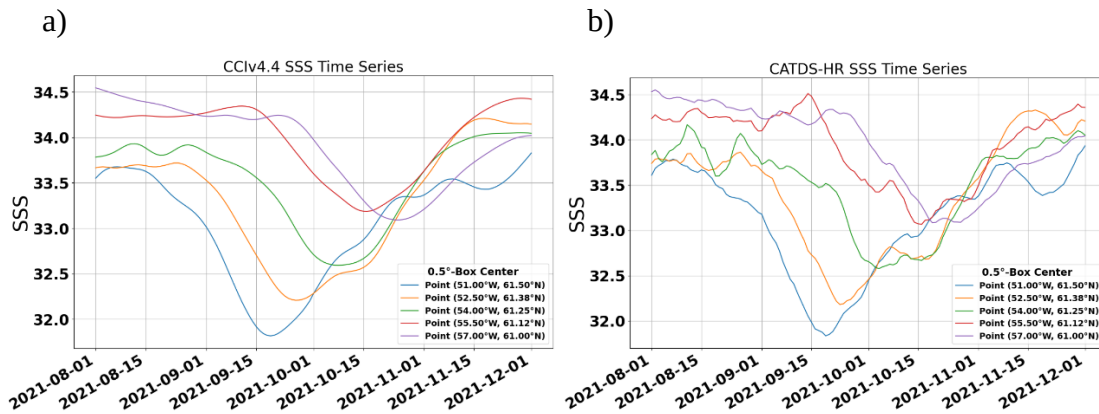


Figure 10: time series of SSS at different longitudes in the eastern to central Labrador Sea (after correcting from an average bias with respect to *in situ* data, Fig. 2c). (a) CCI V4.4; (b) CATDS-HR

The time series for CCI V4.4 are indeed much smoother than the ones in the CATDS-HR product. In this case, the sharper features depicted by CATDS-HR are more realistic of what could have happened than the smoother CCI V4.4 product. Thus, the tendency for the CATDS-HR product to be closer to the *in situ* data (with smaller rms differences) as previously discussed. However, it is also likely that the high-frequency variability in CATDS-HR is more influenced by noise in the satellite retrievals. Both products (and to a lesser degree the not-shown CATDS CEC V8 analysis) capture the significant drop in salinity associated with this large export of freshwater from the shelf (drop larger than 2 pss near the shelf break, but still over 1 pss in the central part of the gyre), as well as the time lag in the event portrayed by more than one month between the more central location and the vicinity of the shelf break.

5. Conclusions

The signal-to-noise ratio of L-Band radiometry to salinity strongly decreases from warm to cold temperatures, by more than a factor of three between 30°C and 0°C. Hence, detecting geophysical SSS signals from L-Band radiometry at high latitudes is challenging. We have

found that the satellite salinity products are able to reproduce a significant share of the variability in the NASPG south of Greenland and the interior Labrador Sea on monthly time scales. In the southern Irminger Sea, where *in situ* variability is lower, the CCI V4.4 product presents uncertainties too high to represent its seasonal and interannual variability. There is probably a residual influence of RFI contamination before 2015, with too low SSS in some places East of Greenland, but this is difficult to clearly identify. Additionally, the CCI V4.4 product appears closer to the data starting in mid-2015 or 2016 (roughly for the SMOS-SMAP combined period), and probably better in summer-fall (June to November). However, it is nonetheless not as close to the data as the CADTS-HR product, likely due to the latter's better fit to higher frequencies.

In the CCI V4.4 product, there are missing data on the shelves due to more stringent screening of land, ice or RFI contamination than in the CADTS CEC V8 and CATDS-HR products. This choice results in the loss of the coastal summer signals identified by Castelao and Medeiros (2022) near West Greenland, such as in August 2012. Further from shore, the CCI V4.4 product generally performs well, offering hope that its good spatial coverage and relatively high spatial resolution (better than 50 km) might help characterize the variability of freshwater exchange from the South Greenland shelves to the ocean interior, in particular in the warmer and ice-free period from June through November since 2015. This is illustrated by a significant freshwater export event from the Southwest Greenland shelf to the interior Labrador Sea in September-October 2021, portrayed with sharper time resolution in the CATDS-HR product. Moreover, the smaller rms variability of the difference to *in situ* data (since 2015) in the low variability regions of the central North Atlantic subpolar gyre for the CATDS-HR product suggests the presence of high-frequency information (day to weeks) in the L-band satellite radiometric data that are not captured in the CCI V4.4 fields which result from a Gaussian time optimal interpolation.

We also illustrated large average biases in these products near land and over the shelves, contributing to significant differences in the horizontal SSS gradients across the shelf break and slope regions near Greenland, as shown for a freshening event in September-October 2021 off southwest Greenland. Further effort is required to correct these average biases related to the climatology used to adjust the long term mean of the satellite salinity products we investigated. With careful consideration of the remaining uncertainties that were estimated, we conclude that the CCI V4.4 fields (or the CATD-HR ones) can be used to

investigate large events such as the fresh event in late summer 2021, providing a large-scale context not obtained from the in-situ data.

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Data availability statement. CCI SSS version 4.4 is available at <https://dx.doi.org/10.5285/f2ca631f29a24c47a7e98654ddf2c7d9> (Boutin et al., 2024). CATDS SSS products are available at the CATDS Production Data Center (CPDC), www.catds.fr. In particular, the CEC CATDS High Resolution V0 Sea Surface Salinity maps (CATDS-HR) are produced by LOCEAN/IPSL (UMR CNRS/UPMC/IRD/MNHN) laboratory and ACRI-st company that participate to the Ocean Salinity Expertise Center (CECOS) of Centre Aval de Traitement des Données SMOS (CATDS) (<https://doi.org/10.17882/90082>). A large part of the in-situ data can be obtained from the PiMEP ESA site for satellite salinity product validation. SSS drifter data correspond to the ones in Duyck et al (2022, 2023) papers and at the Global Drifter Center at AOML. The MEOP data base is hosted by the MEOP consortium (<https://meop.net/>). The CCGS Amundsen thermosalinograph data are found in CCIN (Canadian Cryospheric Information Network) 12715 archive. Glider data are associated with Clement et al. (2022). We also thank the Royal Danish Navy for sharing TSG data collected by HDMS Lauge Koch and provided by Joint GEOMETOC Support Centre at The Danish Ministry of Defence Acquisition and Logistics Organisation. The 2017 Mission Arctic Citizen Data Sailing Expedition are from Carlson et al. (2021).

CRedit authorship contribution statement

Gilles Reverdin: Writing, Methodology, Data curation, Conceptualization. Fabrice Bonjean; Methodology, Formal analysis, Conceptualization, Visualization, Editing, Supervision. Louise Kilian: Formal analysis, Visualization. J. Boutin: Conceptualization, review and

652 editing. Jean-Luc Vergely: Methodology, Formal Analysis, Software, Data Production.....
653 Nicholas Foukal: Editing, Data Production, Data Curation; Elodie Duyck: Data production,
654 Data curation; Femke de Jong: Data production; Colin Stedmon: Data curation, Editing;
655 Dimitry Khvorostyanov: Data qualification, Visualization.

656

657 **Declaration of competing interest**

658 The authors declare that they have no known competing financial interests or personal
659 relationships that could have appeared to influence the work reported in this paper.

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