EVALUATION OF AQUARIUS SEA SURFACE SALINITY IN THE SOUTH CHINA SEA

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ABSTRACT: Sea surface salinity (SSS) is a basic property of the ocean. Its variability indicates dynamic processes such as mixing and circulation. It can be sensed from space now, using an L-band microwave sensor, Aquarius, with a resolution of 150 km and a target accuracy of 0.2psu. It is not clear yet if the SSS product from Aquarius is applicable in the marginal seas. Here in this study, we evaluated the Version 3.0 SSS product of Aquarius (v.3.0) by comparing it with concurrent in-situ measured salinity data (both underway mapping and Argo floats data) in the South China Sea. A root mean square error of 0.74 and 0.53, for underway and Argo data respectively, was obtained. This result was much lower than those obtained in the open ocean. The imperfect removal of the effect of Radio Frequency Interference (RFI) was thought to be the main reason resulting in such a high error of Aquarius SSS in this region. It was thus suggested that cautions should be kept when using SSS in quantitative studies in the South China Sea. Furthermore, the spatial distribution and seasonal variance of SSS observed by Aquarius were analyzed. It was found that they were basically consistent with those reported in historical publications. Therefore qualitative studies based on Aquarius SSS will be acceptable.

1. INTRODUCTION

The salinity of the ocean is an important variable of research of physical and chemical process. Global climate changing, whose main characteristic is global warming, is becoming an advanced research hotspot. As the impact of ocean on the global climate change is obtaining more and more attention, sea surface salinity(SSS), a variable reflecting the water circulation, the carbon circulation, and air-sea interaction, is also becoming more and more significant. The investigation on the salinity distribution in South China Sea, one of the Three Marginal Seas in Asia, also has practical significance.

The traditional method of obtaining SSS was in-situ sampling and buoys, by which it was difficult to get global and seasonal-to-interannual variability of sea surface salinity. In 1970s, Skylab in America set about trying to measure salinity from space. With the launch of two recent salinity satellite missions, namely, the Soil Moisture and Ocean Salinity Mission (SMOS) by the European Space Agency in November 2009 and the NASA/CONAE Aquarius mission in June 2011, it is now possible to monitor the SSS from the satellite sensors. SMOS and Aquarius have difference revisiting period, spatial resolution and accuracy, so we can obtain high-accuracy global salinity map by integrating two data sources.

One of the science goals of Aquarius is to the global, monthly-average salinity measures with a resolution of 150km and an accuracy of 0.2psu. In the analysis report Lagerloef et al. published on NASA in February 2013, the global monthly average and seasonal average root mean square error(RMSE) is 0.3psu and 0.27psu, respectively. In 2014, Smitha et al. compared Aquarius SSS(v2.0) and Argo data, and verified that the accuracy of Aquarius in Indian Ocean is approximately 0.45psu0. The average RMSE of Aquarius SSS(V1.3) in South China Sea was 0.62psu, which was proved by Wang et al. in 2014. Kim et al. pointed out that, Aquarius SSS(V2.0) was generally lower than

CTD SSS by 0.40-0.93psu in East China Sea.

In June 2014, NASA released Aquarius Version 3.0，which further reduced the effects from Reflected Galactic Radiation, sea surface roughness, Radio Frequency Interference and other factors. However, it is so far unclear that if the accuracy of new version data has been improved in South China Sea. Here in this study, we would compare satellite data(V3.0) with underway data and Argo data, to verify the validation of the version 3.0 data in South China Sea, and furthermore, provide a reference for if we can use Aquarius data on investigation in South China Sea.

2. MATERIALS and APPROACH

2.1 Data

2.1.1 Remote Sensing data

We used the Aquarius Level-2 Data Products, Version 3.0, distributed for validations by the NASA, download from OceanColor website (http://oceancolor. gsfc.nasa.gov/cgi/aquarius/). The data reader *read_aquarius_hdf_L2.pro* is downloaded from data center of NASA, JPL(http ://podaac. jpl. nasa. gov/).

2.1.2 In-site Data

(1) Underway Data

Underway data is from Spring Voyage in April,2012 in multidisciplinary comprehensive inquiry in South China Sea hold by National Research Foundation; Summer Voyage in August,2012 in the 973 program.

(2) Argo Data

Argo floats data is downloaded from the world ocean database of NODC(National Oceanographic Data Center), WOD13(World Ocean Database 2013 ， http://www.nodc.noaa.gov/OC5/SELECT/dbsearch/dbsearch.html). Although the data of Argo floats is from the surface to the depth of 2000m, we can use the minimum data to evaluate the satellite SSS data 0. Refer to the method of Robert 0, we choose the data of minimum depth, 1~7m.

2.2 Approach

Recording to the data validation report of Aquarius team, in order to get more 为 validate matching data, we soften the matching window, with the time window of ±3days，spatial window of 75km0。

To compare the remote sensing SSS and in-situ data, we calculate the relative error(ε)、bias(δ)、root-mean-square error(RMSE) and the coefficient of determination（R^2）:

$$\varepsilon = \left(\frac{1}{n} \sum_{i=1}^{n} \left| \frac{x_i^{rs} - x_i^{mea}}{x_i^{mea}} \right| \right) \times 100\% \tag{1}$$

$$\delta = \frac{1}{n}\sum_{i=1}^{n}(x_i^{rs} - x_i^{mea}) \tag{2}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i^{rs} - x_i^{mea}\right)^2} \tag{3}$$

Where the x^{rs} is the remote sensing data，$x^{mea}$is the in-situ data.

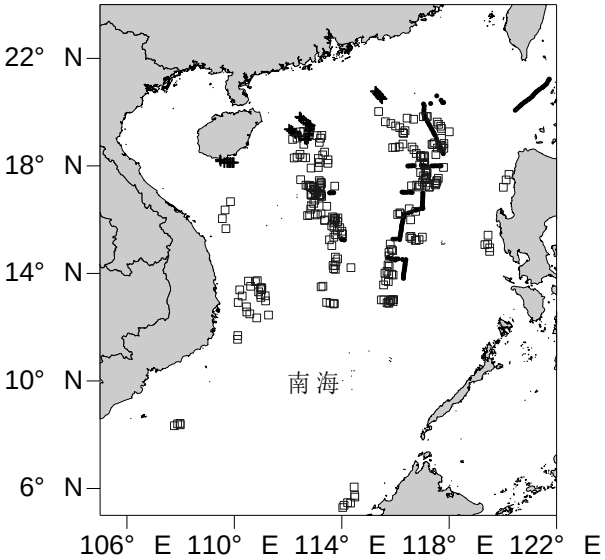


Fig 1 . Survey area and distribution of stations

Spring voyage in April 2012（●）；Summer voyage in August 2012（＋）；Argo floats（□）

3 RESULTS

3.1 Comparison with underway data

The matching points of voyage in April, 2012 and the voyage in August, 2012 and remote sensing data are in Fig.1. It can be seen from Table.1 and Fig2(a), the average RMSE of two voyages is 0.748psu(N=222), which is higher than the result of open ocean(~0.30psu) and Indian Ocean(0.45psu). The coefficient of determination is only 0.278, which means that the correlation between in-situ data and remote sensing data is low. Of course, the result is partly because the distribution of SSS data in SCS is relatively intensive. The more intensive the data distribution is, the effect of residual error to R^2 is more significant. In the matching points, main of the SSS data is between 32-34psu, while in the open ocean, the zone of SSS data is larger, which is between 32-37psu 0.

Table 1 Statistic Analysis of Matching Result between
Underway Data and Satellite Data of SSS in South China Sea

	N	**ε(%)**	**δ**	**RMSE**
Voyage in 2012.4	179	2.2	-0.72	0.766
Voyage in 2012.8	43	1.9	-0.64	0.667

Total	222	2.1	-0.70	0.748

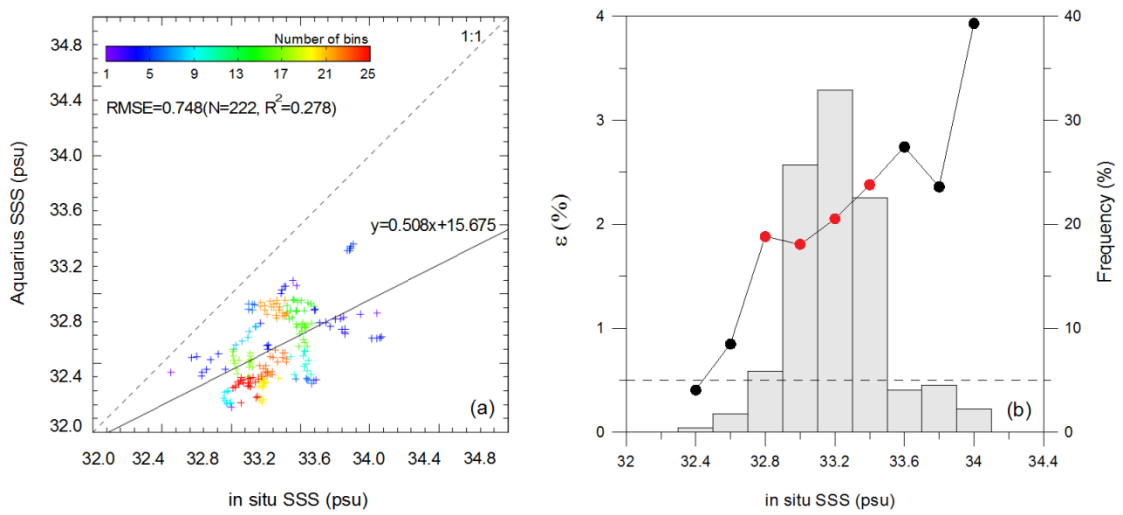


Fig 2. Comparison between Underway Data and Satellite Data of SSS

(a) Scatter diagram of underway data and satellite data on matching points, where color means distribution density. (the number of value in 0.2×0.2psu); (b) Dots mean relative error, with the Y-axis in the left. Red dots are the values with the distribution greater than 5%; the Y-axis of distribution frequency histogram is in the right.

From Fig.2 we can see that, the salinity of underway data is between 32 and 34psu, and more than 80% of data concentrates between 33-36psu. Fig2.b shows the relative error ε of each section, in which the distribution frequency 87% of the total amount of data is greater than 5%, and ε increases with the increase of salinity. For the data over 34psu, the relative error is close to 4% and the bias(δ) is -1.34psu. According to the literature of Lagerloef et al., in open ocean, the Aquarius SSS data would be lower than underway data when the underway data is around 34psu, and these points mainly contribute in circumpolar latitude0. However, South China Sea is marginal sea in low latitude, the salinity contribution of SCS is influenced by monsoon circulation, runoff, diluted water of estuary and other factors, for which the error of Aquarius SSS in SCS is more obvious.

3.2 Comparison with Argo Data

The square signs in Fig 1 . Survey area and distribution of stations are the matching points of satellite data and Argo data. In this paper we select the Argo float data in 2013 to test the validation of Aquarius data. The compares results are in Fig.3, with the RMSE of 0.53psu, the relative error of 1.26%, and the bias of -0.31psu. Although the Argo data is generally lower than satellite data, the distribution of Argo data is more disperse, and the determination coefficient is also lower, which means that the linear dependence of Argo data and satellite is weak. Similar to the compares result of underway data and satellite data, the relative error of the data with the distribution greater than 5%, increases with the salinity increases, and maximizing at 34psu(3%).

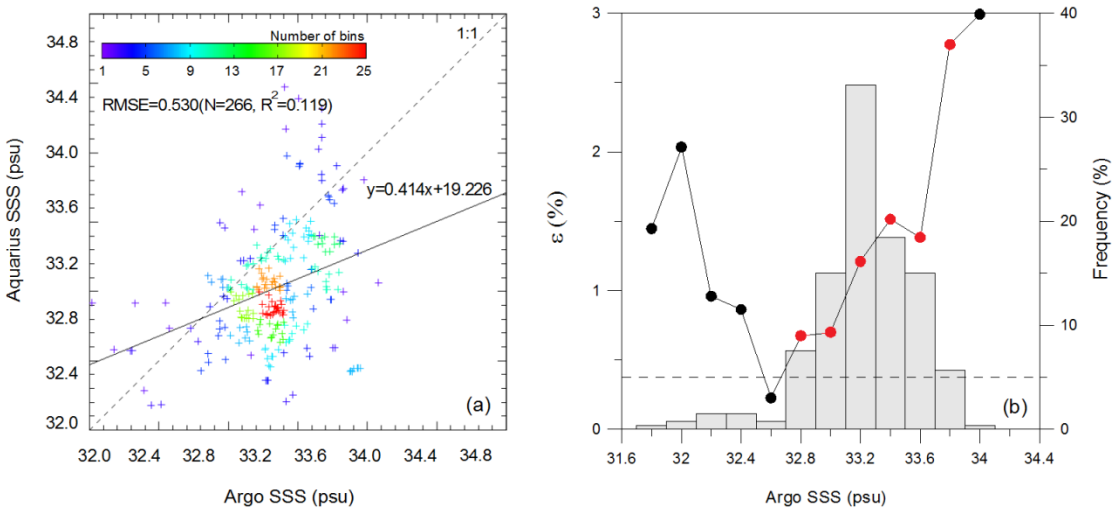


Fig 3. Comparison between Argo Data and Satellite Data of SSS

3.3 Spatial Distribution and Seasonal Variation

In 3.1 and 3.2 section, we compare the Aquarius L2 data with underway data and Argo data， and the result is that Aquarius SSS underestimates by approximately 0.31-0.71psu. Furthermore, we would analyze the validation of Aquarius SSS from the spatial and temporal distribution of salinity.

Fig.4 shows that the salinity in SCS is between 32-34psu，with a trend that increases with the distance with seacoast. Affected by diluted water of runoff, SSS is lower in the Zhujiang River, Mekong, Rajang and other estuary area. In winter, the SSS in area around Bass Strait is highest, which is affected by high salinity water from Pacific Ocean. North to the Zhongsha Islands, there exists an relatively steady area around 114.5 ℃(the red square in Fig.4). The high salinity water from West Pacific Ocean enter in SCS through Sulu Sea, which is agree with the hydrologic survey result in of Mao、Yang in SCS.

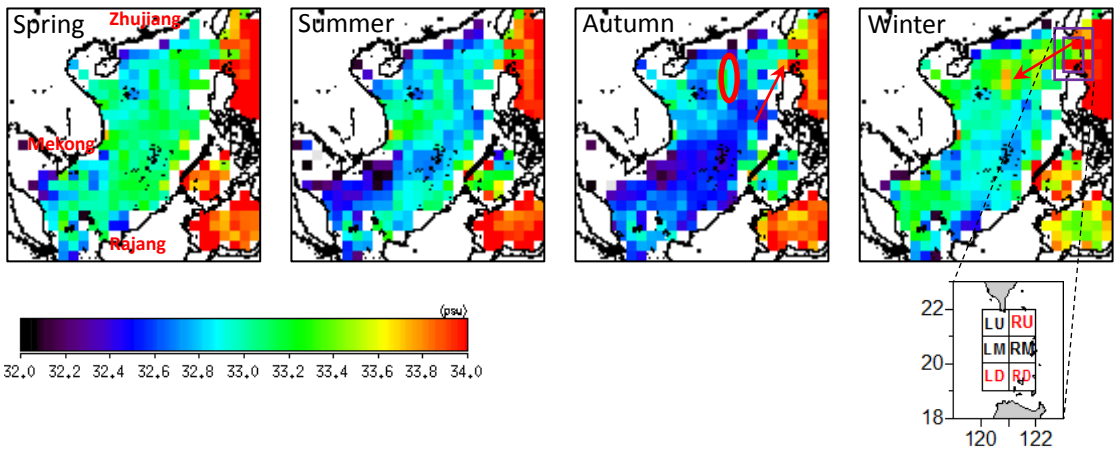


Fig 4. Distribution of climate state of Aquarius SSS（L(Left) is 120 ℃ in Luzon Strait； R(Right) is 121 ℃, divided into U（Up）、M（Middle）、D(Down) sections, respectively）

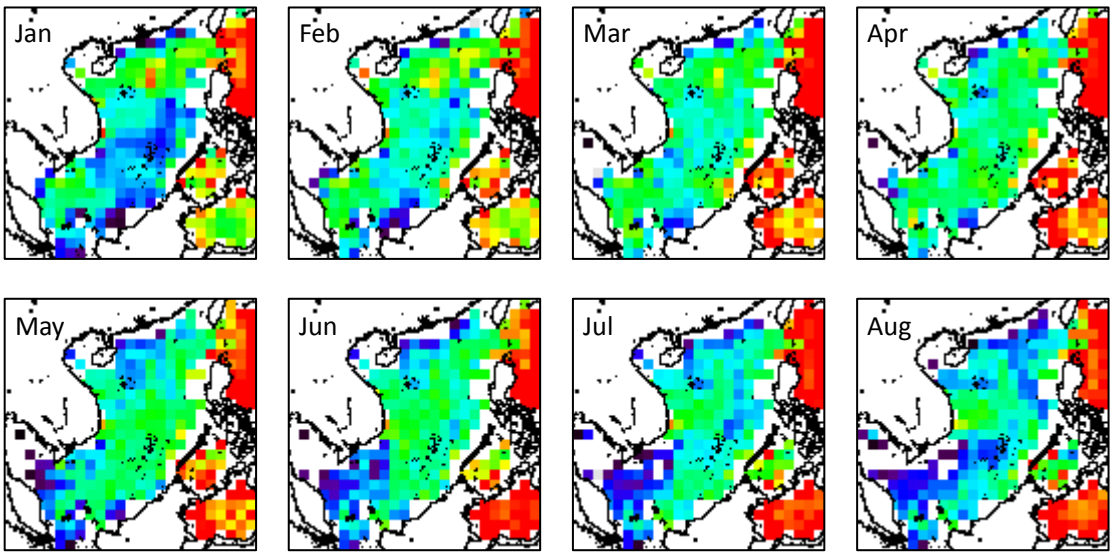
Table 2. Seasonal Average Salinity Value in Luzon Strait

	LU	LM	LD	RU	RM	RD
Spring	33.1555	32.9767	34.0689	33.8916	33.4275	33.9187
Summer	32.9996	32.8762	33.7416	33.892	33.1949	34.091
Autumn	33.1621	32.8939	33.7544	33.878	33.1025	34.0416
Winter	33.3931	33.2181	34.023	34.1403	33.4422	34.05

Focusing on Luzon Strait, the channel between Pacific Ocean and South China Sea(Fig.4), from Table.2, we can see that, the SSS value in RU、RD and LD is higher than 33.5psu in all of seasons , mainly because of the high salinity water of Pacific Ocean. The SSS value of LU、LM and RM areas is generally lower than 33.5psu, mainly because of the SCS water and the interaction between two kinds of water. On the horizontal direction, between 21 ℃N and 22 ℃N, the Pacific water transport to South China Sea in winter, which would influent the southwest of Luzon Strait. In area between 19 ℃N and 20 ℃N， the water from South China Sea diffuse eastern in autumn. And the transport is not obvious in 21-22 ℃N. this is basically agree to the results of Bao、Huang.

As for the seasonal variation, the tropical maritime monsoon climate obviously affects South China Sea. So the distribution of SSS is mainly influenced by northeast monsoon in winter and southwest monsoon in summer. From November to March next year, the northeast wind prevails. The high salinity water tongue of Pacific Ocean transport southwestern from Bass Strait to the Xisha Islands, and the low salinity water in east South China Sea transports northern along the east coast at the same time(Fig.5). Between April and September, the southwest wind prevails, resulting in that the low salinity water transport northeastern from Malaysia, Gulf of Thailand. Meanwhile, affected by rainfall, SSS value in the north area decreases, and reaches the minimum value in October. This is roughly in line with areal oceanography of china ocean in *Introduction to Marine Science*。

Limited by the in-situ investigation condition, most of the literatures before focused on local areas, such as Tonkin Bay, Bass Strait, Nansha Islands area and so on. Through Aquarius data, we can observe the whole situation of salinity in South China Sea, and that the results are basically accordance. Therefore, we hold that, for large scale investigation, Aquarius is a roughly reliable data source.



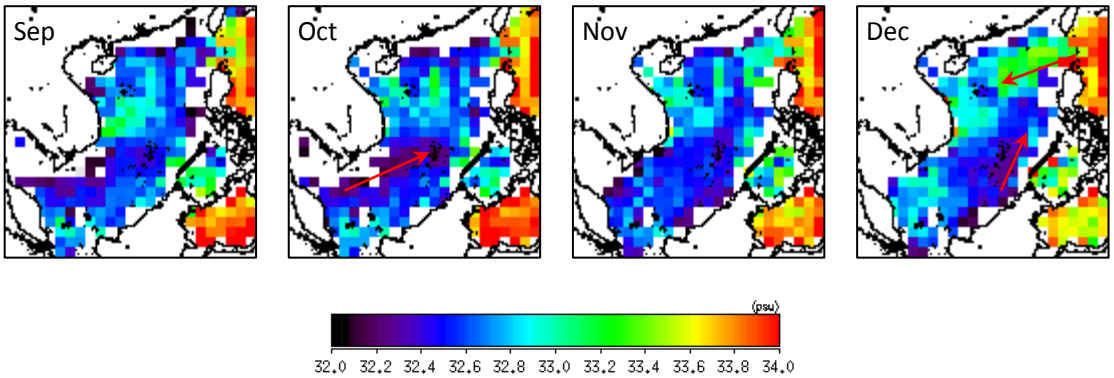


Fig 5. Monthly average distribution of climate state of Aquarius SSS

4、DISCUSSION

4.1 Accuracy in Difference Sea Area

Aquarius observe salinity through passive and active L-band (1.413 GHz) microwave sensor, so the accuracy of satellite data may be affected by Radio Frequency Interference(RFI). Meanwhile, in the process of inverse, the accuracy of brightness temperature, sea surface roughness and other factors would also influence the accuracy of SSS in different degrees. What is the main factor affecting the accuracy in South China Sea?

Table.3 Results of Previous Investigations

Area	Version of Data	R	RMSE	bias
Tropical Indian Ocean	V1.2	0.80	0.95	-0.42
Tropical Atlantic Ocean	V1.2	0.81	0.64	-0.29
Tropical Pacific Ocean	V1.2	0.86	0.91	-0.48
North Indian Ocean	V1.3	0.84-	0.45	-
South China Sea	V1.3	0.46	0.62	0.35
Global	V2.0	0.92	0.22	-

From Table.3 we can see that, although the RMSE in that version was much higher than the goal value, but the correlation coefficient(R) in open ocean preforms well. However, both of the RMSE and R of data in SCS are far from the goal.

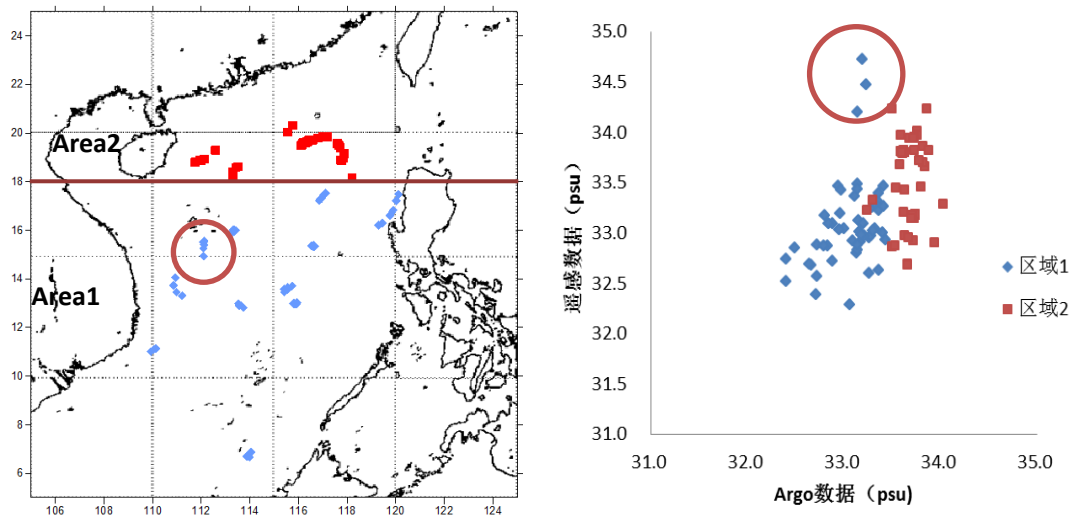
4.2 Influence of RFI

RFI(Radio Frequency Interference) is the interference exists when the electromagnetic wave with the frequency close to the target electromagnetic is received by satellite sensor. The characteristic of RFI is inhomogeneous distribution, 99% of which located on land.

Wang(2013)[22] detected RFI in north South China Sea by Stokes parameters and detecting algorithm of angular domain, and the result was that north South China Sea is an area with serious contamination of RFI. There were lots of emission sources in the survey region, most of which were located in Great Pearl River Delta and Taipei.

In that study, Version1.3 data of Aquarius was been RFI corrected, after which the RMSE decrease to around 0.6

from 1.2. However, with the data upgraded, and the effect of RFI in Version 3.0 data removed, there is no effect from RFI on the accuracy of data, theoretically. Next we would compare the data in two areas, the area with lower contaminate(Area 1) and higher contaminate(Aera2). The data used in comparison is satellite data and Argo data in January, 2013.



a. Matching points of satellite data and Argo data in January,2013

b. Comparison of satellite data and Argo data in January,2013

Fig6. Comparison result of satellite data and Argo data

According to the distribution of RFI , we divide South China Sea into two areas, with the boundary of 18 ℃N(Fig.6a). Fig.6b and Table 4 show the comparison result.

Table4. Statistical Result of Comparison of Two Region in January, 2013

	Volume	R	R^2	Bias	RMSE
Aera1	63	0.57	0.24	-0.05	0.43
Aera2	43	-0.15	0.06	-0.09	0.45
Total	106	0.48	0.26	-0.06	0.44

From Table.4, we can see that in the area with higher effect of RFI(Area2), the correlation of satellite data and Argo data is negative. In Fig.9b, the Argo data is around 34psu, but the span of satellite data is large. The data in Aera1 performs better, with the correlation coefficient(R) of 0.57, which is still too low. It is proved that the influence of RFI has not been removed entirely, but it is not the only factor leading to low accuracy in South China Sea.

In Fig.9b, there exist three abnormal points having high bias, corresponding to the three points in red circle in Fig.9a, located on around 112 ℃E, 15 ℃N， near to Xisha Islands. We speculate that there exists other interference on Xisha Islands.

5. CONCLUSION

In this study, we evaluated the Version 3.0 SSS product of Aquarius by comparing it with concurrent underway measured salinity data in the South China Sea. The result is root mean square error of 0.74 and 0.53, for underway and Argo data respectively, which is much lower than the goal and those obtained in the open ocean. The imperfect removal of the effect of Radio Frequency Interference (RFI) was thought to be the main reason resulting in such a high error of Aquarius SSS in this region.

Therefore, we suggest that cautions should be kept when using SSS in quantitative studies in the South China Sea. Furthermore, the spatial distribution and seasonal variance of SSS observed by Aquarius is basically consistent with those reported in historical publications, so that qualitative studies based on Aquarius SSS will be acceptable.

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