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Editorial

Editorial for the Special Issue "Sea Surface Salinity Remote Sensing"

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Received: 27 May 2019; Accepted: 30 May 2019; Published: 31 May 2019

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Abstract: This Special Issue gathers papers reporting research on various aspects of remote sensing of sea surface salinity (SSS) and the use of satellites SSS in oceanography. It includes contributions presenting improvements in empirical or theoretical radiative transfer models; mitigation techniques of external interference such as radio frequency interferences (RFI) and land contamination; comparisons and validation of remote sensing products with in situ observations; retrieval techniques for improved coastal SSS monitoring, high latitude SSS monitoring and assessment of ocean interactions with the cryosphere; and data fusion techniques combining SSS with sea surface temperature (SST). New instrument technology for the future of SSS remote sensing is also presented.

Keywords: sea surface salinity; ocean surface roughness; microwave radiometry; remote sensing; forward model; retrieval algorithm

1. Introduction

Sea surface salinity (SSS) is an essential climate variable [1]. It is a key component of the water cycle, as a tracer of precipitation and evaporation, river outflow and ice melt/freeze. It is a key driver of oceanic circulation through its role in ocean density. It is also a critical parameter for understanding the variability of ocean carbon fluxes, providing information on water masses and of their chemical properties.

In situ SSS observation coverage is lacking due to limited accessibility and the rough environment of most oceanic regions, which limits long term deployment and maintenance of in situ instruments. The lack of long term observations with good spatial coverage is exacerbated in the high latitude oceans such as the Arctic and the Southern Oceans. Since the year 2000, the number of in situ observations and their spatial and temporal coverage have increased substantially with the deployment of the Argo network of free drifting profiling floats [2]. There are now approximately 4000 Argo floats deployed globally that measure conductivity, temperature and depth/pressure (CTD), from which vertical profiles of salinity and temperature are retrieved from 2000 m deep to 5-10 m below the surface. Despite the continuous deployment of Argo floats and other sensors in the global oceans, spatial and temporal coverage remains sparse in many regions, and combining satellite and in situ measurements is necessary to derive an overview of the complete system.

SSS in the open ocean has been monitored from space since 2010 by the European Space Agency's Soil Moisture and Ocean Salinity (SMOS) [3] mission, the National Air and Space Administration (NASA) and Comisión Nacional de Actividades Espaciales's Aquarius/SAC-D mission [4,5], and more recently by NASA's Soil Moisture Active Passive (SMAP) mission [6,7]. This special issue gathers contributions on research related to various aspects of remote sensing of sea surface salinity and the combined use of satellite SSS with other observations.

The topics covered by the special issue include improvements in empirical or theoretical radiative transfer models, mitigation techniques of external interference such as RFI, Sun, and land contamination, comparisons and validation of remote sensing products with in situ observations, retrieval techniques for improved coastal SSS monitoring, high latitude SSS and ocean interactions with the cryosphere, and data fusion techniques combining SSS with sea surface temperature (SST). New instrument technology for SSS remote sensing is also presented with the future Water Cycle Observation Mission (WCOM) and the microwave imager combined active/passive (MICAP) payload. The next section reports a short summary of the varied contributions to the special issue.

2. Overview of Contributions

The contributions reported in this special issue include retrieval algorithm improvements and validation of SSS from Aquarius, SMAP and SMOS missions, applications of space-borne SSS combined with in-situ and model SSS to oceanographic studies, and an introduction to future SSS missions.

2.1. Algorithm Improvements and Validation of SSS

The Aquarius Mission formally ended on 31 December 2017, a little more than 2 years after the spacecraft failure in June 2015. The last major milestone was the release of the final version of the salinity product Version 5. Le Vine et al. [8] provide an overview of the improvements in the algorithm of the final version and discuss the overall performance of the product. They also provide a discussion of the remaining issues to be addressed, such as the unknown origin of the SST-dependent bias in SSS, the seasonal variations in calibration and the observed biases over the low- (cold sky) and high- (land) end of the brightness temperature range. They conclude that the understanding developed with Aquarius is being transferred to SMAP, which shows an accuracy approaching that of Aquarius. Meissner et al. [9] present the changes in the retrieval algorithm for Aquarius Version 5 and for SMAP Version 3 SSS products, in particular they highlight the changes in corrections for the absorption by atmospheric oxygen, the SST dependence of the surface roughness and the reflected galaxy. The authors find that the difference between Aquarius Version 5 and Argo is within 0.1 psu, with an estimated global RMS uncertainty for monthly 100 km averages of 0.128 psu. Further evaluations of the Aquarius product are presented by Kao et al. [10]. From a triple point analysis using Aquarius, in situ observations and SSS from the Hybrid Coordinate Ocean Model (HYCOM) products, Kao et al. show that Aquarius' mission requirements (0.2 psu root mean square error) are exceeded, with the root mean square errors of Aquarius Level-2 and Level-3 products being estimated at 0.17 psu and 0.13 psu, respectively. The authors advise that caution should be exercised when using Aquarius salinity data in areas with high RFI and heavy rainfall, close to the coastlines where leakage of land signals may significantly affect the quality of the SSS retrievals, and in high-latitude oceans where the L-band radiometer has poor sensitivity to SSS.

A few contributions focus on SSS retrievals in challenging regions, such as enclosed seas, coastal waters and cold oceans in the high latitudes. Olmedo et al. [11] present a methodology for improving SMOS SSS retrievals in enclosed seas that usually suffer from large contaminations due to land emission or RFI. The method combines debiased non-Bayesian retrieval, data interpolating empirical orthogonal functions (DINEOF) and multifractal fusion (using SST products). The authors report improved SSS retrieval over the North Atlantic Ocean and the Mediterranean Sea. The error in SMOS SSS in the Mediterranean Sea is practically halved and the improved product reproduces the dynamic and fronts as reported by in situ data and high resolution SST products. Using a debiased non-Bayesian retrieval approach with an enhanced time-dependent bias correction, Olmedo et al [12] produce an improved SMOS SSS product for the Arctic and subarctic regions. With the new time-dependent calibration designed to mitigate seasonal bias, the standard deviation of the SSS difference with Argo measurements is between 0.25 and 0.35 psu and the major features of the inter-annual SSS variations observed by thermosalinographs are also captured by SMOS. The study's results also suggest that the use of remotely-sensed SSS may help better constrain models in regions lacking in situ observations.

The Gulf of Mexico is another challenging region for SSS retrievals. Vazquez-Cuervo et al. [13] present an evaluation of three SMAP and one SMOS SSS products using continuous surface buoys and observations of opportunity from the World Ocean Database in order to mitigate the insufficient temporal and spatial coverage of the Argo network in such a variable region. While they find that the four products are remarkably consistent on seasonal time scales and that they reproduce dominant salinity features, the SMAP product at 70 km spatial resolution is lacking in terms of data availability in the nearshore region and it performs poorly within 100 km of the coast relative to other products. The other products (JPL SMAP, REMSS 40 km SMAP, and SMOS) show performances similar to each other, with root mean square differences (RMSD) between 0.5 and 1.5 psu further away than 100 km from the coast and increasing biases and RMSD at 100 km or less from the coast. REMSS 40 km generally shows the lowest RMSD in the nearshore region but has lower data availability. SMOS shows generally larger biases and RMSD, but has the lowest RMSD at some buoy locations. A few other contributions highlighting the use of satellite SSS in coastal or high latitude oceans are discussed in the next section.

Significant differences have been reported between the various satellite SSS products of SMOS, Aquarius and SMAP, as well as between satellite and in situ SSS. Dinnat et al. [14] present an overview of satellite SSS products and their differences, and an analysis of the impact of the retrieval parameters on the differences. All satellite products exhibit SSS errors with a strong dependence on the SST, but this dependence varies significantly with the sensor and version of the product. The authors show that these differences are first and foremost due to differences in the dielectric constant model, then to the atmospheric corrections, and to a lesser extent to the ancillary product used for the SST.

2.2. Oceanography with Space-Borne SSS

The South Asian Summer Monsoon (SASM) is a critical source of freshwater and its onset and intensity impacts drought and flood events in South Asia, agricultural yields, water resources, energy production, population health and the economy. Yuan et al. [15] assess the relationship between the SSS anomaly (SSSA) and SASM using observational and statistical evidence. They show that a positive SSSA leads to a thinning of the barrier layer and to a decrease in SST anomaly. A time delay of SSSA changes between the northern and southern hemisphere intensifies cross-equatorial SST gradients and currents, contributing to the onset of the summer monsoon.

In the Arctic Ocean, SSS is impacted by freshwater flows from river discharge, sea ice formation and melt, precipitations and evaporation, and oceanic transport from the North Pacific and Atlantic oceans. However, in situ SSS observations in the Arctic Ocean are sparse and insufficient to depict the spatial and temporal variability and to address the question of how climate variability affects the Arctic Ocean waters. Tang et al. [16] provide an assessment of SMAP SSS north of 50°N and its use in monitoring freshwater fluxes in the Arctic from rivers and transport from other basins. They find that SMAP SSS has a good correlation with in situ data and a RMSD 1.2 psu. In contrast, the HYCOM SSS has a smaller RMSD but suffers from significant systematic biases. They show that SMAP SSS in the Kara Sea has the potential to provide an assessment of variable interannual runoff where the model assimilates climatological runoffs without interannual changes. Despite its limited accuracy in the Arctic, SMAP observed large changes in SSS at the Arctic Ocean gateways. This confirms that satellite SSS could be used in the Arctic monitoring system as a proxy of the upper ocean layer freshwater exchanges with subarctic oceans.

Grodsky et al. [17] present another study of satellite SSS in cold coastal waters. They investigate the circulation dynamic in the Gulf of Maine and its interactions with the northwestern Atlantic Shelf using the SMAP data and in situ observations from moorings, ship-based thermosalinographs and gliders. Despite the presence of an SST-dependent bias that is amplified in winter/early spring and of a land contamination-induced bias, monthly SSS anomalies show important water intrusions in the Gulf of Maine in the winters of 2016/17 and 2017/18. The water intrusion patterns are generally consistent with measurements from SMOS, and the timing and general magnitude of a near-surface freshening in the Gulf of Maine in 2016 is confirmed by measurements by a couple of buoys. The authors conclude with an analysis of regional currents and wind anomalies to present a possible scenario for the water intrusions. They identify stronger than usual geostrophic currents along the Scotian Shelf Current (SSC), likely due to a southwestward wind anomaly over the NW Atlantic reflecting a weakening of prevailing alongshore westerly winds on the shelf near southeastern Nova Scotia. This suggests that the strong increase in the SSC, which transports the fresh Scotian Shelf water southwestward down the coast, is the cause of the observed fresh anomalies.

Vazquez-Cuervo and Gomez-Valdes [18] compare SMAP SSS and in situ measurements from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) to assess the 2015-2016 freshening event in the Southern California Current System. They report biases between SMAP SSS and CalCOFI of less than 0.1 PSU in periods of low stratification, increasing to greater than 0.4 during periods of high stratification. SMAP observed the southward propagation of freshening due to the Northeast Pacific heat wave, extending down the Baja California Coast. SMAP SSS was used to identify changes in salinity associated with a coastal upwelling system. The authors conclude that SMAP SSS can be used to monitor the freshening in a coastal region associated with a major warming event.

Castellanos et al. [19] analyze the seasonal variation of the surface currents and transports in three of the world's most energetic regions in the tropical and South Atlantic: the North Brazil Current Retroflection, the Brazil-Malvinas Confluence, and the Agulhas Current Retroflection. They use SSS from SMOS and Argo, and the SSS and surface velocity from the HYCOM model. After deriving the monthly functional relationship between SSS and surface velocity using the high resolution model, they used the SMOS SSS fields to characterize the flow in three retroflection regions. Consistent patterns of seasonal variability for the water and salt transports associated with the retroflections are obtained.

2.3. Future SSS Missions

Two papers report on future missions for SSS remote sensing. Zhang et al. [20] present a sensitivity study to assess the configuration of the microwave imager combined active/passive (MICAP) payload, which is designed to simultaneously retrieve SSS, SST and wind speed (WS) by means of multi-frequency radiometry at 1.4 GHz, 6.9 GHz, 18.7 GHz and 23.8 GHz, combined with a 1.26 GHz scatterometer. The simulations indicate that errors in retrieved SSS, SST, and WS achieve the accuracy requirements without the need for the 23.8 GHz channel, and that the L-band scatterometer is essential to contain the error. The Water Cycle Observation Mission (WCOM) is an Earth science mission focused on the observation of the water cycle global climate change intensity through three different payloads. WCOM's main payload is the interferometric microwave imager (IMI). IMI is a tri-frequency, one-dimensional aperture synthesis microwave radiometer operating at the L-, S-, and C-bands designed to perform measurements of soil moisture and ocean salinity. Li et al. [21] present simulations from the end-to-end simulator of WCOM/IMI that use antenna patterns measured using a prototype of IMI. They find general good agreement between original and retrieved SSS, with a root mean square error of 0.26 psu for a single measurement in open sea, but strong contamination is observed in coastal areas. They also find a large spatial error that could be alleviated through an increase in the number of antenna elements.

3. Conclusions

The contributions reported in this special issue highlight the thriving research on SSS remote sensing and its applications to a better understanding of the oceans and their interactions with the rest of the hydrological system. Two satellite missions are still ongoing to this date, and their calibration and retrieval algorithm continue to benefit from sustained research, leading to improved and enhanced products. Future missions to measure SSS are also being planned and should enable continuity in the regular and global observation of this essential climate variable. They should also provide expanded capabilities by using multiple frequencies.

Author Contributions: The two authors contributed equally to all aspects of this editorial.

Acknowledgments: The Guest Editors would like to thank the authors who contributed to this Special Issue and the reviewers who dedicated their time and provided the authors with valuable and constructive recommendations. They would also like to thank the editorial team of Remote Sensing for their support.

Conflicts of Interest: The authors declare no conflict of interest.

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