Remote sensing of sea surface salinity: A bibliometric analysis

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ABSTRACT

In recent years, rapid advances in technologies have allowed significant positive changes within the field of satellite observations of the global ocean. This paper reviews the available global scientific literature that focuses on the study of salinity by remote sensing, tracking its evolution and trends by combining social network analysis and bibliometrics. Furthermore, the study shows the relationships and co-occurrences between authors, countries and keywords retrieved from the abstracts and citations database provided by Scopus. An analysis of 581 publications has been carried out. The achieved results, which highlight a worldwide increase in scientific interest in this field over the last decade, may constitute a useful tool for a global vision and for a potential improvement in the international efforts employed in the study of salinity from remote sensing.

INTRODUCTION

The salinity of the oceans is one of the key parameters for physical oceanography (Dinnat *et al*., 2019), one of the main variables for monitoring activities and modeling ocean circulation (Klemas, 2011; Falco *et al*., 2022). Salinity is fundamental in global thermohaline ocean circulation, hydrological cycle and climate variability (Boutin *et al*., 2021). Salinity and temperature control the density of seawater. Density influences the stratification of the ocean, the formation of water masses and finally the general circulation of the ocean itself. Due to its role, sea surface salinity (SSS) has been identified by the Global Climate Observing System (GCOS) as an essential variable for climate studies (Aulicino *et al*., 2018). Despite its well-recognized importance, there are few long-term time series measurements of salinity collected *in situ*, covering the global ocean (Klemas, 2011). Until the early 2000s, most observations and sampling took place through commercial navigation or during oceanographic campaigns. Despite the initial advantage of studying the salinity in the ocean, those methods revealed limitations in terms of spatial and temporal coverage. The acquisition of salinity information has recorded the first major improvement from the second half of the 2000s onwards, thanks to a network of floating instruments left adrift (Dinnat *et al*., 2019). However, the most important change occurred with the first satellite observations of the oceans.

In recent decades, thanks to the launch of two satellite missions, namely ESA Soil Moisture and Ocean Salinity (SMOS) in 2009 and NASA Aquarius in 2011, it has been possible to monitor the global synoptic of sea surface salinity (SSS) using microwave radiometers (Kerr *et al*., 2010; Le Vine *et al*., 2010). A microwave radiometer is a passive sensor capable of measuring the power naturally emitted by a body at a physical temperature above 0 K, proportional to the so-called brightness temperature (Ulaby *et al*., 1981). For the SSS detection, the two mentioned satellites use L-band radiometers, from 1,400 to 1,427 GHz, which is reserved for radio astronomy and Earth remote sensing (Pablos and Vall-Llossera, 2014). SMOS and Aquarius operate in the same L-band, but they are different in both the construction of radiometers and their operation (Dinnat *et al*., 2019; Champagne *et al*., 2016). The Aquarius mission ended in June 2015 due to a technical malfunction, while the SMOS satellite is still in orbit at the end of 2022. In January 2015, NASA launched a new Soil Moisture Active Passive (SMAP) mission. The SMAP mission aims to measure soil moisture, its radiometer-radar instrument is similar to the one used for the Aquarius mission, and it allows SMAP to provide SSS estimates (Bao *et al*., 2019). SMAP has a spatial resolution of about 40 km with a time repetition of 2-3 days; SMOS spatial resolution is about 45-50 km with a time repetition of 3 days; Aquarius indeed had a resolution of about 100-150 km and a repetition of 7 days (Fournier *et al*., 2019). Several differences exist in the instrumental approaches, as well as in the retrieval algorithms and in the dielectric constant models (Dinnat *et al*., 2019), so that the three satellite products present SSS accuracy that generally varies with the sensor and version of the products (Aulicino *et al*., 2019). Together, they provide an unprecedented source of salinity information over the global oceans, useful to improve models and compensate for the spatial gaps and the scarcity of *in situ* observations (Aulicino *et al*., 2022).

Given these considerations, the purpose of this manuscript is to explore the global scientific literature concerning the study of salinity from satellite, to trace its evolution and obtain a systematic review of its temporal developments, the geographical distribution of the main studies and the connections between the different areas of investigation. To this goal, social network analysis and bibliometrics have been combined.

The term 'scientometrics' refers to the study of the scientific literature through measurement and analysis (Perumal and Muthuramalingam, 2021). Bibliometry is a fundamental subfield of scientometrics, and it was first

introduced by Pritchard in 1969 (Duan *et al*., 2020). It deals with the study of the academic literature, through mathematical and statistical methods, with the aim of evaluating global research trends in a specific area of investigation (Geng *et al*., 2017). Recently, this method has also been applied to the study of remote sensing and its applications in different scientific fields (Hu *et al*., 2017; Khudzari *et al*., 2018). However, to date, it has yet to be used to assess the study of salinity by remote sensing.

In recent years, the number of publications on the study of SSS by remote sensing has increased remarkably. Therefore, it is important to highlight how the research on this topic is progressing. The final aim of this work is to provide useful information to the scientific community and show potential shortcomings in the research field, as a means of improving future studies and initiatives. The tool used in this work is VOSViewer, a software that allows both the realization and visualization of bibliometric maps (Van Eck and Waltman, 2021).

The paper is structured as follows: section 2 summarizes the criteria related to the bibliographic research carried out, as well as the method of bibliometric analysis applied to the data collection; section 3 introduces the results obtained with specific reference to the prevailing authors, countries, and keywords within the research; the conclusions are provided in Section 4.

MATERIALS AND METHODS

Bibliographic research and data collection

The bibliometric analysis was performed on a dataset of publications collected through Scopus, Elsevier's abstract and citation database. In our case, the string used was as follows: << "sea surface salinity" AND (satellite OR "remot* sens*") >>. The Scopus search queried the "Article title", "Abstract", "Keywords" database for all the document types published in the English language before December 31st, 2021. The dataset was exported as .csv file on January 31st, 2022, and includes "Citation Information", "Bibliographic Information", "Abstract", "Keywords" and "References". To further refine the data, a careful manual check was carried out to exclude off-topic publications, *i.e.*, studies that were not related to the remotely sensed observation of SSS. The analyses described in this study were then performed starting from the year of the first publication (*i.e.*, 1976) and focused on remote sensing of SSS indexed in Scopus.

Bibliometric network analysis

Bibliometric network analysis is a method that is used to understand the research trends within a specific field and based on the results of the scientific literature dataset (Van Eck, 2006). By linking bibliometric data with social network analysis, it is possible to investigate the relationships between researchers, countries, organizations, and keywords carried out in the research (*e.g.*, Appolloni *et al*., 2020; Cesarano *et al*., 2021). The VOSViewer software (version 1.6.17) can create cluster maps that are based on the data network, and it also allows us to visualize and investigate them (Van Eck and Waltman, 2021). These graphic representations may include different types of outputs (*e.g.*, authors, keywords, journals), and they are realized using citations, bibliographic couplings, co-citations, or co-author relationships (Perumal and Muthuramalingam, 2021). In this study, we examine in depth the relationships between researchers, countries, and keywords.

In the cluster maps, the elements' size depends on the "Total Link Strength" (TLS) (*i.e.*, the strength of one element's connections with the others), as well as the number of publications and citations. The connections between the different clusters are represented by curved lines where the thickness depends on the "strength of the connections". Specifically, in the case of co-authorship, the connection strength depends on the number of publications of which two researchers, organizations or countries have "co-authored"; for co-occurrences, instead, it represents the number of times two keywords are paired. Finally, the map resolution determines the number of displayed clusters. This value was set to 1 for all the analyses presented in this study. As suggested in previous studies (*e.g.*, Khudzari *et al.*, 2018; Appolloni *et al.*, 2020; Cesarano *et al.*, 2021), the default settings of VOSviewer were applied for limiting the co-authorship analysis to articles with a maximum of 25 authors per publication. Among these, we only selected authors and countries with at least five publications. As for keywords, we only processed terms that occurred in at least five of the selected publications.

RESULTS

Bibliometric research and data collection

The bibliometric analysis started from the study of the Scopus-indexed publications obtained through the applied research string. The use of the string << "sea surface salinity" AND (satellite OR "remot* sens*") >> proved to be the most inclusive for the literature concerning the study of satellite salinity. Table 1 summarizes the number of available publications and the time period considered. In addition, the number of open-access publications is also indicated; however, this is not a selective criterion in the following analysis. The resulting data were manually examined by all the authors independently to remove off-topic products and to provide a complete and consistent dataset. This process included a title and abstract screen-

ing, content analysis, and a cross-check of the independent reviews. A total of 581 publications since 1976 were preserved and then included in the bibliometric analysis. Among the excluded publications, the largest percentage deals with SSS ship-based observations or numerical modeling papers in which satellite remote sensing is included only as an indirect activity (*e.g.*, for providing information about different sea surface parameters, such as temperature or ocean currents) (Table 1).

Dataset bibliometric analysis

After the pioneer study on remote sensing of SSS at 21-cm wavelength by Thomann (1976), the existence of a few works that date back to the end of 90s (*e.g.*, Le Vine *et al*., 1998: Njoku *et al.*, 1999) show an early interest in the study of salinity from remote sensing before 2000. Nevertheless, significant concerns from the scientific community seems to be relatively recent. As Figure 1 shows, the time distribution of the 581 publications analyzed reveals a remarkable growth during the last decade. Since 2012, following the launch of the first two satellite missions (*i.e.*, SMOS and Aquarius), and thanks to the first available scientific results, a dramatic increase in the number of publications can be observed (Figure 1).

A total of 43 countries have published papers that delve into the study of satellite salinity. The United States (US), a main actor in the Aquarius and SMAP missions, is the leading country in terms of the number of publications indexed in Scopus, namely 263. Then, we can find France (120 publications) and Spain (89), whose interest in the SMOS mission is fundamental. China (86), Italy (36) and the United Kingdom (35) follows (Figure 2a). The geographical distribution by continent (Figure 2b) shows Europe as the leading producer of publications (42%), followed by North America (32%), Asia (20%), South America (4%), Africa and Oceania (1%).

Figures 3 and Figure 4 summarize the main institutions and researchers involved in these studies. The "CSIC - Consejo Superior de Investigaciones Cientificas", seems to lead the research in this field, with 140 publications, collecting most of the Spanish efforts in this field of research. In the US, the scientific concern is strongly supported by two NASA institutes, the "Jet Propulsion Laboratory" on the West coast, with 69 publications, and the "Goddard Space Flight Center" on the East coast, with 61 publications, together with the "California Institute of

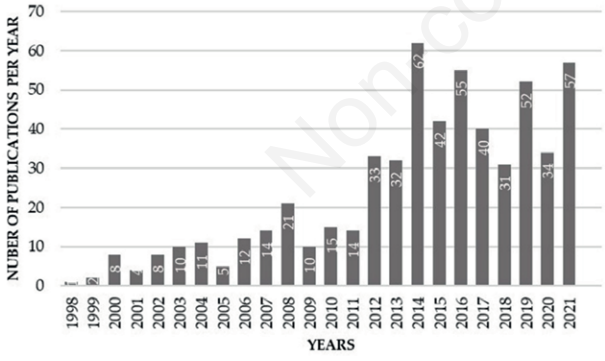

Figure 1. Number of publications indexed in Scopus including the string <<"sea surface salinity" AND (satellite OR "remot* sens*")>>.

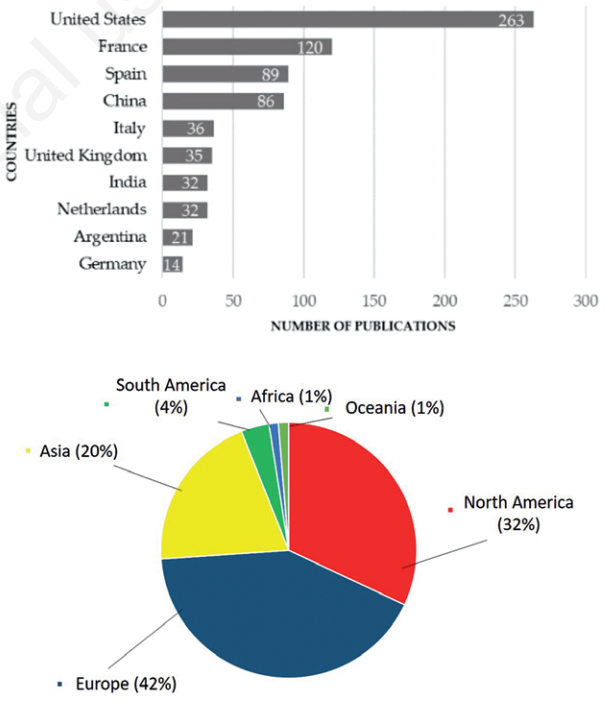

Figure 2. Geographical distribution of publications indexed in Scopus (a) per country, including top ten countries, and (b) per continent.

Table 1. Summary of the publications results obtained through the search string.

Search string	Number of publications	Time frame	Open Access
TITLE-ABS-KEY	1057	1976-2021	477
("sea surface salinity" AND (satellite OR "remot* sens*")			
Final refined dataset	581	1976-2021	275

Technology", with 61 publications as well. France, instead, shows very different research circumstances. Even though there is strong collaboration and interconnection between groups, research is formally fragmented among different institutes, such as the "Centre National de la Recherche Scientifique" (56), the "Institut de Recherche pour le Developpement" (51), the "Sorbonne Universite" (51) and the "Institut Francais de Recherche pour l'Exploitation de la Mer" (49) (Figure 3).

Among the top authors, Prof Jacqueline Boutin emerges as a pioneer and main reference in the subject (Figure 4). She is currently the research director at Sorbonne Universite/Laboratoire d'Océanographie et du Climat-Expérimentations et Approches Numériques (LOCEAN), Paris, where the exploitation of SSS from the SMOS satellite mission represents one of her main interests. The following authors mostly belong to French and Spanish research groups, constituting an important network of collaboration.

Thanks to the Scopus database we have investigated other bibliometric characteristics such as the types, scientific areas, and sources of indexed publications. Articles account for most publications indexed in Scopus (65%), followed by Conference Papers (31%) Reviews (2%), Books and Book Chapters (1%), and Letters, Notes, Editorials or Erratum (1%) (Figure 5). Table 2 lists the top fifteen publication sources for SSS remote sensing studies. "The International Geoscience and Remote Sensing Symposium" (IGARSS) is the first in the ranking with 80 publications (15.2%), followed by the "Journal of Geo-

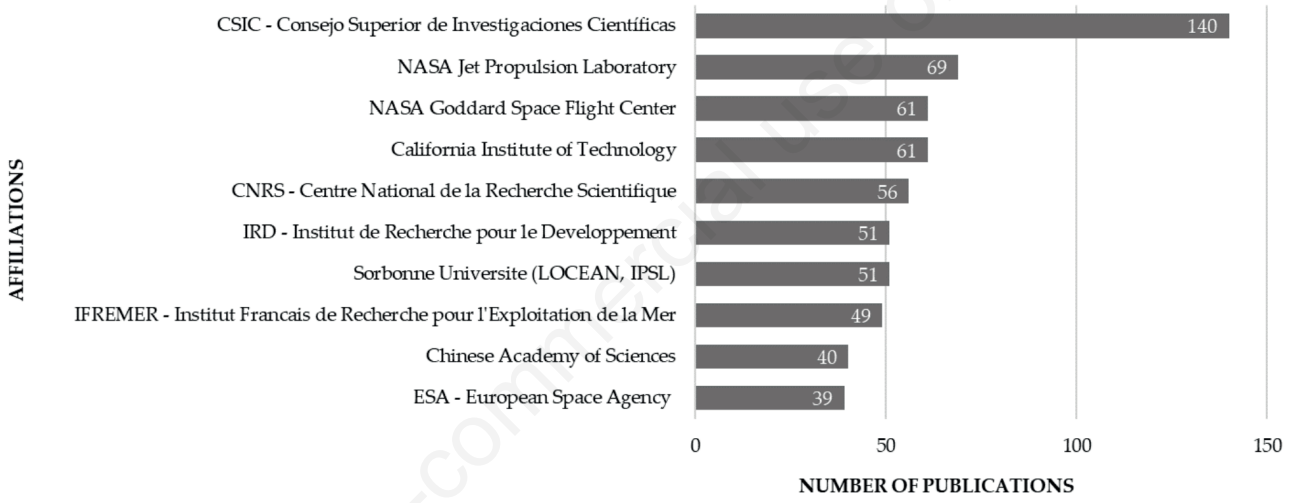

Figure 3. Top ten affiliations associated with publications indexed in Scopus.

Table 2. Top fifteen publication sources (number of publications indexed in Scopus).

Source	Publications	Percentage of total publications
International Geoscience And Remote Sensing Symposium IGARSS	80	15.2%
Journal Of Geophysical Research Oceans	60	11.4%
Remote Sensing	54	10.3%
IEEE Transactions On Geoscience And Remote Sensing	42	8.0%
Remote Sensing Of Environment	32	6.1%
Proceedings Of SPIE The International Society For Optical Engineering	28	5.3%
Geophysical Research Letters	18	3.4%
IEEE Journal Of Selected Topics In Applied Earth Observations And Remote Sensing	18	3.5%
International Journal Of Remote Sensing	17	3.2%
Journal Of Atmospheric And Oceanic Technology	16	3.0%
IEEE Geoscience And Remote Sensing Letters	11	2.1%
Ocean Science	7	1.3%
Acta Oceanologica Sinica	6	1.1%
European Space Agency Special Publication ESA SP	6	1.1%
Iop Conference Series Earth And Environmental Science	6	1.1%

physical Research Oceans" (11.4%), "Remote Sensing" (10.3%), "IEEE Transactions On Geoscience And Remote Sensing" (8%), and "Remote Sensing Of Environment" (6.1%). Figure 6 provides the temporal trend of these top five journals indexed in Scopus, pointing out the remarkable increase in the total number of publications recorded during recent years.

Finally, as expected, the subject areas analysis (Table 3) highlights the predominant role of "Earth and Planetary Sciences" (47.5%), followed by "Engineering" (15%) and "Computer Science" (13.8%). Nonetheless, it also shows that the analyzed theme is addressed through a multidisciplinary approach, declined in the framework of several different subjects.

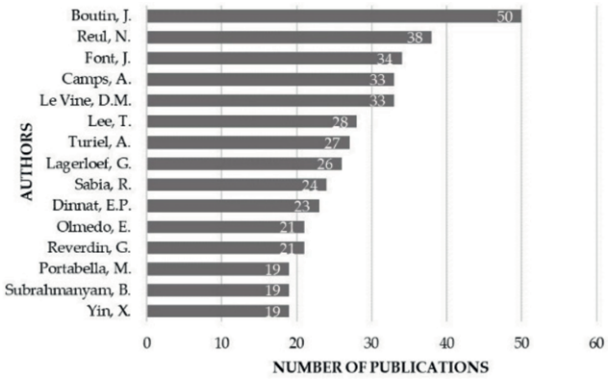

Figure 4. Top fifteen authors publications indexed in Scopus.

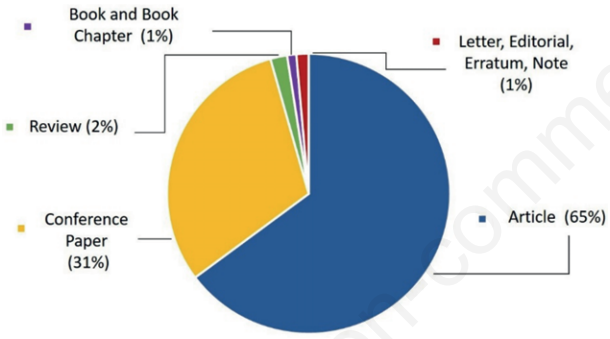

Figure 5. Publications focused on SSS remote sensing indexed in Scopus by type (in percentage).

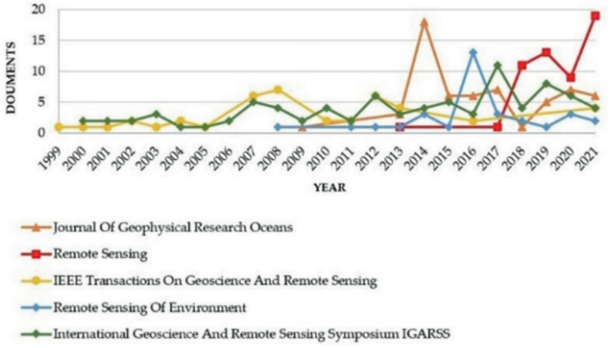

Figure 6. Publications of the top five scientific journals focused on SSS remote sensing indexed in Scopus per year by source between 1999 and 2021.

Bibliometric network analysis

The bibliometric network analysis was carried out on the final refined Scopus dataset as previously described in Section 2.

Authors

The authors, co-authorship analysis included 1278 authors. Analyzing only authors with at least five publications, the number lowered to 107 researchers. These can be grouped into eight main clusters. The top fifteen authors are summarized in Table 4, where TLS, links, number of publications and citations are also reported. As expected, Table 4 is generally consistent with the list of authors per number of publications indexed in Scopus presented in Figure 4. From the bibliometric analysis, several clusters are well delineated, with some being interconnected and others maintaining their independence (Figure 7). Indeed, some authors show strong collaborations within their own clusters but not with other ones.

The main cluster is represented by the red network that groups mostly French scientists belonging to the SMOS community. The yellow cluster is populated by scientists involved in the exploitation of SMOS SSS products too, in this case generally from Spanish research institutes. The blue network also includes several Spanish scientists but pointing out the collaborations that grew up around Prof Jordi Font and Adriano Camps efforts in the development, preparation and improvement of the SMOS mis-

Table 3. Percentage of publications indexed in Scopus by subject area.

Subject area	Percentage of total publications
Earth and Planetary Sciences	47.5%
Engineering	15.0%
Computer Science	13.8%
Agricultural and Biological Sciences	6.4%
Physics and Astronomy	5.5%
Environmental Science	3.5%
Mathematics	3.2%
Materials Science	3.1%
Social Sciences	0.8%
Others	1.1%

sion and its Microwave Imaging Radiometer with Aperture Synthesis (MIRAS) instrument. These three clusters are deeply interconnected and highlights the existing intense collaboration among the grouped scientist. Two minor clusters (*i.e.*, the cyan and orange ones) are also connected to the main three blocks; they mostly include the ocean salinity researchers belonging to the Chinese scientific community.

Conversely, the green and purple large clusters group the US scientists involved in this field of research. Prof Tong Lee can be identified as the main representative of the green network. Together with Severine Fournier, he also represents the main point of interaction between EU and US ocean salinity communities. This cluster is strongly connected to the purple network that includes eminent experts in the development, improvement and optimization of the instruments onboard the EU and US ocean salinity satellites (*e.g.*, G.S.E. Lagerloef, D.M. Le Vine and E.P. Dinnat), as well as to the small brown cluster (Figure 7).

Countries

The co-authorship countries network includes 50 countries, 21 with at least five publications indexed in Scopus. As stated above (Figure 2b), the role of the EU countries is predominant (42% of publications). The list of the top fifteen countries resembles the information per number of publications reported in Figure 2a. Nevertheless, even though US authors provided more publications and obtained a higher number of citations, France occupies the first place in terms of TLS (Table 5). This result is confirmed by the network map (Figure 8) that repre-

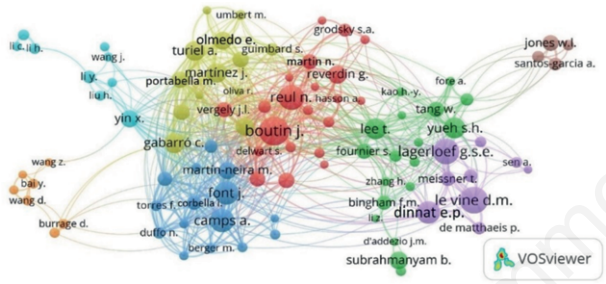

Figure 7. Co-authorship network map of authors based on total link strength. Colors refer to different clusters. The bigger the circle size the greater total link strength the author has. The closer the circles are the more often the authors are found in the same publications.

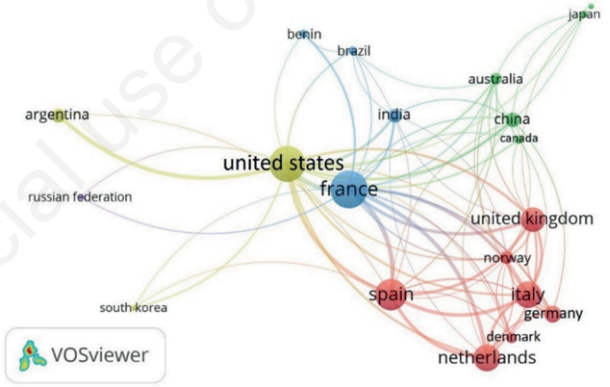

Figure 8. Co-authorship network map of countries based on total link strength. Colors refer to different clusters. Circle size indicates a countries publication frequency. Circle proximity indicates increased occurrence of two countries being found in the same publication.

Table 4. Summary of the top fifteen authors per total link strength (TLS) in Scopus indexed publications.

Author	TLS	Links	Publications	Citations
Boutin, J.	203	46	50	1632
Gabarró C.	164	38	23	502
Font J.	157	38	34	2474
Reul N.	148	38	38	1388
Martìnez J.	143	34	23	189
Camps A.	134	33	33	1097
Turiel A.	127	33	27	231
Portabella M.	117	31	19	165
Sabia R.	104	40	24	256
Gonzàlez-Gambau V.	101	23	16	67
Corbella I.	97	24	13	381
Lagerloef G.S.E.	97	31	26	1125
Olmedo E.	93	17	21	165
Martìn-Neira M.	92	28	18	642
Lee T.	90	37	28	641

sents the way in which countries and clusters are connected.

From the bibliometric analysis, in fact, five clusters emerge. The remoteness of the connections outlines the scarce collaboration between some countries and a stronger dialogue between others. Crucial is the role of France (blue cluster) and the US (yellow cluster), as we can see from their central position on the map. Although these countries also develop collaborations, the limited number and remoteness of links with other countries, especially for US, suggest that they tend to favor independent national research activities and solid exclusive collaborations within their cluster. Conversely, the relevant cluster led by Spain (in red) presents strong interconnections between several countries (*i.e.*, UK, Italy, Norway, Denmark, Germany and the Netherlands) and a general equilibrium among the partners. Another cluster is represented by the green network led by China that brings together several countries (*i.e.*, Canada, Australia and Japan) that cannot be ordered according to typically geographical or linguistic criteria, but that share common thematic interests in the framework of scientific research concerning the study of salinity by remote sensing. Finally, Russian Federation represents a self-standing unit with only few links with external countries (*i.e.*, France and US) (Figure 8).

Keywords

The analysis of the co-occurrence of keywords includes 2899 words, 218 of which with at least five keyword occurrences. From the network analysis five clusters emerge. The term "sea surface salinity" is the most recurring keyword, followed by "remote sensing", "sea surface", "salinity", "oceanography" and "SMOS" (Table 6).

Figure 9 highlights the relevance and the relationships of the keywords. The circles size demonstrates how frequently a term appears as keyword in the different publications. Node proximity indicates how the research topics are strongly related to each other, *i.e.*, the frequency of two terms occurring together in either the abstract, title or keyword listing of the publications. The network map also reflects how the matter is investigated. The five clusters are well-defined, and they identify the specific aspects of existing research activities. On the other hand, they are strongly interconnected and partially overlapping.

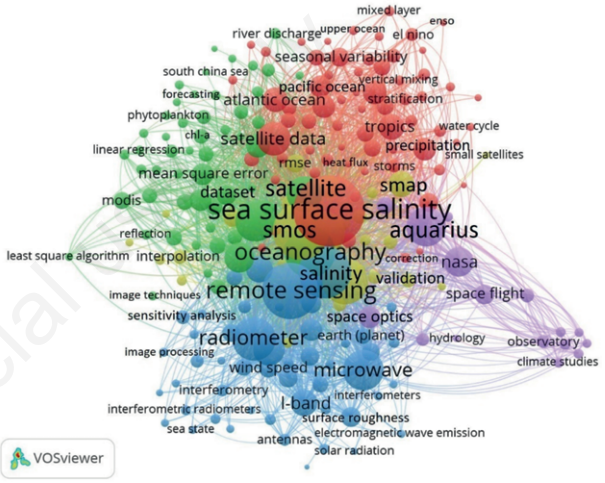

Figure 9. Co-occurrence network map of keywords based on total link strength. Colors refer to different clusters, circle size indicates keyword frequency. Circle proximity indicates the frequency of two keywords being found in the same publication. The size of the keyword label is proportional to its total link strength.

Table 5. Top fifteen countries per total link strength (TLS) in Scopus indexed publications.

Country	TLS	Links	Publications	Citations
France	157	17	122	4369
United States	145	18	267	4709
Spain	111	13	89	3317
Italy	78	8	36	1037
Netherlands	78	10	33	2519
United Kingdom	69	12	35	676
Germany	32	9	14	232
China	23	10	92	548
Argentina	22	2	21	580
India	22	7	32	335
Norway	19	10	8	71
Australia	16	9	10	102
Denmark	13	7	5	49
Benin	9	3	7	108
Brazil	9	6	7	65

The main cluster is the red one that has a crucial role; the predominant keyword is "sea surface salinity" around which several connections between this cluster and the others occur. It groups the words related to the general importance of SSS studies, the water cycle and the climate. Among others, the cluster includes words like "air-sea interaction" and "seasonal variability", "global ocean" and "climatology", "enso" and "el nino", "precipitation" and "evaporation", "vertical mixing" and "stratification, "upper ocean" and "mixed layer".

The second cluster, represented in green, is more focused on the oceanographic aspects; here the dominant words are "oceanography", "sea surface temperature", "satellite data", "*in situ* measurement", and "satellite". Many of these keywords are located in the very center of the map but they are not visible in Figure 9 because covered by stronger items (in terms of TLS) belonging to other clusters. Several terms linked to the water quality and the primary productivity are also present here (*e.g.*, "ocean color", "phytoplankton", "chl-a", "cdom", "river discharge", "biochemistry", "ecosystems", "modis"), as well as items related to the satellite data processing and analysis (*e.g.*, "dataset", "mean square error", "linear regression", "least square algorithm", "estimation method", "image technique", "accuracy", neural network", "machine learning").

The third cluster is represented by the blue network that groups the terms referring to satellite studies, *e.g.*, "remote sensing", "microwave", "radiometer", "brightness temperature", "l-band", "interferometry", "antennas", "sensitivity analysis".

As mentioned above, these three clusters are deeply interconnected and they all present a high number of links towards the fourth network, the yellow cluster, whose items are largely shaded by red, blue and green terms. This cluster gathers the words related to the main satellite missions such as "SMAP", "SMOS", "active/passive", "image resolution", "radio interference", "quality control", "interpolation", "rmse", "uncertainty analysis".

The fifth grouping (in purple) seems to be oriented to the Aquarius mission, as proved by words like "nasa", "space optics", "orbits", "space flight" and, of course, "Aquarius". As expected, this cluster is strongly related to the yellow one that includes the other two main SSS satellite missions (*i.e.*, SMOS and SMAP).

Table 6. Top fifteen keywords per occurrence in Scopus indexed publications.

Keyword	TLS	Occurrence
Sea surface salinity	4444	465
Sea surface	2791	248
Remote Sensing	2787	282
Salinity	2443	242
Oceanography	2248	195
Soil moisture	1875	158
SMOS	1771	165
Radiometer	1701	153
Microwave	1504	145
Sea surface temperature	1441	136
Aquarius	1406	138
Satellite	1152	97
Satellite data	1013	96
Brightness temperature	892	74
Algorithm	782	70

DISCUSSION AND CONCLUSIONS

In this study, we analyze the scientific literature concerning the study of salinity from remote sensing. Global satellite observations led to a better understanding of the influence of salinity on ocean circulation, biogeochemistry and climate variability, as well as better monitoring of the water cycle (Reul *et al*., 2020). The first publications indexed in Scopus date back to the late 70s. However, only since 2012 the increase in the number of published articles has shown significant growth in this relatively new field of research.

Literature analysis usually helps to define strategic decisions about which research areas to support and which areas need better management. For these reasons bibliometrics has assumed considerable relevance in recent years becoming an important tool for science (Reuters, 2008). In this work we specifically explore authors, countries, and keywords with the purpose of providing a global view, highlighting the strengths of this research and possible improvements for the future. The existence of well-defined research groups such as the French, Spanish and US ones emerged. Even though these clusters appear to be strictly interconnected, the analysis of the co-authorship countries network shows that several countries (*e.g.*, US and France) have a preference for independent national research activities and for exclusive collaborations within their clusters. This suggests that there is a wide possibility to further strengthen links between different countries by encouraging greater cooperation for scientific progress in the monitoring of SSS from satellites.

The analysis of the co-occurrence of keywords groups the main terms representative of the SSS satellite research in five well-defined clusters that identify the specific aspects of existing research activities. These clusters are highly consistent in being organized around main topics (*i.e.*, the general importance of SSS studies in the climatic context, the oceanographic aspects, the satellite capabilities) and the main missions (*i.e.*, SMOS, SMAP, Aquarius). Moreover, they are strongly interconnected due to the elevate number of links crossing the boundary of a single group. This confirms that all the research topics are strongly

related to each other and that the engineering aspects are evolving in synergy with the scientific results. As suggested by Vinogradova *et al*., (2019), future satellite SSS missions will benefit from this synergistic approach and from consolidating strong partnerships based on the common purpose of advancing salinity studies and applications for societal benefit.

Nevertheless, from a deeper analysis of the selected articles some problems regarding the ability to study SSS by remote sensing emerge. One of the main issues concerns the validation of the existing products, probably due to the difficulties in the comparison between *in situ* and satellite observations (Boutin *et al*., 2016). Satellite data are integrated over a large surface, and they generally provide daily, weekly, or monthly information. Conversely, *in situ* data are punctual in space and time. In addition, satellite salinity is measured at the surface level while *in situ* salinity is generally measured at a few meters' depth. Recently, Thouvenin-Masson *et al.* (2022) assessed that this sampling difference predicts a different sensitivity of the instruments to small-scale variability. This problem is particularly evident in regions with high SSS variability. Unfortunately, together with the intrinsic spatio-temporal variability of available L-band observations, this issue limits the potential use of satellite SSS retrievals in other fields of research (*e.g.*, polar and coastal oceanography, air-sea interaction, marine biology and ecology, sea pollution) that would be affected by accuracy and gaps of the available SSS products. Also, the analyzed literature shows that these issues still limit the incorporation of SSS data collected through satellites into environmental models for their initialization and assimilation, so that this field of research is still at an early stage (Vinogradova *et al.*, 2019).

In recent years statistical analyses, machine learning, image reconstruction and technological innovation have tried to address these issues and led to great progress in the SSS satellite research (*e.g.*, Olmedo *et al.*, 2018; Buongiorno-Nardelli, 2020; Boutin *et al.*, 2021; Guimbard *et al.*, 2021; Li *et al.*, 2022; Jang *et al*., 2021; Bao *et al*., 2021). SSS satellite data are now frequently assimilated in operational numerical weather prediction systems, helping to improve the forecasting of the global hydrological cycle. However, many improvements are still necessary to improve this area of investigation, which is particularly important for the future study and understanding of oceanographic and climate dynamics, as well as of the biological and ecological systems. To improve remote sensing of SSS in cold regions, for example, additional studies should focus on P-band frequencies where, differently from L-band, the sensitivity to salinity is nearly invariant with water temperature (Vinogradova *et al*., 2019). Furthermore, to improve the consistency of low microwave frequency observations across all oceans and temperatures, future research should also focus on seawater dielectric constant and atmospheric attenuation (Dinnat *et al*., 2019). These efforts will also reduce dependency on empirical corrections. To these goals, additional ground truth SSS information is certainly desirable. An interesting summary of useful recommendations for salinity remote sensing for the next decade has been provided by Vinogradova *et al*. (2019) (see Table 1). They include: ensuring the continuity of space-based SSS measurements; improving accuracy, resolution, and coverage of satellite SSS observing systems, especially in polar oceans; advancing the integration of the observed SSS into global ocean observing network and modeling/assimilation; improving the understanding of SSS data uncertainties and the effects of sampling differences from *in situ* measurements; developing innovative, cost-effective solutions for future satellite missions and exploring multi-frequency instrument concept to enable simultaneous measurements of various ocean parameters; pursuing international collaborations in terms of technology, calibration/validation framework, and cost-sharing.

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