Comparison analysis between Aquarius sea surface salinity and World Ocean Database in situ analyzed sea surface salinity

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Abstract A new monthly sea surface salinity (SSS) product calculated from profile data within the World Ocean Database (WOD) is compared and contrasted with Aquarius SSS, both standard and Combined Active-Passive (CAP) products, from September 2011 through September 2013. Aquarius exhibits similar biases as shown in previous comparison SSS studies, with negative biases in the tropics transitioning to positive biases in the higher latitudes when compared to WOD SSS. These biases are generally much weaker in CAP than the standard version, indicating that the biases are strongly related to the differences in algorithms used to retrieve satellite SSS. Non-Argo data utilized in the study are shown to be of great use to validate Aquarius in regions with little to no Argo coverage and helps provide SSS measurements in regions where there are known errors in Aquarius retrievals. The annual cycle of WOD and Aquarius is found to be very similar, with Aquarius being generally more coherent and robust. All three products’ annual cycles compared favorably to the World Ocean Atlas 2013. The interannual changes in all three products generally corresponded well to one another and to changes in evaporation and precipitation (E-P). Overall, Aquarius compares very well with in situ sea surface salinity fields under multiple comparison examinations; however, both products have their own strengths and weaknesses and a synthesis of the two should be used to study global scale SSS variability.

1. Introduction

Sea surface salinity (SSS) is an important variable of the ocean. A recent study by Durack and Wijffels [2010] showed that over the past ~50 years, salty regions of the ocean have become saltier and fresh regions fresher, suggesting a strengthening of the global hydrological cycle. Furthermore, Durack et al. [2012] showed through the observed changes in SSS combined with global climate models that a global surface temperature increase of 1°C would increase the global hydrological cycle by an estimated 8 ± 5%. This agrees with the general idea that in a warming world the hydrological cycle will become stronger [Held and Soden, 2006] and dry regions dominated by evaporation will become drier and wet regions dominated by precipitation will become wetter.

In addition to SSS changes being a natural marker of changes in the global hydrological cycle, its importance to deep water formation and ocean circulation cannot be overstated. The thermohaline circulation depends on a delicate balance between temperature and salinity as do all density driven currents in the ocean. Broecker [1991] put forth the first generalized view of the thermohaline circulation and noted that changes in salinity due to changes in freshwater fluxes could result in changes in the thermohaline circulation. Multiple studies [e.g., Fichefet et al., 2003; Gregory et al., 2005; Rahmstorf and Ganopolski, 1999] have used models to evaluate changes in the thermohaline circulation in a warming world. For the most part, increases in freshwater fluxes causing a decrease in salinity resulted in a decrease in the strength of the thermohaline circulation in the North Atlantic. An important property of the thermohaline circulation is it redistributes heat from the tropics to high latitudes; thus, any changes in the thermohaline circulation would affect the global distribution of heat.

Therefore, it is critical to monitor SSS variability due to its status as an important marker for the hydrological cycle and an important component of the thermohaline circulation. In recent years, the Aquarius/Satélite de Aplicaciones Científicas (SAC)-D [Lagerloef et al., 2008] and Soil Moisture and Ocean Salinity (SMOS)
Kerr et al., 2010] satellite missions have been measuring SSS on a near-global scale. A crucial component of these satellite missions is validation of the satellite SSS measurements. Monthly validation of satellite SSS measurements with in situ observations is possible due to the international project, Argo [Argo Steering Team, 1998], and its vast fleet of profiling floats.

Recent studies [e.g., Boutin et al., 2012; Vinogradova and Ponte, 2013; Grodsky and Carton, 2012; Lagerloef et al., 2013] all compared satellite SSS measurements to in situ observations. In general, over the subtropical regions away from land, in situ and satellite SSS measurements match up very well. However, in tropical regions, high latitudes, river outflow, and coastal regions the differences can be quite large. A challenge in validating satellite data is that the footprints are much larger than single point in situ observations. SMOS has a footprint of ~40 km. Aquarius has three ellipsoidal footprints: 76 × 94 km, 84 × 120 km, and 96 × 156 km.

For this study, we compare and analyze Level 3 gridded monthly Aquarius SSS to gridded in situ derived SSS. We choose to compare Aquarius to gridded in situ fields rather than individual profiles due to Aquarius’ larger footprint. This study expands on the previous analyses in two different ways. First, a new monthly SSS gridded data set computed from not only Argo profiling data, but also from a multitude of other instruments (moored buoys, CTDs, bottles, gliders, and ice drifters) are used. The use of non-Argo data was vital because ~30% of the Argo data used in our study was discarded because the shallowest measurements were deeper than 5.25 m. We also look at the importance of non-Argo SSS data in regions where Argo floats are sparse and how it relates to Aquarius validation and regional SSS studies. Second, in addition to performing a direct comparison with the satellite data, a look at how the annual cycles compare is also completed by analyzing the first harmonic of the Fourier decomposition. These cycles are also compared to the annual harmonics of the World Ocean Atlas 2013 [Zweng et al., 2013] SSS climatology. The interannual changes of SSS are compared and contrasted between the in situ and satellite products. Finally, SSS and E-P interannual changes are discussed. For this study, all salinity values are on the Practical Salinity Scale 1978 (PSS-78) and are therefore unitless.

2. Data

For our comparison analyses, several difference plots are calculated from a multitude of various SSS and ancillary data sets that are described below. Unless otherwise noted, all gridded monthly fields are on a 1° × 1° resolution for the time period of September 2011 through September 2013.

2.1. In Situ Analyzed Sea Surface Salinity Fields

To create monthly in situ analyzed SSS fields, we started with all available SSS in situ profile data from the World Ocean Database [http://www.nodc.noaa.gov/OC5/WOD/pr_wod.html] [Boyer et al., 2013] which is a product of the National Oceanographic Data Center. In our time domain of September 2011 to September 2013, there were a total of 426,212 salinity profiles. For this study, only salinity measurements less than 5.25 m from the surface were considered. A depth of 5.25 m was chosen as at this depth we are able to include many Argo profiling floats, and in addition, other instruments’ shallowest measurements are often at least 1 m deep, and rarely at the sea surface due to the difficulty of obtaining measurements right at the sea surface. The depth is not extended any deeper than 5.25 m as it has been shown (see Figure 5 in Henocq et al. [2009]) that increasing rainfall rates caused larger differences in salinity between 1 and 10 m depths than 1 and 5 m depths. This depth constraint eliminated 31.3% of Argo measurements for the period since many Argo floats shut off sensors below 5 m to prevent biofouling. It also eliminated 22.0% of measurements from other instrument types. Thus, a total of 305,576 profiles were in our depth range, of which 45,524 did not pass quality control checks leaving a total of 260,052 total profiles used in the analyses. For a full list of the quality control checks, please review Johnson et al. [2013a]. Table 1 illustrates the data distribution among different data types, with Argo profiling floats dominating the distribution. However, a substantial amount of SSS data is also attributed to CTD and moored buoys. All moored buoy data are daily means from the Pacific Marine Environmental Laboratory (PMEL) tropical moored buoy data set. The moored buoy array network consists of the Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network (TAO/TRITON), Prediction and Research Moored Array in the Atlantic (PIRATA), and Research Moored Array for African-Asian-Australian Monsoon Analysis and Prediction (RAMA). Figure 1 illustrates the
spatial distribution of SSS observations over our time domain. Argo data are in gray to emphasize the measurements from other instruments. 

The gridding technique used to calculate the in situ analyzed SSS fields is very similar to the technique implemented when computing the World Ocean Atlas 2013 (WOA13) climatologies [Zweng et al., 2013], with a few differences. We begin by computing monthly mean anomalies for each month in our time domain. These are computed by taking the differences between the in situ SSS observations and the monthly climatological SSS value from the World Ocean Atlas 2009 [Antonov et al., 2010] at each 1° × 1° grid point. Once all mean anomalies are calculated for each month, the mean anomalies are objectively analyzed following the same technique used in computing the salinity climatology for WOA13. For a detailed overview of the objective analysis procedure, see Zweng et al. [2013]. Once the anomalies are objectively analyzed they then go through subjective quality control screening in which each monthly anomaly field is reviewed for “bullseyes.” “Bullseyes” are concentric closed contours emanating from a specific location. These “bullseyes” often appear in the analyzed fields due to a single profile with an abnormally large anomaly compared to surrounding data. Bullseyes are not necessarily bad data; they often represent small or mesoscale anomalies not representative of the larger area. Data that produced these “bullseyes” are removed and the anomaly fields are rerun. Once these fields are finalized, they are added to their respective WOA09 monthly climatology yielding a full salinity field. It is important to note that because WOA09 is added to the salinity anomaly fields, regions of poor data coverage will essentially be the monthly climatology (see Figure 1 to locate data-poor regions). The monthly salinity anomalies are available at http://www.nodc.noaa.gov/OC5/3M_HEAT_CONTENT/. We will refer to the WOD-derived SSS fields as WODSSS.

2.2. World Ocean Atlas 2013


2.3. Aquarius

The Aquarius satellite observes SSS by measuring microwave emissions from the sea surface at the 1.413 GHz frequency (L-band) using three microwave radiometers [Lagerloef et al., 2008]. For this study, we
used the Level 3 Standard Mapped Image version 2.5.1 Aquarius/SAC-D monthly SSS fields. The data used were not separated based on ascending/descending phase like other comparison analysis studies [e.g., Grodsky and Carton, 2012]. The initial reasoning for separation was due to seasonal biases, especially during the descending phase in the Southern Hemisphere [Lagerloef et al., 2013]. However, version 2.5.1 has been shown to have these biases mostly eliminated (G. Lagerloef, personal communication, 2013), and thus for this study, especially in regards to comparing annual cycles, we use the combined phase data. All salinities less than 0 and greater than 100 were masked out before analyzing the Aquarius v2.5.1 data. These erroneous values are mostly confined to high-latitude regions where sea ice and/or land contamination caused errors in the salinity retrievals.

In addition to the aforementioned v2.5.1, we also utilized the Level 3 Standard Mapped Image CAP version 2.5.1 Aquarius/SAC-D monthly SSS fields. The major difference between the standard version 2.5.1 and the CAP version is that the CAP version uses a Combined Active-Passive (CAP) [Yueh and Chaubell, 2012] algorithm that enables wind speed/direction and sea surface salinity to be retrieved simultaneously from Aquarius data by minimizing the sum of squared differences between model and observations [Yueh et al., 2013; Yueh and Chaubell, 2012]. There is no dependence on the wind directions from the National Centers for Environmental Prediction (NCEP) like that of the standard version for Aquarius. Wind speed and direction are important components of calculating the surface roughness correction on which Aquarius sea surface salinity retrievals depend. The v2.5.1 CAP data set can also utilize a rain correction (S. Yueh, personal communication, 2014). When rain droplets strike the ocean surface it creates roughness which increases the brightness temperature that Aquarius measures; this ultimately reduces the measured SSS. This correction reduces surface freshening under rain (S. Yueh, 2014) [Tang et al., 2014]. For this study, the rain-corrected v2.5.1 CAP data set was used. We will refer to Aquarius v2.5.1 as AQ251 and Aquarius CAP v2.5.1 as AQCAP251.

2.4. Evaporation and Precipitation

The monthly gridded ocean evaporation data come from the Woods Hole Oceanographic Institution (WHOI) Objectively Analyzed Air-sea Fluxes (OAFlux) project (http://oaflux.whoi.edu/dataproducts.html). The data were initially in units of cm·yr⁻¹ and were converted into mm·d⁻¹. For a detailed analysis of how these fields are calculated, please review Yu et al. [2008].

The monthly gridded precipitation data are from the Global Precipitation Climatology Project (GPCP). We use the GPCP version 2.2 monthly gridded precipitation data. In a very general sense, the GPCP version 2.2 data are a merged product that combines satellite precipitation estimates with surface rain gauge observations [Adler et al., 2003]. The monthly gridded data are in units of mm·d⁻¹. The initial gridded data were on a 2.5° × 2.5° spatial scale. With all other comparison data on a 1° × 1° grid, we used bilinear interpolation to regrid the precipitation data on to a finer 1° × 1° grid. For a full review of the GPCP version 2.2 data, please review Adler et al. [2003] and Huffman et al. [2009]. We will refer to the WHOI OAFlux evaporation data set as OAFlux and the precipitation GPCP version 2.2 will be referred to as GPCP.
3. Discussion and Results

3.1. In Situ Comparison

Multiple studies [e.g., Qu et al., 2014; Vinogradova and Ponte, 2013] use the Asia-Pacific Data Research Center (APDRC) gridded Argo data products as a validation data set for Aquarius. The APDRC uses a variational interpolation algorithm to map salinity onto a three-dimensional grid on standard levels (for more documentation see: http://apdrc.soest.hawaii.edu/projects/Argo/data/Documentation/). Because this data set has been used for validating Aquarius in the past [e.g., Qu et al., 2014; Vinogradova and Ponte, 2013], a comparison between our gridded SSS data and the APDRC Argo-only gridded data was conducted to ensure that our own SSS gridded data set is comparable to the APDRC data set.

The APDRC monthly mean fields from September 2011 to September 2013 (http://apdrc.soest.hawaii.edu/dods/public_data/Argo_Products/monthly_mean) were compared to the WODSSS monthly gridded fields. The monthly comparison statistics root-mean-square error (RMSE) and bias (APDRC-WODSSS) are shown in Figure 2. The RMSE remains below 0.20 for the entire 2+ year time period. There is a very small positive bias (APDRC > WODSSS) for most months, however, it never reaches above 0.02 for any given month.

Annual (September 2011 to September 2013) scatter diagrams were also plotted (Figures 3a–3d) to further evaluate the differences seen between WODSSS and APDRC. The statistics show that when comparing both data sets to AQ251 (Figures 3a and 3c), both WODSSS and APDRC are nearly identical with similar bias (~0.02), standard deviation of the differences (~0.24), and correlation (~0.97) with a slight edge to WODSSS. However, there are noticeable differences when both are compared to AQCAP251 (Figures 3b and 3d). While
bias is doubled in WODSSS (−0.017 compared to −0.008 for APDRC), the standard deviation of the differences is improved by nearly 13% when using WODSSS. There is also a noticeable tailing-off feature in the APDRC plots where regions of low SSS are measured to be much higher than AQ251 and AQCAP251. This tailing-off feature is not evident in the WODSSS plots; however, there is a small positive bias in WODSSS for the same low surface SSS waters. These specific points are located near the Bay of Bengal.

Figure 4a illustrates the monthly RMSE for AQ251-WODSSS, AQCAP251-WODSSS, AQ251-APDRC, and AQCAP251-APDRC. The RMSE for both Aquarius products is slightly smaller for most months when using WODSSS as the “observed” SSS instead of APDRC. The 25 month RMSE average for AQ251-WODSSS is 0.304 and 0.314 for AQ251-APDRC, resulting in a very small −0.010 difference. Similarly, the 25 month average RMSE for AQCAP251-WODSSS is 0.266 and 0.281 for AQCAP251-APDRC, resulting in a small −0.015 difference. This indicates that on average AQ251 and AQCAP251 are slightly closer to WODSSS than APDRC. The monthly biases also exhibit similar magnitudes and month-to-month variability (Figure 4b). There also appears to be a low amplitude annual cycle in the monthly biases. These results compare very well with the recent Aquarius CAP analyses from Tang et al. [2014]. There is also a noticeable difference in RMSE and bias when using AQ251 and AQCAP251 which will be discussed in the next section.

Overall, WODSSS compares very well to the APDRC SSS data set. There is very little bias between the two (Figure 2) and an RMSE that is below 0.20 for each month (Figure 2). The slight Aquarius (both versions) validation improvement when using WODSSS as compared to APDRC is likely caused by a combination of additional data used in the WOD analyses, differences in the objective analyses, and using the background climatology in computing the analyzed fields (see section 2.1).

### 3.2. Aquarius SSS Compared to WOD SSS

The average monthly differences (September 2011 to September 2013) between AQ251/AQCAP251 and WODSSS are shown in Figures 5a and 5b. The zonal average of each difference is shown in Figure 5c. From
Figures 5a and 5c, large negative biases (AQ251 < WODSSS) exist from roughly 25°S to 25°N. The large negative biases in the tropics, especially in regards to AQ251, would appear to have a direct relation to surface freshening induced by rainfall along the Intertropical Convergence Zone (ITCZ) and South Pacific Convergence Zone (SPCZ). Vertical salinity stratification in high precipitation locales in the upper couple of meters has been analyzed in a few studies [Reverdin et al., 2012; Boutin et al., 2013; Drucker and Riser, 2014]. Argo typically makes its shallowest salinity measurement near 5 m depth as this is when the CTD pump is turned off on its way to the surface [Riser et al., 2008]. Aquarius is measuring the top 2 cm, thus any salinity stratification between 2 cm and 5 m will not be well-captured by the in situ fields. However, recent work by Drucker and Riser [2014] showed that while heavy precipitation events can cause large vertical salinity stratifications (>0.1) in the near-surface waters, they are often short lived and very infrequent, thus only contributing up to 0.03 bias when Aquarius is compared to Argo in the tropics. The zonal biases that are seen in Figure 5c are much greater than the 0.03 bias found by Drucker and Riser [2014], thus salinity stratification is not the main source of negative biases in the tropical region.

Figure 5b shows the average monthly difference between AQCAP251 and WODSSS and the zonal average of these differences are shown in Figure 5c. There is a large decrease in the negative bias seen in the tropical regions when the CAP algorithm is utilized as compared to the standard Aquarius v2.5.1. Recent work by Tang et al. [2014] showed that the month-to-month bias (when compared to Argo) for the rain-corrected CAP data (the data that is used in this study) was shifted up by 0.03 when compared to the bias using the nonrain-corrected CAP data over the global ocean. Because this bias (0.03) is 3–4 times smaller than the zonal average bias improvement we see from AQ251 to AQCAP251 in Figure 5c, we conclude that the improvement in bias in the tropics seen in AQCAP251 when compared to AQ251 is a direct result of the usage of the CAP algorithm and not due to the addition of the rain correction. Thus, the biggest influence on bias in the tropics is the difference in the salinity retrieval algorithms between AQ251 and AQCAP251. Additionally, large river outflows such as the Amazon and Ganges-Brahmaputra contribute large negative...
biases. However, a change in the salinity retrieval algorithms (Figures 5a and 5b) has little effect on the differences seen in river outflow regions.

In the subtropical regions, in both Figures 5a and 5b, the WODSSS and AQ251/AQCAP251 appear to generally agree outside of coastal regions. Based on the annual salinity climatology from WOA13 [Zweng et al., 2013], the maximum SSS in each ocean basin occurs in the open ocean subtropical regions where evaporation dominates precipitation. With little precipitation, a weak wind field (due to the presence of subtropical high pressures), and a region well sampled by Argo (Figure 1), we would expect Aquarius (both products) and WOD to agree. The agreement is spatially contained to a very small area centered around 30°N and 30°S. Large discrepancies near coastal locations are due to a combination of land contamination in satellite salinity retrievals [Zine et al., 2007] and a lack of in situ data along the coast (Figure 1).

In higher latitudes, the zonal averages (biases) (Figure 5c) become positive, and in some cases are greater than 0.20 (i.e., 45°S for AQ251-WODSSS). There are several error sources in this region. In the high latitudes, measuring SSS is especially difficult due to cold sea surface temperatures (SST), high winds, and melting/freezing of sea ice. Aquarius measurements are less sensitive to SSS in cold SST regions. High winds increase the surface roughness of the ocean which increases the difficulty of accurately measuring SSS [Lagerloef et al., 2008]. Melting/freezing of sea ice causes sea ice contamination errors in the SSS retrieval. There is a notable decrease in positive bias between AQCAP251 and AQ251 in the high southern latitudes (30°S–50°S). This large improvement in bias occurs in a region known for strong westerly winds (i.e., Roaring Forties) quite possibly signifying that the CAP algorithm is handling the roughness correction for high wind speeds better in this region. The same improvement in bias is not seen in the high northern latitudes likely because the biases in this region are more dominated by land and sea-ice contamination in the satellite SSS.

Figure 6. Summer (July, August, September) 2012 (a) SSS differences between AQ251 and WODSSS and (b) average precipitation (mm d⁻¹).
It should be noted that the North Pacific exhibits a strong positive bias (Figures 5a and 5b) in v2.5.1 for both Aquarius products, whereas this bias was much weaker in the standard version 2.0, and just slightly weaker in the CAP version 2.0. Figure 6a shows the North Pacific summer (July, August, and September) SSS difference between AQ251 and WODSSS. Figure 6b shows the average precipitation over this same time period. There is a lack of precipitation over the area of strongest SSS difference. Climatologically, during the summer months, there is also a weak wind field in this region \[\text{Risien and Chelton}, 2008\]. With a weak wind field and little precipitation, the North Pacific biases cannot be explained through surface roughness issues or near-surface salinity gradients. It is likely that a change in the satellite retrieval algorithms from version 2 to version 2.5.1 caused this increase in bias.

Overall, the zonal average of the average monthly differences follow the same positive/negative bias pattern in both AQ251-WODSSS and AQCAP251-WODSSS (Figure 5c), with AQCAP251-WODSSS generally less biased than AQ251-WODSSS, especially in the tropical and Southern Ocean regions. In Figure 4, it is shown that AQCAP251 consistently produces smaller RMSE than AQ251 throughout the 2+ year time period, indicating AQCAP251 is measuring closer to in situ than AQ251. The 25 month average RMSE for AQ251 is 0.306 and AQCAP251 is 0.266 when compared to WODSSS. This represents an improvement of 13% when using AQCAP251. It is important to note that the improvement of RMSE when using AQCAP251 is a result of using the CAP algorithm and not the usage of the rain correction as \text{Tang et al.} [2014] found no real difference in RMSE between CAP with no rain correction and CAP with rain correction when compared to Argo. Subsequently, it indicates that utilizing the CAP algorithm makes a strong difference in the validation of the Aquarius instrument.
3.2.1. Non-Argo Measurements: Importance to Validation of Aquarius and Regional SSS Studies

There are regions of the global ocean (i.e., near coast, high latitudes; see Figure 1) where the distribution of Argo profiling floats is simply not adequate for validation of satellite SSS measurements nor is it adequate for regional scale SSS studies. Non-Argo data (i.e., CTD, moored buoys, gliders, etc.) provide, in some regions, the data that are necessary to perform these tasks. Figure 7a shows the distribution of CTD SSS data and the number of months during our time domain in which no Argo floats surfaced within a one-degree box of the CTD measurement. Figure 7b is the same as Figure 7a, except for moored buoy, bottle, drifting buoy, and glider data combined. Off of the northeast coast of the United States, southeast coast of Canada, the North Sea, and off the coast of Japan, there are many months of CTD SSS data where Argo floats never surfaced (Figure 7a). Near the northeast coast of the United States and southeast coast of Canada (80°W–40°W, 38°N–54°N) there are a total of 8286 CTD profiles and 1103 Argo profiles. The northern European waters (20°W–30°E, 45°N–80°N) contain 6044 CTD profiles and 2911 Argo profiles. Finally, coastal Japan (126°E–144°E, 30°N–42°N) contains 8713 CTD profiles and 3536 Argo profiles. In each of these regions, the amount of CTD profiles at least doubles the amount of Argo profiles.

Figure 8a shows the September 2011 one-degree bin-averaged CTD SSS data from CTD along the water ways between Norway and Svalbard. There is not a single Argomeasurement made during this month in this region, however, there are numerous CTD measurements. The CTD measurements allow us to compare SSS measurements to Aquarius, which was done in Figure 8b. As shown, Aquarius has a positive bias greater than 1.4 in parts of this region. This high bias cannot be confirmed with Argo profiles because the most eastern extent of Argo data for this region is 17°E throughout the 25 month time period; however, there are other months such as August 2012 (not shown) where there is a sufficient amount of CTD data that continues to show the high bias of Aquarius in this region. If Aquarius is to be used to study high latitudes, then Argo deployments in these regions need to be increased, and/or data outside of Argo floats will be needed to serve as a reference for Aquarius.

In addition to utilizing non-Argo data in regions where there is a lack of Argo data, we can also utilize non-Argo data in regions where there are Argo data. One example of this is to use moored buoy data to observe near-surface salinity stratification such as was done in Henocq et al. [2009]. Many moored buoy observations shallowest measurements are made at 1 m depth, which is on average 4 or more meters shallower than Argo measurements. Henocq et al. [2009] found that, on a local scale, changes in SSS between 1 and 5 m

Figure 8: September 2011 (a) one-degree bin-averaged CTD SSS and (b) difference between CTD one-degree bin average and AQ251.
depths can reach 1.0 in rainy regions. We still have little understanding on the development and eventual dissipation of these stratification events, but with moored buoy data and other near surface measurements from other instruments, we can begin to build the bridge on what happens between the surface and 5–10 m depths during stratification events. So even though it has been shown that these precipitation induced salinity stratification events occur infrequently and on short time scales and minimally effect the global bias seen between Aquarius and Argo [Drucker and Riser, 2014], they are still important events to understand.

As shown in Figures 7a and 7b, there are many regions, especially near coasts, where Argo float data, by itself, does not meet the need for optimal validation of Aquarius data. Furthermore, there are a few regions (i.e., European coast, NW Atlantic) where it is known that Aquarius has RFI issues, and in these same regions there are CTD data (and lack of Argo data). Thus, not only is supplementary data needed for validation purposes, it is vital for closing the gaps where Aquarius does not perform very well (i.e., RFI regions, coastlines, high latitudes, etc.). In addition, instrumentation outside of Argo (i.e., moored buoys, gliders, etc.) will assist in bridging the gap and helping our understanding of near surface salinity stratification events. Higher level products, like the blended satellite and in situ SSS product created by Xie et al. [2014], will need to utilize all SSS data available to accurately depict SSS. More near-surface instrumentation and measurements are also needed [Lagerloef et al., 2009; Henocq et al., 2009].
3.3. Annual Cycle

The annual cycle of WODSSS, AQ251, and AQCAP 251 was constructed through a Fourier decomposition of the September 2011 to August 2013 monthly fields. We first averaged the 2 year monthly fields then calculated the first harmonic of the Fourier series. The Fourier decomposition follows the methodology used by Boyer and Levitus [2002]. Figures 9a–9c illustrate the amplitude of the first harmonic. The locations of largest salinity amplitudes (ITCZ, SPCZ, and river outflows) compare very well to those calculated by Boyer and Levitus [2002] in which they analyzed the annual cycle by applying a Fourier decomposition to the monthly climatological means of WOA98. In general, WODSSS, AQ251, and AQCAP251 annual amplitudes compare very well to one another.

Figures 10a and 10b show the annual amplitude differences between AQ251 and WODSSS and AQCAP251 and WODSSS, respectively. AQ251 and AQCAP251 have larger amplitudes along most major river plumes, likely because Aquarius’s larger footprint can more robustly and accurately depict SSS in these regions than can sparsely located in situ observations (see Figure 1). AQ251 and AQCAP251 also exhibit larger amplitudes along the ITCZ, likely for the same reasons. AQ251 exhibits much larger amplitudes in the northern North Atlantic and Nordic Seas region, whereas AQCAP251 is not larger than WODSSS in this region. This is likely related to the satellite salinity error sources discussed in section 3.2 (i.e., RFI, sea ice contamination, melting and freezing of sea ice, and difference in retrieval algorithms). Higher amplitudes in the Aquarius products

Figure 10. Difference in the first harmonic (September 2011 to August 2013) for (a) AQ251-WODSSS amplitude, (b) AQCAP251-WODSSS amplitude, (c) AQ251–WODSSS phase, (d) AQCAP251–WODSSS phase, (e) AQ251–WODSSS percent variance, and (f) AQCAP251–WODSSS percent variance.
along and just off the coast of Colombia and Ecuador in the equatorial Pacific are due to the low surface salinity waters being brought in from the south Pacific equatorial countercurrent [Boyer and Levitus, 2002] and are likely better represented through Aquarius. Both AQ251 and AQCAP251 exhibit larger annual cycles near the Antarctic ice sheet, however, it is much larger in AQ251. This is likely related to melting and freezing of sea ice in addition to sea ice contamination errors; however, the larger amplitudes in AQ251 stretch further north which are more likely due to the salinity retrieval errors in the high wind speed and low SST waters. The lack of larger differences in AQCAP251 supports that it is a retrieval-based issue. It is important to note that where there is a lack of in situ observations, the monthly field is in essence the WOA09 climatology, which will often yield a lower amplitude signal because the 57-year time period covered in the climatology is much greater than the 2 years we are examining, and thus variability will be smoothed out a great deal.

The month in which maximum SSS (phase) occurs generally agrees between WODSSS, AQ251, and AQCAP251 (Figures 9e–9h). The largest disagreements (Figures 10c and 10d) between the in situ and Aquarius phases are in the high southern latitudes near Antarctica. The phase for the Aquarius products near the Antarctic ice sheet is generally during the austral spring, where we would expect more melting and lower SSS values. The phase for WODSSS is generally around austral winter, where the freezing of sea ice should cause an increase in SSS due to brine rejection during the freezing process. Thus, this difference is likely a result of errors in the satellite salinity retrievals in this area due to the cold SST, windy conditions, and sea ice contamination. In addition to the high southern latitudes, we also notice large phase differences in the central/eastern North Atlantic and the central/eastern North Pacific. These occur due to very low salinity amplitudes in these regions and therefore large differences in the phase are expected.

The percent variance accounted for by the first harmonic is very similar in all three SSS products (Figures 9i–9l). In general, higher values mirror regions of higher amplitude, which is expected. As was the case with the annual amplitudes, most percent variance differences (Figures 10e and 10f) between the Aquarius products and WOD occur due to the footprint of Aquarius and its ability to measure SSS over a more connected area than the in situ product.

There is a similar pattern when comparing the annual harmonic of the monthly climatological fields from WOA13 to the WODSSS, AQ251, and AQCAP251 (Figure 9). Comparing the annual harmonic of the WOA13 climatology to the WOA98 climatology which was used in Boyer and Levitus [2002], there is a noticeable decrease in amplitude of SSS in WOA13 (Figure 9d). This is a result of the dampening effect from averaging together six decadal monthly climatologies. Thus, when comparing WODSSS, AQ251, and AQCAP251 to the annual amplitude of WOA13, it is important to ensure the structures are similar, as it is expected that the amplitudes for WODSSS, AQ251, and AQCAP251 will be larger than that of WOA13. The annual amplitude structure for all three are very similar to WOA13, as can be seen when reviewing Figures 9a–9d. The phases and percent variance accounted for by the first harmonic between WOA13 and WODSSS, AQ251, and AQCAP251 are also very similar (Figures 9e–9i).

Despite some technical limitations and reservations of analyzing the annual cycle with Aquarius as discussed by Lagerloef et al. [2013]; Aquarius agrees very well with the in situ derived annual cycle. When comparing the annual cycles of WODSSS, AQ251, and AQCAP251 (Figure 9) to that of Figure 3 in Boyer and Levitus [2002], there is very little change in the structure of the largest amplitudes and phases of the annual cycle. This is of importance because Figure 3 from Boyer and Levitus [2002] is based on WOA98, in which the majority of SSS data came from shipboard data (bottles, CTD). Thus, even with a large increase in SSS data from satellites and Argo, the annual cycle has remained unchanged in structure.

3.4. Interannual Variability Comparison

Monitoring SSS changes is vital to climate studies as changes in SSS over time have been linked to changes in the global hydrological cycle [Durack et al., 2012]. If Aquarius is to be used to study SSS variability then we must first ensure that the changes Aquarius measures are similar to the changes in situ observations measure.

3.4.1. Changes in Annual Cycle

We first compare the interannual variability of all three SSS products’ annual cycle. The first year is from September 2011 to August 2012 (denoted 11/12), and the second year is from September 2012 to August 2013 (denoted 12/13). As was done in section 3.3, a Fourier decomposition was applied to each year. Similarly,
because SSS changes are often reflected by E-P changes, a similar Fourier decomposition of E-P for each year was performed.

Figures 11a–11l illustrate the annual amplitude for 11/12, 12/13, and their difference (12/13–11/12) for WODSSS, AQ251, AQCAP251, and E-P. Focusing on the 12/13–11/12 salinity difference figures (Figures 11c, 11f, and 11i), we see that all three salinity products exhibit similar changes in annual amplitude from 11/12 to 12/13. This can be more clearly illustrated when we examine the differences in year-to-year annual amplitude changes between AQ251 and WODSSS (Figure 12a) and the differences in year-to-year annual amplitude changes between AQCAP251 and WODSSS (Figure 12b). Outside of coastal locales and major river outflow regions, where the differences in interannual amplitude changes between Aquarius and WODSSS...
can be greater than 0.5, the magnitude of interannual changes in annual amplitude is very similar between the satellite and in situ products. Furthermore, when the Aquarius and WODSSS differences in interannual amplitude changes (Figures 12a and 12b) are compared to the differences in the 2 year averaged annual amplitudes (Figures 10a and 10b) the ITCZ feature in Figures 10a and 10b is removed in Figures 12a and 12b signifying that Aquarius and WOD are measuring similar year-to-year magnitude changes in the annual amplitude for this region, but Aquarius is measuring a higher 2 year averaged annual amplitude than WOD as seen in Figures 10a and 10b. Conversely, high values in river outflow regions and other coastal locales appear in both Figures 12a and 12b and Figures 10a and 10b signifying that not only are the 2 year averaged annual amplitudes different (Figures 10a and 10b), but the year-to-year changes in the magnitude of the annual amplitude are also different (Figures 12a and 12b). As discussed previously, we believe Aquarius is better able to resolve the SSS structure near river outflows due to a larger footprint and better coverage. In addition, there is normally little in situ data near the river mouths (Figure 1), and thus they are likely not being well represented in the in situ product. The interannual changes in phase generally agree between all three SSS products (Figures 12c and 12d) outside of the regions discussed in section 3.3.

Figures 11j–11l show the annual amplitude of E-P for 11/12, 12/13, and 12/13–11/12, respectively. Regions whose SSS variability is mostly influenced by E-P should share similar annual harmonic structure as these two have been shown to be closely related in annual harmonic analysis (Boyer and Levitus, 2002). Based on Figure 11, the SSS annual amplitude from all three products closely resembles the E-P annual amplitude for much of the ocean in both 11/12 (Figure 11j) and 12/13 (Figure 11k). It is important to note that many of the regions with high E-P amplitude are very similar to the regions Yu (2011) depicted as being the locales where the dominant term in the mixed layer salinity (MLS) budget was E-P (see Figure 9 in Yu [2011]). In
addition to E-P, Yu [2011] found that horizontal advection by both geostrophic and Ekman velocities, and vertical entrainment also played a major role in the MLS budget. Next, we compare the interannual changes in SSS for all three salinity products and compare their year-to-year changes to changes in E-P.

### 3.4.2. SSS and E-P: Interannual Similarities and Differences

The changes in salinity from 11/12 to 12/13 are illustrated in Figures 13a–13c. There is general agreement between all three products on which regions became saltier or fresher from 11/12 to 12/13. However, in some cases, the magnitude of year-to-year SSS change is different (Figures 14a–14c). Figure 14a is the difference between the absolute value of the 11/12–12/13 SSS change in AQ251 as compared to the absolute value of the 11/12–12/13 SSS change in WODSSS. Similarly, Figure 14b is AQCAP251 compared to WODSSS, and Figure 14c is AQCAP251 compared to AQ251. Figures 14a and 14b show larger year-to-year changes in the satellite products along the SPCZ, off the coast of Ecuador/Colombia, and near numerous river outflow regions. These higher magnitudes are likely due to Aquarius’ ability to resolve SSS in high variability regions better than WODSSS. Figure 14a and less so in Figure 14b show large year-to-year changes in high latitude regions when compared to WODSSS which is likely due to errors in Aquarius retrievals near sea-ice margins and in cold windy waters. WODSSS depicts larger changes than Aquarius (both products) in the southern Gulf of Mexico and the South China Sea. The larger changes in the southern Gulf of Mexico and the South China Sea are likely due to spurious data sampling in the regions (see Figure 1). Figure 14c depicts AQCAP251 with slightly higher year-to-year changes in SSS compared to AQ251 along the ITCZ, SPCZ, and along the Amazon plume.

Figure 13d illustrates the 11/12–12/13 changes in E-P. There are only a few regions where E-P is the dominate term in the MLS budget. These regions are mainly confined to the ITCZ, SPCZ, and the western North Pacific [Yu, 2011].
Comparing Figure 13d to Figures 13a–13c, and focusing on the regions where SSS variability is dominated by E-P, there is a noticeable relationship with the interannual changes in SSS and the interannual changes in E-P over the western North Pacific and the SPCZ, but not over the ITCZ. The SPCZ progressed northward from 11/12 to 12/13. This resulted in an increase in SSS from where the original SPCZ was located in 11/12 to a decrease in salinity at its current location in 12/13. This is similar to what is seen between calendar years 2011 and 2012 [Johnson et al., 2013b].

The ITCZ strengthened between 11/12 and 12/13 in the tropical Pacific (Figure 13d); however, the salinity reflection does not quite come through in the central tropical Pacific (Figures 13a–13c). Typically, along the ITCZ, there is a 3 month time lag between precipitation and salinity reflection [Delcroix, 1998], and there is a substantial increase in precipitation in this region from June to August 2012 to June to August 2013 (not shown). Thus, the salinity changes lag behind the precipitation changes. The decrease in salinity from the August to October 2012 time period to the August to October 2013 time period confirms this (not shown).

Overall, WODSSS, AQ251, and AQCAP251 capture similar interannual changes between 11/12 and 12/13. The AQ251 and AQCAP251 are generally larger in the magnitude of these year-to-year changes in some regions (i.e., SPCZ region) with AQCAP251 being slightly larger in interannual changes than AQ251. The SSS changes are reflected in the E-P fields over regions where E-P is expected to dominate SSS variability [Yu, 2011]. However, in regions where horizontal advection and other factors mostly determine the MLS budget, the correlation between year-to-year change in SSS and E-P is weak or absent (e.g., Amazon outflow, eastern tropical Indian, northern North Pacific, etc.).

4. Conclusions

Overall, the Aquarius products compare very well to WODSSS. The negative bias of Aquarius in the tropics transitions to a positive bias in the higher latitudes when compared to WODSSS, consistent with other studies [i.e., Lagerloef et al., 2013]. It is found that the negative biases in the tropics and southern latitudes are greatly reduced when using the CAP algorithm, which implies that the majority of bias is retrieval-based.
and not near-surface salinity stratification. The effect on bias from near surface salinity stratification has recently been found to be quite small (0.03 in tropics) [Drucker and Riser, 2014]. In addition to a reduction in the zonally averaged biases, the CAP algorithm exhibits a smaller RMSE than the standard Aquarius version when compared to WODSSS. The CAP algorithm improves RMSE by 13% over the standard version when compared to WODSSS.

Strong differences between in situ and Aquarius (both products) also exist in coastal locations, river outflow boundaries, and high latitudes. Coastal locations are undersampled in our current in situ observation network (Figure 1) and Aquarius has multiple issues measuring SSS near coasts (land contamination, RFI in certain regions). River outflow regions also suffer from a lack of in situ observations (Figure 1) while Aquarius generally performs well in capturing the low salinity signature of the river discharge. Finally, high latitudes offer many error sources. There is a lack of in situ data, and in addition, Aquarius has difficulty measuring SSS accurately in high wind and low SST water. There is also the possibility of sea ice contamination.

The comparison analyses performed in this study further examined the annual cycle and relationships, where both in situ and Aquarius exhibited similar SSS annual cycles with both Aquarius products generally depicting a more robust and coherent annual cycle than WODSSS. These annual cycles were also similar to the long-term (57 year) mean of the World Ocean Atlas 2013 climatology, albeit much more robust. The SSS annual cycles compared reasonably well to the E-P annual cycle, a dominant factor in determining SSS variability in some regions of the ocean (i.e., ITCZ, SPCZ). Further analysis examined the year-to-year variability of SSS by reviewing changes in SSS in addition to changes in the SSS annual cycle. The satellite and in situ products depicted similar interannual variability with both Aquarius products exhibiting slightly larger year-to-year changes in certain regions (i.e., SPCZ) than WODSSS.

The WODSSS fields provide a strong comparison data set for Aquarius SSS products. The WODSSS improves on routine validation data sets such as the Argo-only gridded product from APDRC by utilizing additional SSS data from non-Argo instruments (e.g., moored buoy and CTD). Furthermore, the additional data used in WODSSS allow validation in regions where little to no Argo data is available. Some of these regions (i.e., NW Atlantic, Arctic, coastal, etc.) are also regions of highly questionable Aquarius data, and thus not only does it allow opportunity of validation in these regions, but it also improves on the Aquarius measurements. Thus, to study global sea surface salinity variability going forward, a synthesis of in situ and Aquarius data should be utilized.


