Research Project co-funded by the
European Commission
Research Directorate-General
7th Framework Programme
Project No. 284391

E-AIMS

Euro-Argo Improvements for the GMES Marine Service

Sea Surface Salinity: Results and Recommendations

D4.4.3

Ref: E-AIMS: D4.443-v2

Date: November 2015

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1. Introduction

1.1. General presentation

This document is an update of the previous D4.443 document submitted by the end of 2014. It presents the results and recommendations concerning the use of the Argo system for the calibration and validation (Cal/Val) of **remote sensed sea surface salinity** products. The information presented here is based on the validation activities being carried out by the SMOS Barcelona Expert Centre (SMOS-BEC).

This is the deliverable D4.443 (E-AIMS WP4 Task 4.4) identified in the description of work [AD-1], in the table WT 2, page 4, which is due by the end of December 2014.

1.2. Applicable documents

AD-1: Annex 1 to the grant agreement N0 312642: "Description of work", date 24 April 2012.

AD-2: INDRA, SMOS Level 2 and Auxiliary Data Products Specifications SO-TN-IDR-GS-0006. Version 6.1, 2012.

AD-3: Guimbard, S., and coauthors. SMOS Semi-empirical ocean forward model adjustment. IEEE Trans. Geosci. Remote Sens., 50 (5), 1676-1687, 2012.

AD-4: SMOS-BEC. Ocean and land products description. Version 1.3, 2014.

AD-5: Antonov, J.I., and coauthors. World Ocean Atlas 2009, Volume 2: Salinity. S. Levitus, Ed. NOAA Atlas NESDIS 69, U.S. Government Printing Office, Washington, D.C., 184 pp., 2010.

AD-6: Jordà, G, and coauthors . The SMOS L3 mapping algorithm for sea surface salinity. IEEE Trans. Geosci. Remote Sens., 49, 1032-1051, 2011.

AD-7: Umbert, M., and coauthors. New blending algorithm to synergize ocean variables: The case of SMOS sea surface salinity maps. Rem. Sens. Environ., 146, 172-187, 2014.

AD-8: Argo. Argo quality control manual. V2.9. 54 pp., 2013.

AD-9: Boutin, J., and coauthors. First assessment of SMOS data over open ocean. Part II – Sea surface salinity. IEEE Transactions on Geoscience and Remote Sensing, 99, 2012.

AD-10: Boutin, J., and coauthors. Sea surface freshening inferred from SMOS and ARGO salinity: impact of rain. Ocean Sci., 9, 183-192, 2013.

1.3. Sea Surface Salinity products

The SMOS-BEC provides three global SSS products: Binned product (L3), Optimal Interpolation (OI), and SST-fused (L4). The SMOS data used to compute these products come from the Ocean Salinity Level 2 User Data Product (UDP) and Data Analysis Product (DAP). These UDP and DAP files are generated by ESA and include geophysical parameters, a theoretical estimate of their accuracy, and a set of flags and descriptors accounting for the estimated quality for three different empirical models used to account for the emissivity contribution from a non-flat ocean surface (the so-called roughness models). Description of these UDP and ADP files can be found in [AD-2]). The roughness model used at SMOS-BEC (called model three) is described in [AD-3].

The Quality flags and descriptors included in the UDP and DAP files can be used to discard unreliable Sea Surface Salinity retrievals. The SMOS-BEC salinity products use a set of geometrical, retrieval and geophysical filters. The current filtering process is coded as 2013001 and is described in [AD-4].

A brief description about the generation of the three SSS products distributed by SMOS-BEC follows:

Binned SSS maps (L3): Binned maps are constructed by a weighted average of the filtered L2 SSS values on 0.25-degree grid bins, every three day period:

$$S_k^{L3} = \sum_i^{N_k} w_i S_i^{L2}$$

Each weight $w_i$accounts for the theoretical uncertainty of each Level 2 SSS retrieval and its equivalent footprint size (both depending on the pixel position in the SMOS field of view). The sum is done for all L2 SSS retrievals inside the bin and for a time period of three days, N_k.

Optimal Interpolation SSS maps (OI): The optimal interpolation maps are constructed by the weighted average of the three-day L3 binned maps

$$S_k^{OI} = \sum_i^{N} w_{ki} S_i^{L3}$$

The weight w_{ki} accounts for the covariance of the background field error (calculated between the analysis grid point k and the available observations and also calculated between the positions of the available observations) and for the covariance of the observation error. The background field comes from the World Ocean Atlas (WOA) 2009 [AD-5], and the decorrelation scales are provided by [AD-6]. The number of observations, N, corresponds to all valid L3 SSS values inside an influence radius of 300 km during a nine-day period. The observational error is given by the dispersion of all observations included in each L3 binned estimate.

SST-fused SSS maps (L4): The Level 4 (L4) salinity product is created through a data fusion algorithm blending the SSS L3 maps with the OSTIA SST daily product. For any point with a valid SST observation, a salinity value is obtained as follows:

$$S_k^{L4} = w_k T_k + z_k$$

The coefficients w_k and z_k are obtained by a linear spatial regression between OSTIA SST and the L3 SSS (calculated from a single snapshot of both fields). The justification of the approach and the localized regression methodology is described in [AD-7].

An example of the salinity maps given by these various methods is given in Figure 1.

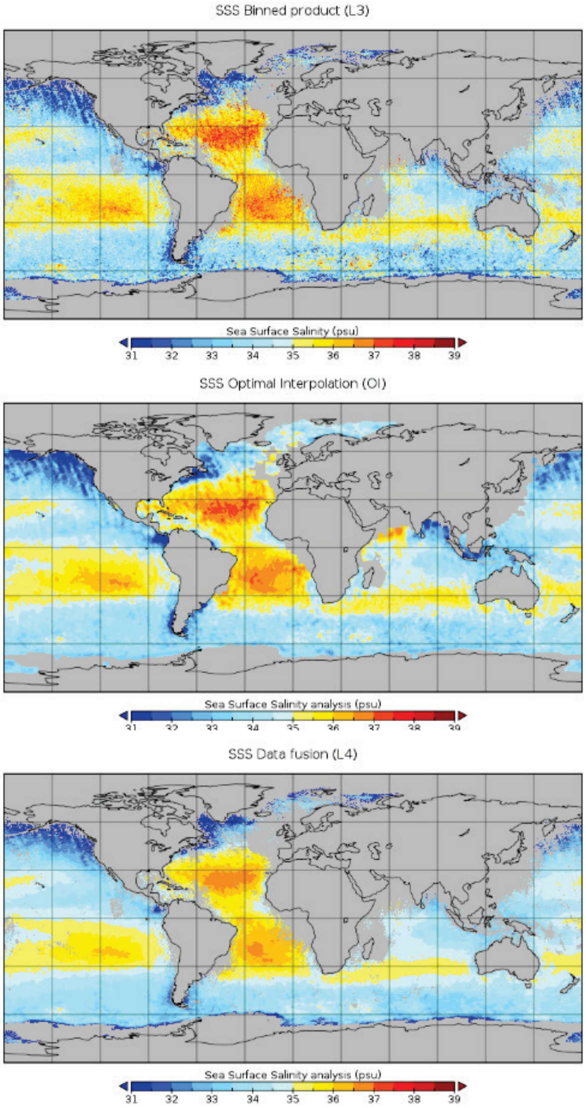

Figure 1: Sea surface salinity (SSS) corresponding to the period December 23, 2013 to January 01, 2014. Top, middle and bottom display the L3, OI and L4 respectively.

2. Argo SSS data

2.1. Argo selection rules

The Argo data used to validate the various SSS products has been selected as follows:

- Only Delayed Mode data are being used.
- Only primary CTD measurements (N_PROF=1) from each profile is used.
- Only data (pressure, temperature and salinity) with the highest Quality Control value (QC=1) is used. See the Quality Control flag value and meaning in Table 2 [AD-8].

- The Quality Control of geographical position and date position is accepted if it has been set to 1 (good), 2 (probably good), 5 (Value changed) or 8 (Interpolated value).
- Uppermost valid salinity measurement, without accepting any salinity value closer than 0.5 m to the surface. Some authors have observed erroneous measurements likely due to inaccuracies in the pressure measurement [AD-9].
- Salinity data from PROVOR, SOLO (as well as the UNKNOWN) instruments are not considered at depths shallower than 5 m, as these profiler types did not pump water at a depth shallower than 5 m [AD-8].

In addition to the uppermost salinity value, we also calculate an interpolated salinity value at a depth of 7.5 m (i.e. the middle depth of the layer between 5 and 10 m). This calculation allows an additional automatic Quality Control based on the comparison between different methods (lineal, splines, etc.). If the difference between the various interpolation methods is not negligible (due to non-resolved vertical gradients, presence of outliers, etc.), the profile is flagged (but not automatically rejected).

2.2. Available data by month and depth

Figure 2 shows the number of obtained profiles, the number of Delayed Mode profiles, and the number of Delayed Mode profiles with valid salinity measurements. The gap between the number of valid profiles and the number of profiles with salinity data has been reduced during the period of study. The plot illustrates the lag between the date of the measurement and the date when the Delayed mode is provided. At this moment (December 2014), more than one year is usually required for the Principal Investigator (PI) responsible of the deployment to process the data. Although the number of measured profiles seems to peak beginning of year 2013, the number of Delayed Mode data has been decreasing since January 2011.

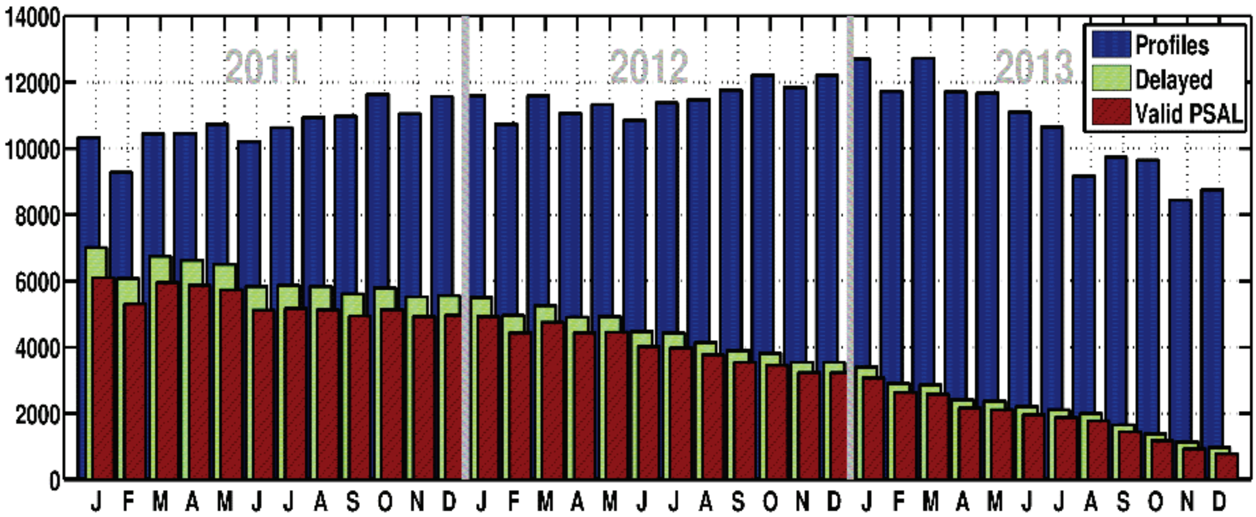

Figure 2: Number of Argo profiles per month during the period January 2011 - December 2013. The reprocessed SMOS data period is 2010-2013.

The impact that such latency in processing the Delayed Mode data has in the geographical distribution of the floats for remote sensing SSS validation is illustrated in Figure 3.

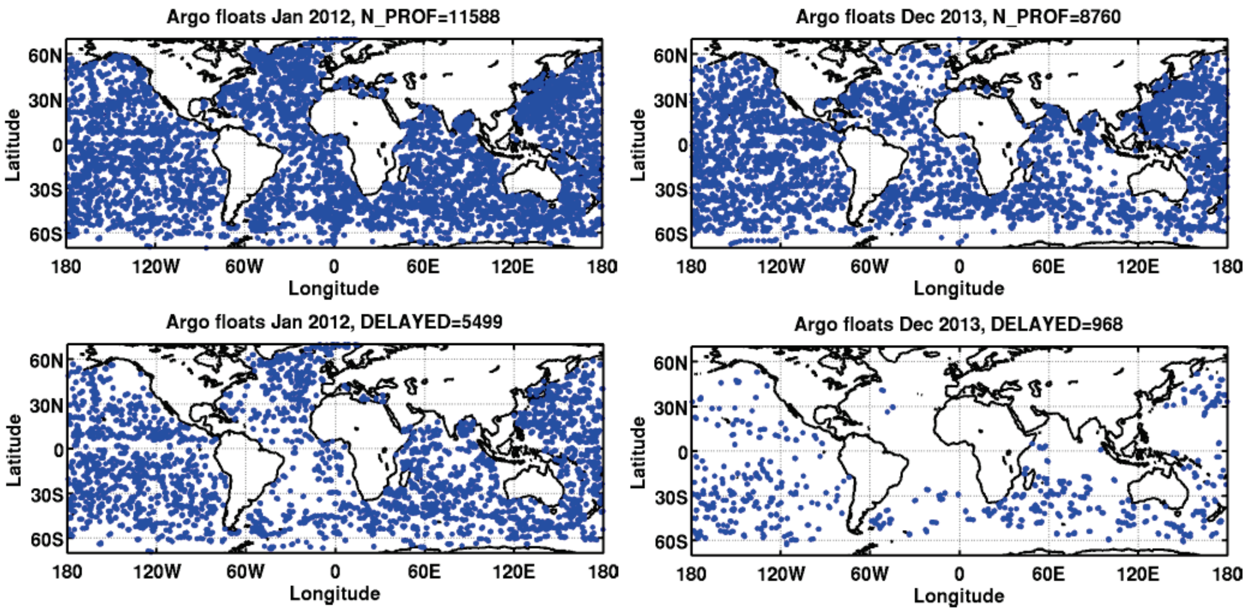

Figure 3: Spatial distribution of available salinity observations for remote sensing SSS validation. On the left, map of profiles for January 2012. On the right, profiles for December 2013. On top, all valid profiles are mapped. On bottom, only those available in Delayed mode.

Excessive delays in processing the Argo profiles reduce the likelihood of a homogeneous sampling of the oceans. For December 2013, at the moment of writing this report (December 2014), only three profiles were available for the whole North Atlantic Ocean. While in January 2012, 47% of the floats are available in Delayed Mode, in December 2013, only 11% are.

The time evolution of the number of available Delayed measurements of temperature and salinity by depths (shallower than 3, 5 and 10 m) is shown in Figure 4.

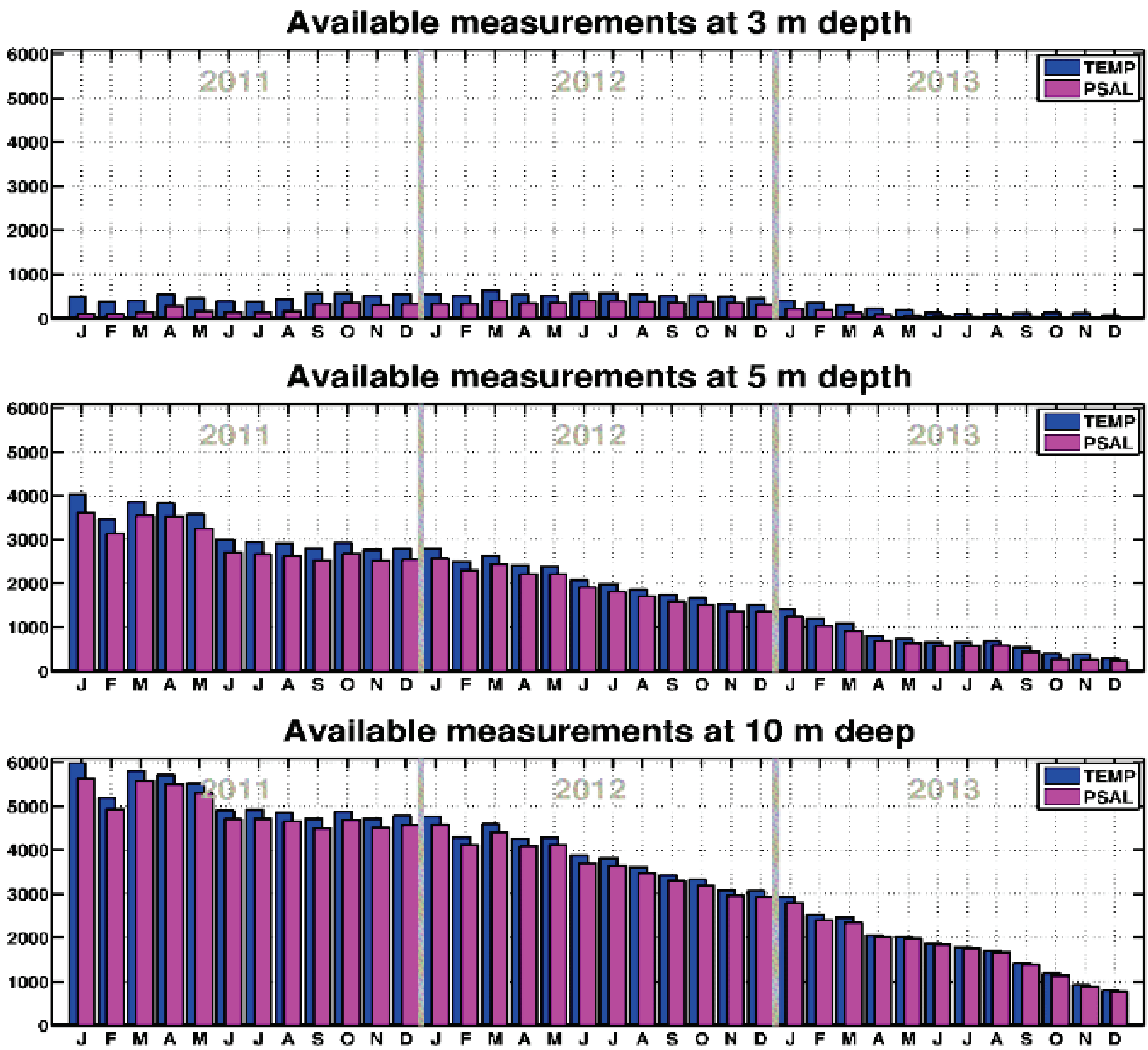

Figure 4: Temperature and salinity measurements per depth (3, 5 and 10 m below the surface) and month since January 2011 to December 2010.

During year 2011, around 5000 Delayed Mode salinity observations are available every month. The number of observations declines during 2012, and during November and December of year 2013, less than one thousand salinity observations are available. According to this plot, only a few data are available in the first 3 meters of the ocean. Despite the fact that remote sensing SSS is measuring the conductivity of the first cm of the ocean, little in-situ Argo observations are available below five meters. Below one meter, no salinity observations are even available during most of the year 2013 (Figure 5).

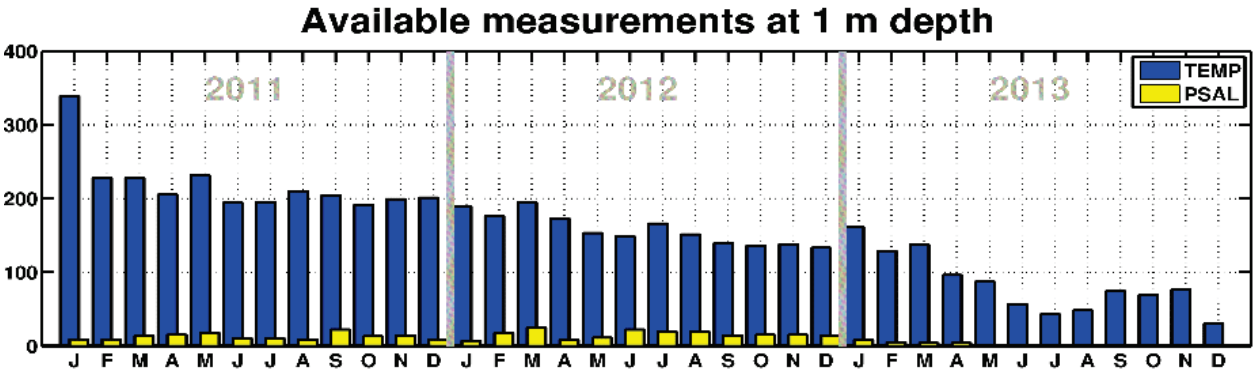

Figure 5: Temperature and salinity measurements shallower than 1 m below the surface. Salinity measurements shallower than 0.5 m are systematically removed.

The spatial distribution of Argo temperature and salinity are shown in Figures 6 and 7.

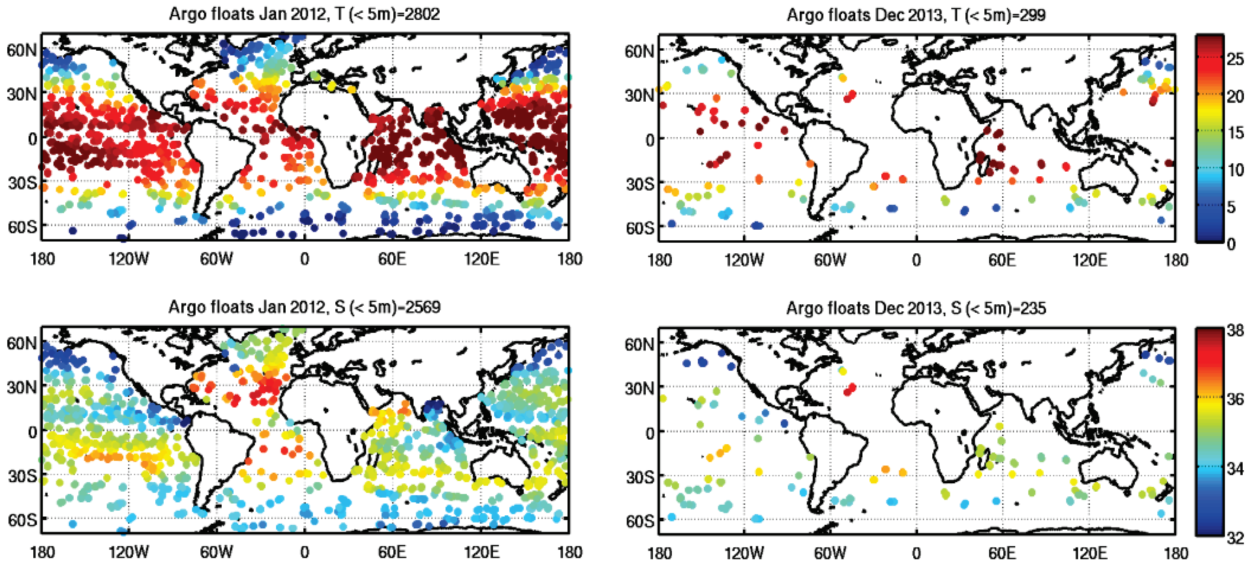

Figure 6: Distribution of temperature and salinity Argo observations in the first five meters below the surface.

The previous figures compare the spatial distribution of the Argo observations in the first five meters of the ocean. They also illustrate the impact of the lack of the Delayed Mode data about the end of the period used to validate SMOS SSS products. The color scale represents the value of the temperature (degrees Celsius) and salinity (in the practical salinity scale).

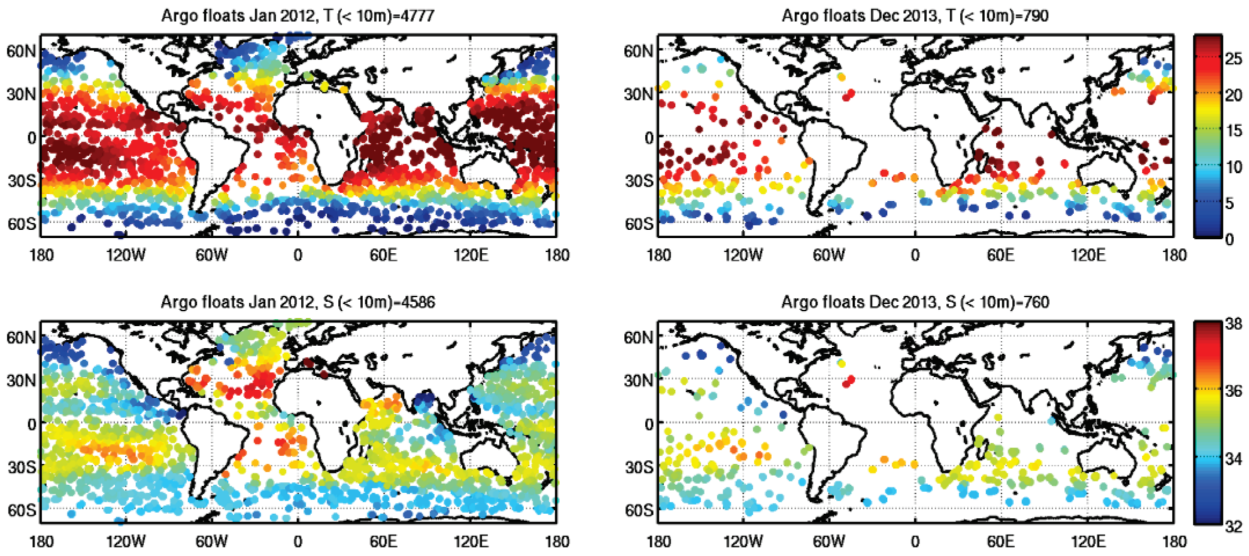

Figure 7: Distribution of temperature and salinity Argo observations in the first ten meters below the surface.

During January 2012 (before the steady decline of the number of Delayed Argo profiles) the available observations for SSS validation look more homogeneous when all the data in the top ten meters are considered for validation than when only the data in the first five meters are taken into account.

3. Results

3.1. Bias and random error (I)

Each in-situ, closest-to-the surface, valid salinity Argo measurement is compared with the SMOS SSS retrieval corresponding to the bin including the measurement. The comparison is done against the 9-day average products of L3, OI and L4. As the 9-day field is calculated every three days, each Argo may be usually compared against three fields. Once all the possible match-ups are constructed for the period January 2011 – December 2013, the average and standard deviation of the SMOS minus Argo value are calculated.

Table 1: Statistics of the tree SSS products and the Argo uppermost salinity value match up pairs. Shown are the number of matchups, the average and standard deviation.

Latitude		Global	60S-60N					30S-30N				
Coast distance				>500 km		>1000 km			>500 km		>1000 km	
Maximum depth					10 m		10 m			10 m		10 m
L3	n	270854	266989	231947	223737	170489	165472	131060	113731	109168	85799	82345
	$\langle \Delta S \rangle$	-0.08	-0.08	-0.03	-0.03	-0.00	-0.00	-0.13	-0.10	-0.09	-0.08	-0.07
	$\sigma_{\Delta S}$	0.68	0.66	0.61	0.60	0.57	0.57	0.49	0.44	0.43	0.40	0.40
OI	n	307013	300937	252693	243052	180196	174611	151009	124996	119652	91133	87219
	$\langle \Delta S \rangle$	-0.10	-0.09	-0.05	-0.05	-0.02	-0.01	-0.14	-0.10	-0.10	-0.08	-0.08
	$\sigma_{\Delta S}$	0.42	0.41	0.37	0.37	0.34	0.34	0.33	0.29	0.29	0.26	0.26
L4	n	270854	266989	231947	223737	170489	165472	131060	113731	109168	85799	82345
	$\langle \Delta S \rangle$	-0.10	-0.10	-0.07	-0.06	-0.04	-0.04	-0.16	-0.15	-0.14	-0.14	-0.14
	$\sigma_{\Delta S}$	0.40	0.38	0.35	0.35	0.33	0.33	0.28	0.26	0.26	0.24	0.24

Table 1 displays the mean and standard deviation of all the match ups according to latitudinal bands. The number of total match-ups are of the order of three-hundred thousand remote sensing and Argo pairs. The number of pairs for the OI is larger than the binned thanks to the extrapolative properties of the optimal interpolation algorithm. Although the L4 data fusion algorithm would allow providing a SSS estimate anywhere a SST value is available, the algorithm is not used to extrapolate, and L4 values are only generated for bins where a L3 value exists. Thus, both products have the same number of match-up pairs. Notice that at Global scale (first column) the *random error* (whose amplitude is approached by the standard deviation of the SMOS minus Argo differences) *is reduced as the processing level increases*. **The largest error (0.68) corresponds to the binned product and the smallest error corresponds to the product generated by the means of a data fusion algorithm (0.40).** The systematic error (the average value) is negative. That means that in all cases, SMOS SSS retrievals are systematically fresher than the in situ uppermost Argo value. This can be due to a bias in the processing or to the fact that Argo data are taken several meters below the ocean surface.

The statistics of the Global differences (first column) do not only reflect the effectiveness of measuring Sea Surface Salinity from space, but also reflect various current algorithm limitations near coastlands or in cold water (the sensitivity of the brightness temperature to conductivity is reduced at cold temperatures). In order to isolate the different contributions, data are stratified by latitudinal land and distance to coast. As soon as the data are restricted in latitude, the random error is reduced. In the case of **OI**, the global error reduces from **0.42** (Global), to **0.41** (bounded by latitude 60), and to **0.33** (bounded to latitude 30). The large effect of restricting the comparison to the tropical band is to remove data pairs in cold waters and also data pairs under the influence of large winds, also known to reduce the accuracy of the salinity retrievals.

To remove the detrimental effect of comparing SMOS and Argo near the coastland, statistics are also computed for match-up pairs located farther than 500 km and 1000 km from major coastlands. In the case of OI, the error is reduced from **0.41** (60 degree latitude limit) to **0.37** and **0.34**, i.e. a reduction of 17% of the amplitude of the random error. At this latitude band, the systematic error is also reduced from **-0.09** to **-0.02**. At the tropical band, the impact of considering match-up pairs far from the coast is even larger, as the standard deviation of the error reduced from **0.33** to **0.29** (500 km) and **0.26** (1000 km). That is, an improvement of the 21%.

Finally, the impact of limiting the SMOS and the Argo comparison to the profiles whose uppermost valid salinity value is in the first ten meters below the surface is also investigated. The impact of removing the profiles with the uppermost salinity value too deep is small, mostly because only five thousand math-up pairs are removed (around the 4% of the profiles).

As a result, during the period 2011-2013, around 300,000 SMOS and Delayed Argo salinity match-up data pairs are available. Some of these data pairs are located in regions where well known issues do exist (land-sea contrast, low surface water temperature, high surface wind). When the data is requested to be more than 1,000 km from the coast, and the upper Argo measurement in the first 10 m below the ocean surface, the number of available floats is reduced to 175,000 (60º latitude band) and 87,000 (30º latitude band). Using these data pairs, it seems reasonable to say that current SMOS data processing produces a salinity estimate with a slight negative bias (**-0.01** and **-0.08** at the 60º and 30º latitude bands respectively) and a random noise of around **0.3 (0.34** and **0.26** at the 60º and 30º latitude bands respectively). The larger negative bias in the tropical band is related to the increase of the frequency of rain events [aD-10].

The spatial distribution of the 175.000 math-up data pairs, where the color indicates the difference between SMOS SSS OI and the uppermost Argo salinity (shallower than 10 m) s shown in Figure 8.

3.2. Error geophysical dependency

Two sources of additional information can be used to investigate sources of error that may affect the robustness of our estimate of the error of SMOS. These sources of information are the Argo temperature, and the auxiliary fields (routinely provided by the European Centre for Medium-Range Weather Forecasts, ECMWF). These auxiliary fields provide information of the sea surface temperature (SST), wind speed, and precipitation, located at the pixels where the SMOS retrievals are calculated.

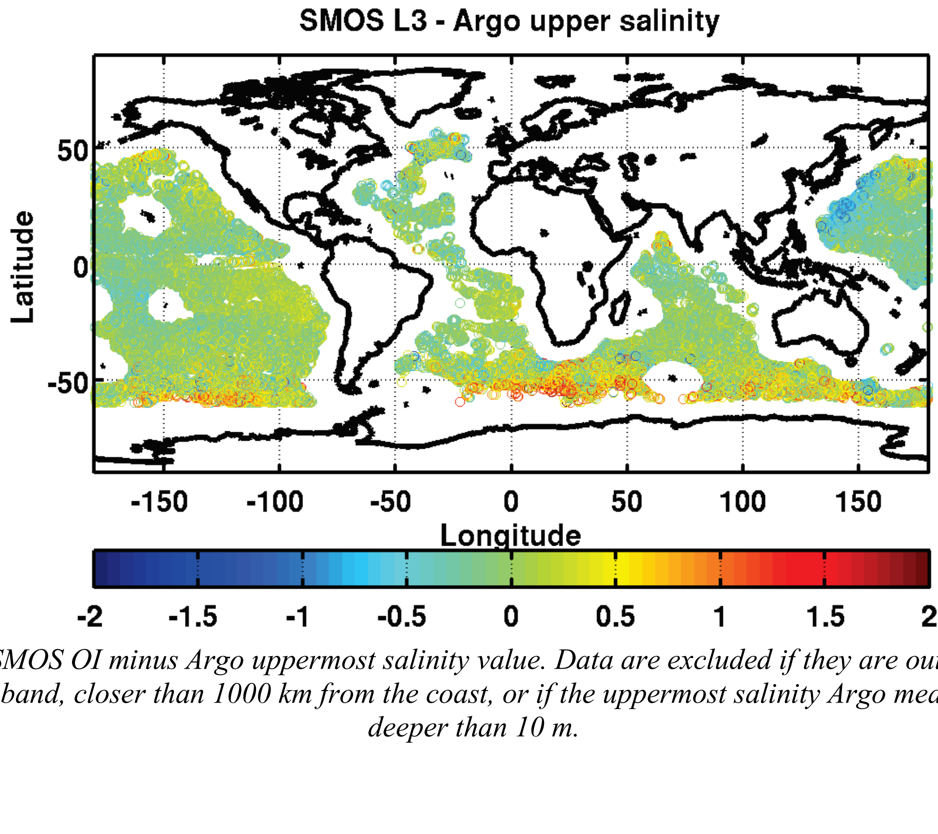

Figure 8: SMOS OI minus Argo uppermost salinity value. Data are excluded if they are outside the 60º latitudinal band, closer than 1000 km from the coast, or if the uppermost salinity Argo measurement is deeper than 10 m.

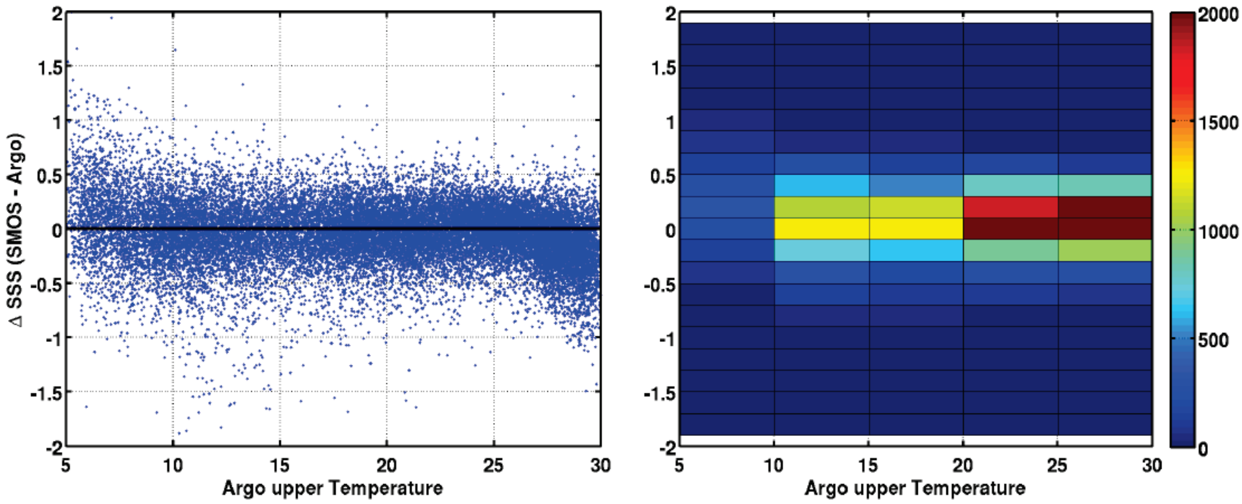

Figure 9: Difference between SMOS OI and Argo salinity value as a function of the of the uppermost temperature value.

Sea Surface Temperature

Figure 9 shows the distribution of the SMOS minus Argo salinity difference as a function of the uppermost Argo SST value. The plot shows that at low temperatures, the SMOS retrievals are clearly biased toward excessively salty estimates, while at high surface temperatures, the bias has an opposite sign. The large bias detected at the tropical band comes from the data located in locations where water is warmer than 28ºC. This can be demonstrated by inspecting the statistics resulting when the in-situ temperature is restricted to be in the range 5ºC-28ºC. In the 60 latitude band, removing the cold match-up pairs reduces the random error size. In the tropical band, removing the warm match up pairs mainly reduces the fresh bias of the SMOS retrievals.

Table 2: Effect of removing macth-up pairs for which the water temperature is colder than 5ºC or warmer than 28ºC.

	60S-60N		30S-30N	
n	174611	140518	87219	63616
$<\Delta S>$	-0.01	-0.01	-0.08	-0.03
$\sigma_{\Delta S}$	0.34	0.30	0.26	0.24

Latitude

Linked to the sensitivity to sea surface temperature, a latitudinal dependency of the error is also expected (larger error at high latitudes), as seen in Figure 10.

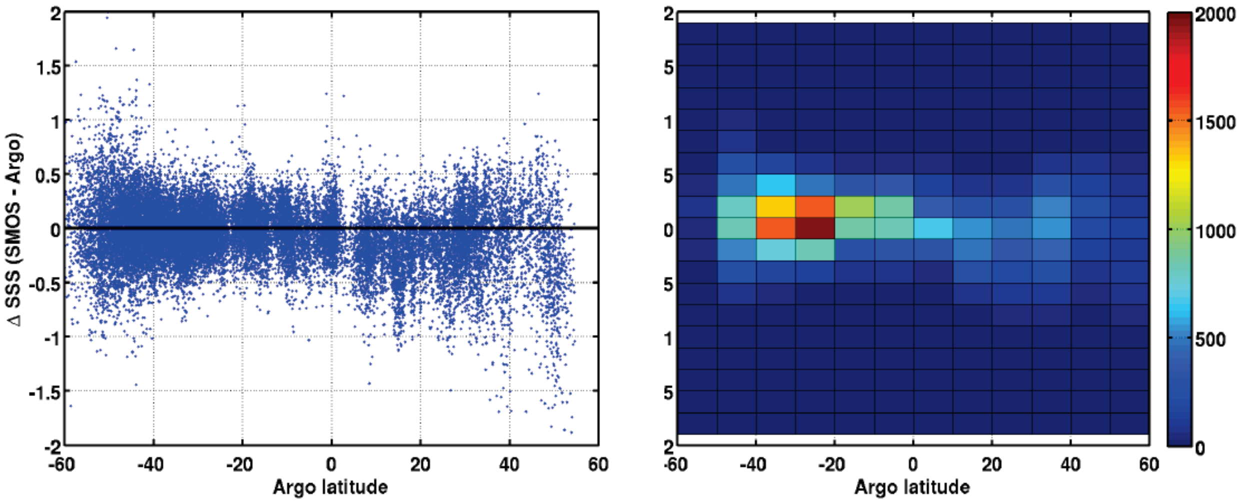

Figure 10: Latitudinal variation of the difference between SMOS and Argo.

The distribution of the SMOS minus Argo salinity differences reflects that the error is systematically lower in the tropics that at high latitudes. The latitudinal differences change with the season (Figure 11), not only because of the seasonal cycle, but also because some not yet fully understood instrumental behaviour.

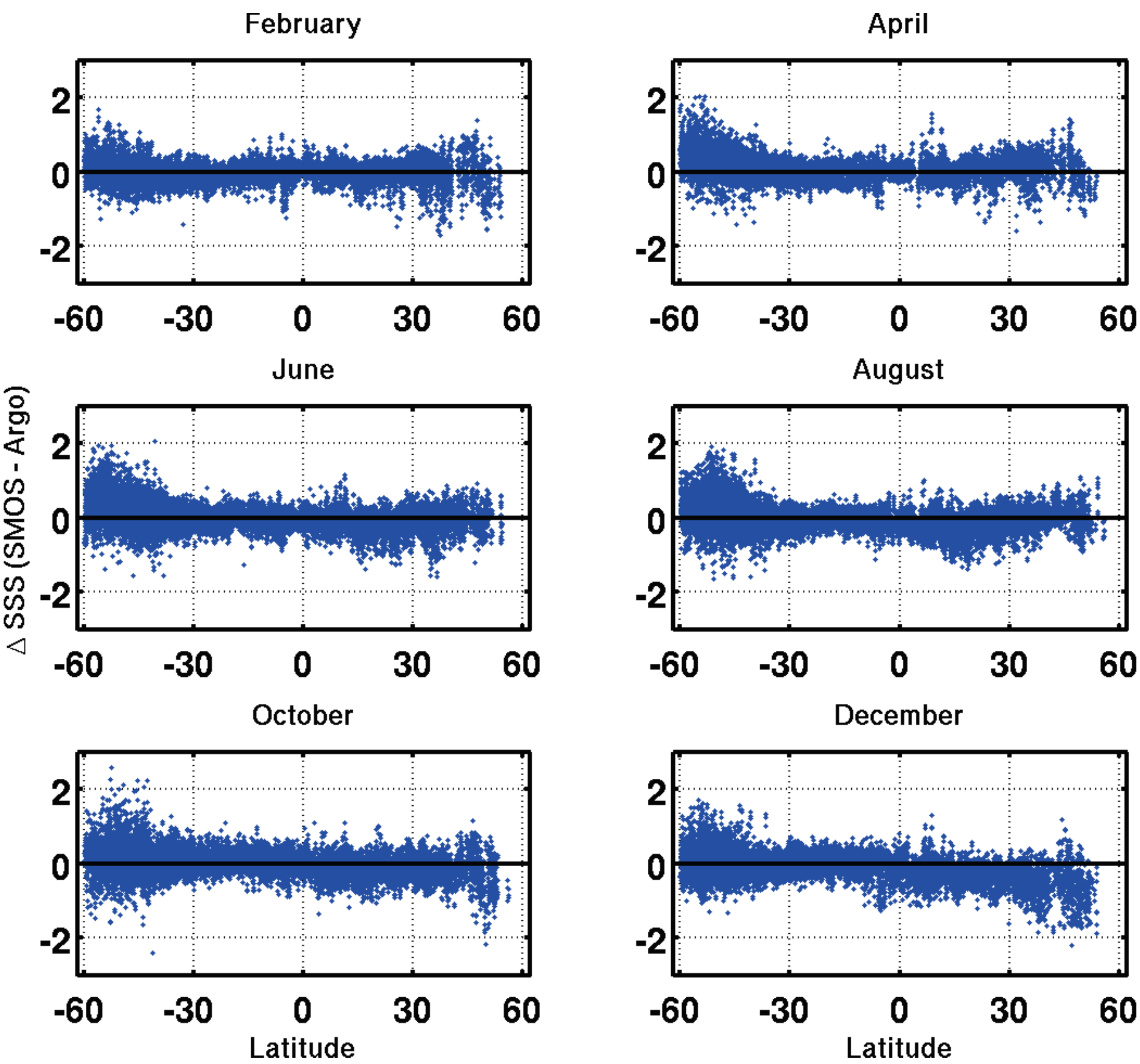

Figure 11: Seasonal changes of the latitudinal variation of the difference between SMOS and Argo.

Wind

One of the auxiliary fields required for the retrieval of the sea surface temperature is the wind speed. In this validation study, the wind speed is binned to the same 0.25-degree grid used in SMOS and using a time period of 3 days. The official SMOS retrieval algorithm disregards any pixel in which the wind speed is larger than 12 m/s. In this comparison, only the wind values used in the retrieval are accounted for, and thus no wind speed values larger than 12 m/s are present. The distribution of the SMOS and Argo salinity differences as a function of the 0.25-grid, 3-day averaged, ECMWF neutral equivalent wind module is shown in Figure 12. Notice that the spread of the differences slightly increases with the intensity of the wind. The histogram of the averaged wind speeds (not shown) indicates that the most usual wind speed values are in the range 6-9 m/s. For winds stronger than 9 m/s, a slight bias in the differences is apparent. By eliminating match-up data pairs with wind speed larger than 9 m/s, has little impact on the random error, but slightly increases the bias of the SMOS SSS products.

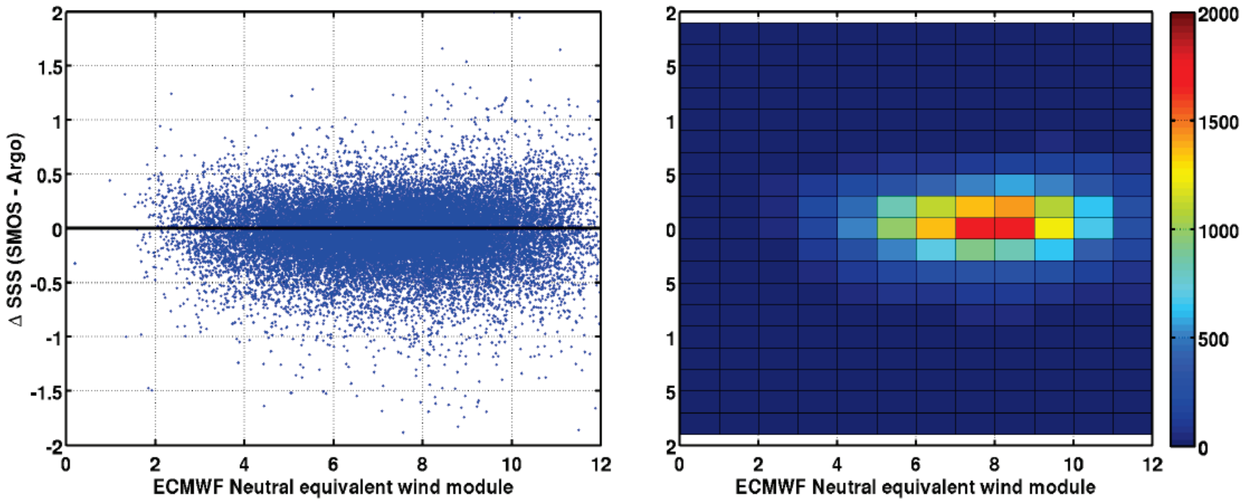

Figure 12: Difference between SMOS and Argo as a function of the ECMWF wind speed (m/s).

Rain

Similar to the wind speed, the precipitation fields provided by ECMWF are binned to the 0.25-degree grid and over a time period of 3 days. The official SMOS retrieval algorithm does not depend on precipitation.

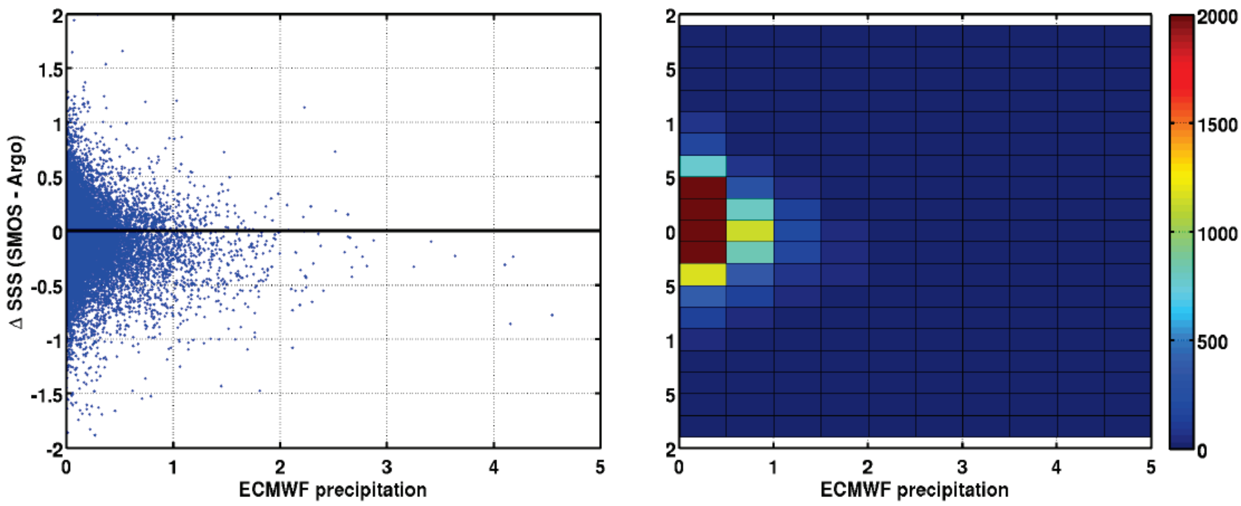

Figure 13: Difference between SMOS and Argo as a function of the ECMWF average precipitation (mm/d).

The distribution of the SMOS and Argo salinity differences as a function of the 0.25-grid, 3-day averaged, ECMWF precipitation is shown in Figure 13. Notice that, for each possible value of rain, the salinity differences seem to distribute homogeneously in an almost symmetrical range. The form of this graphic is fully determined by the histogram of precipitation (Figure 14). In Figure 13, it can be seen that as precipitation increases, the SMOS becomes fresher than the

Argo. This behaviour has been noticed by previous authors [AD-10]. Eliminating pixels where the average rain is larger than 0.5 reduces the bias to **-0.06**.

3.3. Salinity error versus temperature error

The brightness temperature of the ocean measured in the microwave region is proportional to SST. In the case of retrieving salinity using the roughness model number three, only two parameters are used as control parameters: salinity and wind speed. The SST used (called thereafter the *reference SST*) in the geophysical function is kept constant during the salinity retrieval process. Errors in the value of SST used to retrieve the SSS will introduce a source of error in the value of SSS.

By using the uppermost valid temperature of temperature of Argo, an estimate of the accuracy of the reference SST can be provided. Figure 15 compares the spatial distribution of the differences between SMOS SSS and Argo and the spatial distribution of the differences between the reference SST and Argo.

The results in Figure 15 show some coincidences between locations of large SSS differences and locations of large SST differences. The origin of these differences (either due to error in the SST field or errors in the Argo profilers) goes beyond the scope of this report, although the SMOS-BEC validation task is pursuing these results to better understand the origin of these differences.

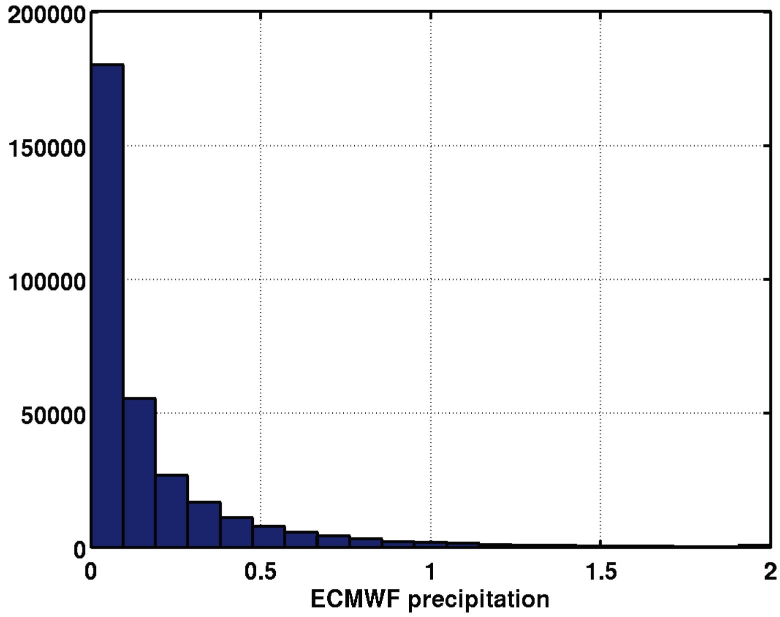

Figure 14: Histogram of precipitation values. First class corresponds to a 0.56 frequency.

The SSS differences as function of the SST differences are shown in Figure 16. It has to be noticed that for large positive SST differences, the SSS differences are clearly biased (positive). Similarly, large negative SST differences, the SSS differences are clearly biased (negative). It must be remembered that for a given brightness temperature, a decrease of the physical SST leads to a smaller salinity. In terms of Figure 16, when the ECMWF SST is too small (negative difference), the SMOS retrieval will be too fresh (negative difference). Similarly, when the ECMWF SST is too large, the SMOS retrieval will be too salty, and the difference by respect to

Argo will be positive. This leads to an additional factor to consider when using Argo to validate SMOS: **If there is a mismatch between the temperature of Argo and ECMWF (independently of the origin), that buoy should not be used to validate SMOS because: either the SMOS SSS is biased due to an erroneous reference SST or the Argo salinity is wrongly calculated using a biased in-situ temperature**.

3.4. Bias and random error (II)

According to the geophysical dependency of the differences between SMOS and Argo, a new set of filter criteria should be used to better estimate the error of SMOS using Argo salinity data. The match-up of SMOS SSS is realized against the uppermost valid salinity value if that value has been measured in the first 10 meters of the water column. The match-up has to be located more than 1000 km from the coast. The surface temperature estimated from the in-situ Argo must be between 5ºC and 28ºC, the average precipitation for the corresponding grid must be smaller than 1 mm/day, and the differences between the Reference SST used for the retrieval of the salinity should differ from the Argo uppermost value by less than 1ºC.

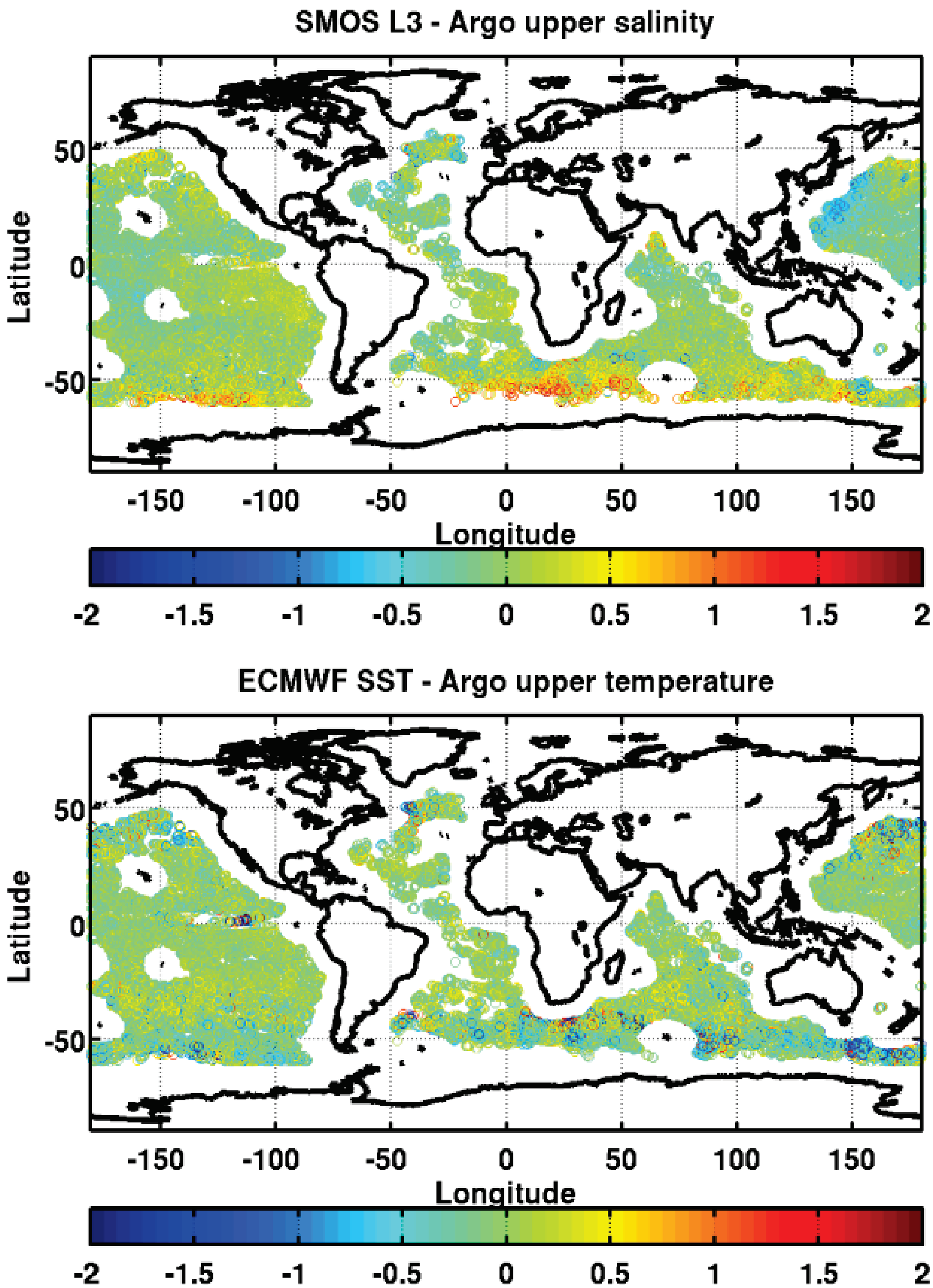

Figure 15: Top: Difference between SMOS SSS and Argo uppermost valid salinity measurement. Bottom: Corresponding difference between Reference SST and Argo uppermost valid temperature measurement.

Table 3 shows the average and standard deviation of the differences between SMOS and the uppermost salinity measurement from Argo according with the new set of match-up restrictions.

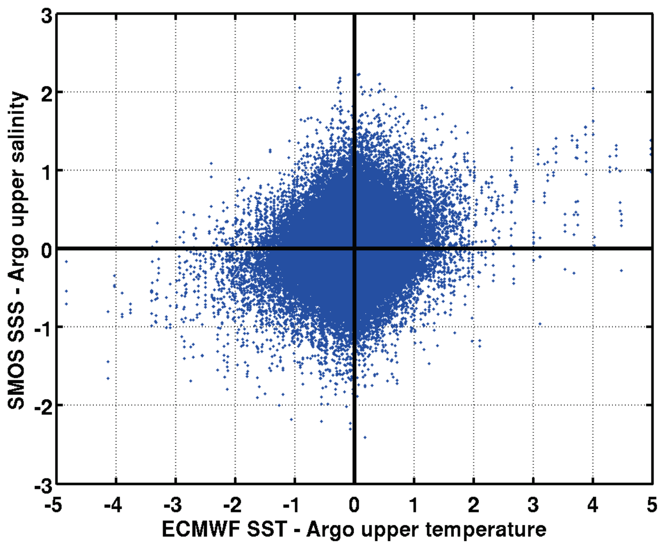

Figure 16: Difference between SMOS and Argo as a function of the difference between the ECMWF temerature and the Argo uppermost temperature.

Table 3: Statistics of the tree SSS products and the Argo uppermost salinity value match up pairs. Shown are the number of matchups, the average and standard deviation.

		60S-60N	30S-30N
L3	n	127746	60217
	$<\Delta S>$	-0.00	-0.02
	$\sigma_{\Delta S}$	0.49	0.37
OI	n	132542	61924
	$<\Delta S>$	-0.01	-0.03
	$\sigma_{\Delta S}$	0.29	0.23
L4	n	127746	60217
	$<\Delta S>$	-0.06	-0.12
	$\sigma_{\Delta S}$	0.28	0.23

4. Sensitivity experiments

This section will assess the robustness of the error estimates stated in Table 3. As the experiments will be done with the **Optimal Interpolation** product (the one that combines small random error variance and small bias), the reference values of the standard deviation are **0.29** for the 60º latitude band and **0.23** for the 30º latitude band.

4.1. Depth of the uppermost salinity measurement

As stated in section 2, two proxies are being used to estimate the sea surface salinity value from each Argo profile: i) the uppermost valid value and ii) the salinity interpolated at 7.5 m. Such an interpolation approach is used as additional Quality Control criteria (three interpolation methods are used to perform the interpolation, rejecting the interpolated value if one of them differs more than 5% from the averaged value). A profile is flagged, and no SSS estimate is provided, if it fails to provide a robust salinity interpolation at 7.5 m.

In this section, the impact of using the upper salinity, the interpolated salinity at 7.5 m or the upper salinity shallower than 10 m is examined.

*Table 4: Validation of SMOS OI SSS data using deeper salinity data than in the Reference experiment (Table 3).*New data set that disregards, when processing the Argo profiles, any value shallower than 15 m. Reduction of the number of observations is due to the failure to provide a robust 7.5 m interpolation from data below 15 m.*

	60S-60N				30S-30N			
	Ref	*Uppermost*	*7.5 m*	*15 m**	***Ref***	*Uppermost*	*7.5 m*	*15 m**
n	**132542**	135850	135850	113306	**61924**	64289	64289	54522
$<\Delta S>$	**-0.01**	-0.01	-0.01	-0.01	**-0.03**	-0.03	-0.03	-0.03
$\sigma_{\Delta S}$	**0.29**	0.29	0.29	0.29	**0.23**	0.24	0.24	0.24

Using no constrain in the depth of the uppermost measure (the 4% of the profiles have an uppermost measure deeper than 10 m) the statistics of the differences between SMOS and Argo is the same at the 60 latitude band, and slightly worse than in the 30 latitude band. The Argo profilers are not sampling the first cm of the ocean. Thus, it seems that once this shallow layer is not sampled, the deep at which the uppermost salinity is taken (but inside the mixed layer) has little impact.

Table 5: Validation of SMOS OI SSS using shallower salinity data. The number of observaitons decreases with the requested closest depth to surface.

	60S-60N					30S-30N				
	1 m	*3 m*	*4 m*	*5 m*	***10 m***	*1 m*	*3 m*	*4 m*	*5 m*	***10 m***
n	303	7988	13991	57138	**132542**	262	6553	10435	35010	**61924**
$<\Delta S>$	0.08	0.04	0.01	-0.03	**-0.01**	0.07	0.04	0.02	-0.04	**-0.03**
$\sigma_{\Delta S}$	0.20	0.24	0.27	0.29	**0.29**	0.17	0.20	0.22	0.24	**0.23**

Table 5 shows that once the depth of the measurement is below 5 m, there is little variation on the estimate of the remotely sensed SSS**. Notice that the bias reverses sign (SMOS slightly saltier than Argo) as soon as Argo data is restricted to samples shallower than 4 meters. The reason of this relative freshening of the Argo near the surface requires further research.**

4.2. Half size Argo array

A series of experiments is now being performed to assess the impact that the Argo array would had been half its size during the period 2011-2013. To perform this situation, a random number is (from an unifoem probability distribution) is issued for each individual profile. If the random number is larger or equal to 0.5, the profile is kept. The results of performing four of such subsampling experiments are shown in Table 6. Notice that having half of the samples provides the same results as the reference experiment. This robustness is due to the large number of SMOS and Argo match-ups.

Table 6: Four experiments in which the Argo array is randomly reduced by half its size.

	60S-60N					**30S-30N**				
	A	*B*	*C*	*D*	***Ref***	*A*	*B*	*C*	*D*	***Ref***
n	66472	66001	66138	66277	**132542**	31071	30817	30839	30952	**61924**
$<\Delta S>$	-0.01	-0.01	-0.01	-0.01	**-0.01**	-0.03	-0.03	-0.02	-0.03	**-0.03**
$\sigma_{\Delta S}$	0.29	0.29	0.29	0.29	**0.29**	0.23	0.24	0.23	0.24	**0.23**

Table 7: As Table 6, but data restricted to December 2013.

	60S-60N					**30S-30N**				
	E	*F*	*G*	*H*	***Ref***	*E*	*F*	*G*	*H*	***Ref***
N	565	557	569	559	**1142**	214	202	205	207	**426**
$<\Delta S>$	-0.15	-0.14	-0.16	-0.15	**-0.15**	-0.10	-0.08	-0.10	-0.10	**-0.10**
$\sigma_{\Delta S}$	0.27	0.26	0.28	0.26	**0.27**	0.20	0.20	0.21	0.20	**0.21**

In Table 7, the subsampling experiment is done, but limiting the validation to a single month (December 2013). The first thing to note is that the standard deviation values shown in tables 6 and 7 are significantly different. This has been verified with the Matlab® function **vartest2**. On the contrary, the differences in the standard deviation when the data is reduced by half are not significantly different (neither for Table 6 nor Table 7). Thus, for **salinity remote sensing validation purposes, the current Argo array size satisfies its requirements with enough redundancy to ensure the robustness of its estimate (both at the long time and for short time monitoring).**

4.3. Use of Real Time data

The last set of experiments addresses the issue of the use of Delayed data only or whether to include the Real Time data. Table 8 displays the results of including both the Delayed and the Real time data. Two experiments are labelled "*All data*". The first one includes any Real time profile. Notice the significant change in the estimation of the standard deviation of the differences. This large increase in the standard deviation suggests the presence of outliers. The set labelled "*All data**" introduces an additional Quality Control test to remove any profile when the difference between SMOS and Argo is found to be larger (in absolute value) than 6. Such a simplified QC test effectively reduces the standard deviation of the differences to the value of the Reference validation experiment.

Table 8: Statistical description of the SMOS and Argo differences when Real Time profiles are also included.

	60S-60N			**30S-30N**		
	Ref	*All data*	*All data**	***Ref***	*All data*	*All data**
n	**132542**	332437	332418	**61924**	177961	177958
$<\Delta S>$	**-0.01**	-0.01	-0.02	**-0.03**	-0.02	-0.02
$\sigma_{\Delta S}$	**0.29**	0.33	0.29	**0.23**	0.24	0.24

The small differences seen in the table Table 8 can be due to differences between the ADJUSTED and the REAL_TIME salinity, as well as differences in location of the real time and the delayed mode matchups.

To account for the direct impact of the salinity corrections in the DELAYED_MODE profiles. The Argo DELAYED_MODE profiles are taken. Comparison between the PSAL_ADJUSTED and the PSAL values are calculated. Moreover, the validation of the SMOS is done against both salinity values. The results are shown in Table 9 and Figure 17. No reduction of the difference against Argo is detected by using the PSAL_ADJUSTED rather than the original PSAL value. The root mean square of the differences between both salinities is 0.02 (the largest salinity correction being of about 0.6). The histogram of the differences is shown in Figure 17. Therefore, the differences seen in Table 8 correspond to differences in the matchup location rather differences in the salinity adjustment process. Note however that our comparison has taken advantage of the proper flagging of pressure, temperature and salinity values.

Table 9: As Table 8, but data restricted to identical profiles.

	60S-60N		
	Ref	*PSAL_ADJUSTED*	*PSAL**
N	**132542**	10593	10593
<ΔS>	**-0.01**	-0.07	-0.07
$\sigma_{\Delta S}$	**0.29**	0.28	0.28

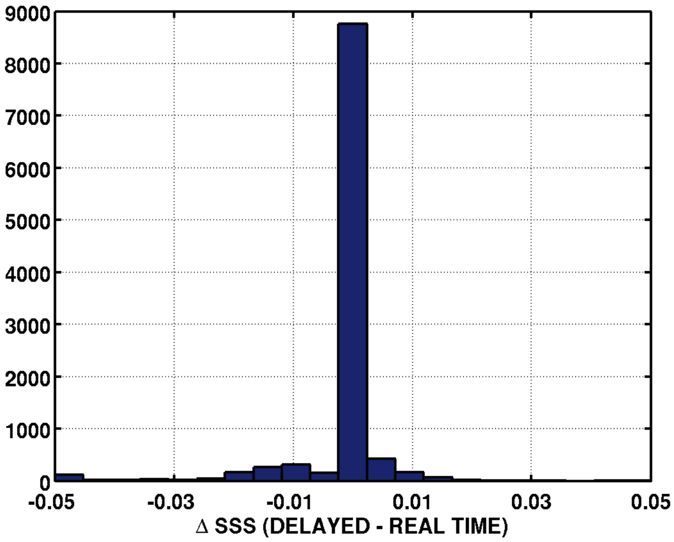

Figure 17: Histogram of the differences between the PSAL_DELAYED and the PSAL values for Delayed Mode Argo profiles. The mean of the differences Is 0.00 and the standard deviation 0.02 (one order of magnitude smaller than the difference between SMOS and Argo).

5. Recommendations for further development of Argo

The differences between three SSS products generated at SMOS-BEC and Argo estimates of the upper ocean salinity have been studied here. These differences contain both the inherent limitations of the technology used to retrieve salinity from space and other geophysical sources of error. The salinity and temperature data from Delayed Argo profiles have been used to include criteria of whether or not use a given data match-up. A set of selection rules have been defined, and robust estimates of the difference between SMOS and Delayed Argo have been found to be **0.29** and **0.23** depending if the pairs are estimated in the latitudinal band of 60S-60N or 30S-30N respectively. A slight negative bias (SMOS fresher) has been systematically found in these SMOS and Argo validations.

Sensitivity studies have been realized to assess the robustness of these estimates by further including restrictions on the maximum depth that the upper Argo measurement has to have to be included in the match-up data, the size of the array and the inclusion of Real Time profiles. According to the results the following recommendations for the future development of Argo are suggested:

Speed up of the scientific calibration (Delayed Mode) process of Argo data. The number of Delayed Mode Argo data has been declining since beginning of year 2011 (Figure 1). This decline leads to situations where some ocean basins are not properly sampled (see the almost absence of Delayed Argo data in the North Atlantic Ocean during December 2013 in Figure 3). Although our results indicate that the salinity adjustment do not modify the salinity (Figure 17), the user takes advantage of the proper flagging of the profile values.

Increase the number of measurements in the upper four meters of the ocean. Currently, the spatial coverage of the oceans of the ocean surface is ensured when we consider measurements in the first ten meters of the ocean (Figures 4, 6, and 7).Thus, the Argo data used to validate SMOS SSS maps include any observation taken in the first ten meters. Our studies have shown that similar results are obtained when SMOS is compared with all data in the first five meters, the 7.5 m interpolated data, or if data where taken in the 15 m. In all these cases the bias between SMOS and Argo is systematically slightly negative (Tables 1, 2, 3, 4, 6, 7, 8, and 9). However, as soon as data are restricted to be taken in the first four meter, or shallower, the bias changes sign (SMOS slightly saltier than Argo). Research of the physical origin of such a behavior requires a further deployment of floats measuring salinity at depths shallower than 4 m. At this moment, the number of Delayed Argo measurements taken in the first meter of the ocean is negligible (Figure 5).

Properly identify if salinity measurements have been acquired with or without water pumping to the conductivity cell. At this moment, this information is not present in the standard Argo files. Currently, the usual approach of Argo users for salinity values is to reject salinity values shallower than five meters for SOLO and PROVOR instruments. Changes in the instrument design and operation affecting this behavior should be properly identified in the standard Argo files.