remote sensing

Article

Geophysics in Antarctic Research: A Bibliometric Analysis

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Abstract: Antarctica is of great importance in terms of global warming, the sustainability of resources, and the conservation of biodiversity. However, due to 99.66% of the continent being covered in ice and snow, geological research and geoscientific study in Antarctica face huge challenges. Geophysical surveys play a crucial role in enhancing comprehension of the fundamental structure of Antarctica. This study used bibliometric analysis to analyze citation data retrieved from the Web of Science for the period from 1982 to 2022 with geophysical research on Antarctica as the topic. According to the analysis results, the amount of Antarctic geophysical research has been steadily growing over the past four decades as related research countries/regions have become increasingly invested in issues pertaining to global warming and sustainability, and international cooperation is in sight. Moreover, based on keyword clustering and an analysis of highly cited papers, six popular research topics have been identified: Antarctic ice sheet instability and sea level change, Southern Ocean and Sea Ice, tectonic activity of the West Antarctic rift system, the paleocontinental rift and reorganization, magmatism and volcanism, and subglacial lakes and subglacial hydrology. This paper provides a detailed overview of these popular research topics and discusses the applications and advantages of the geophysical methods used in each field. Finally, based on keywords regarding abrupt changes, we identify and examine the thematic evolution of the nexus over three consecutive sub-periods (i.e., 1990–1995, 1996–2005, and 2006–2022). The relevance of using geophysics to support numerous and diverse scientific activities in Antarctica becomes very clear after analyzing this set of scientific publications, as is the importance of using multiple geophysical methods (satellite, airborne, surface, and borehole technology) to revolutionize the acquisition of new data in greater detail from inaccessible or hard-to-reach areas. Many of the advances that they have enabled be seen in the Antarctic terrestrial areas (detailed mapping of the geological structures of West and East Antarctica), ice, and snow (tracking glaciers and sea ice, along with the depth and features of ice sheets). These valuable results help identify potential future research opportunities in the field of Antarctic geophysical research and aid academic professionals in keeping up with recent advances.

Keywords: Antarctica; geophysics; remote sensing; bibliometric analysis; ice sheet instability; sea ice; West Antarctic rift system; paleocontinent; magmatism; subglacial lakes

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1. Introduction

Antarctica is one of the cleanest places on Earth. Due to its unique geographical location and ecological features, it represents a matchless "natural laboratory" for vital scientific research to study the past, present, and future [1]. It has long been ranked as a priority research area for Earth-related and environmental science studies in many countries. However, due to the remoteness of the Antarctic continent, its difficulty of access, complex topography, and the fact that 99.66% of the continent is covered by ice and snow, "fieldwork" in Antarctica is challenging and expensive [2]. This means that geophysical methods, especially remote sensing techniques such as satellite imaging and airborne surveys, are the best and most effective options. Geophysics uses the principles and methods of physics to study the structure of the medium, composition, formation, and evolution of the Earth's interior; in many ways, it offers unmatched advantages in terms of geological observations [3]. Conducting geophysical surveys help to improve understanding of the Antarctic continent and its ice sheet, revealing the geomorphology [4], tectonic evolution [5,6], ice-sheet stability [7,8], mineral resources [9–11], and climate change [12–14] in the Antarctic continent.

Antarctic geophysical surveys represent a key research area in Antarctic scientific study. The first long-term geomagnetic station was completed in the early 20th century, marking the beginning of Antarctic geophysical exploration. However, until the 1950s, little was known about the size and shape of the Antarctic continent, the volume of ice stored there, its previous changes, and its impact on the rest of the planet. With the advent of geophysical techniques such as seismic bathymetry, a young glaciologist named Gordon Robin began making the first measurements of ice thickness in 1952 and obtained reliable measurements of ice thicknesses and the bedrock beneath [15–18]. In the 1960s, Robin and his colleagues improved radio-echo-sounding (RES) techniques and utilized aircraft-mounted radar systems to study the internal structure and thickness of the ice sheet [19,20]. For example, during the International Geophysical Year of 1957–1958, scientists from multiple countries conducted extensive radar surveys, collecting crucial data that provided a better understanding of Antarctica's ice sheet [21]. What followed was one of the key scientific expeditions in the history of Antarctic exploration—a joint United Kingdom–United States–Danish program comprising long-range airborne surveys of Antarctica over several seasons during the 1970s [22]. In the late 1980s and early 1990s, with the advent of satellite-based remote sensing, particularly from the European remote sensing satellite (ERS-1), technology once again propelled Antarctic research forward [23]. In the 21st century, the use of autonomous systems, including unmanned aerial vehicles (UAVs) [24,25] and underwater autonomous vehicles (AUVs) [26,27], has also facilitated data collection and the mapping of inaccessible or hazardous regions of Antarctica. To summarize, with advances in polar exploration techniques and novel detection methods, ranging from satellites to airborne and surface unmanned vehicles, to boreholes, there are currently more than 80 countries and regions conducting the international geophysical exploration of Antarctica. The continuing advancement of these technologies, combined with interdisciplinary approaches and international collaboration, has significantly expanded our understanding of Antarctica's geophysical characteristics, glacial processes, and the implications of climate change on the continent.

Bibliometrics is a quantitative analysis method that is based on mathematical statistics. It takes the external characteristics of the scientific literature as the object of study and examines the distribution structure of and quantitative relationships among the literature, which was used to describe, assess, and predict the current status and trends of emerging topical areas in research [28,29]. Although many scholars have contributed to the field of Antarctic geophysical research, only a few related studies have been published that have undertaken a comprehensive review and investigation of this research topic. However, despite the quantity of Antarctica review articles, these studies are typically restricted to either one topic or one area, such as unmanned aerial vehicles (UVAs), whereas systematic geophysical reviews are relatively rare [14,30–34]. Therefore, to effectively explore this emerging trend, it is necessary to analyze the development, hot spots, and trends of this topic more systematically and comprehensively.

For this study, based on publications related to Antarctic geophysical research recorded in the Web of Science (WoS) database, the annual publication quantity of articles, national and institutional publication quantity and cooperation mapping, popular research areas, and the temporal evolution of studies published from 1982 to 2022 were systematically reviewed, using a bibliometric analysis method.

2. Data and Methods

In this study, we employed a unified methodological approach that was capable of unifying classical bibliometric analyses using qualitative descriptors. Our approach and procedures are shown in Figure 1. In accordance with the methodology used, our study was separated into two primary phases: Phase 1 and Phase 2. The first phase consisted of selecting a search database, identifying search terms relevant to the subject matter, and incorporating filters into the search engine. Next, we performed a manual screening by reading all the titles and abstracts of the articles returned in the search, identifying matches, and excluding possible articles that did not fit our objective (Phase 1). After these two steps were complete, we performed all the relevant analyses (Phase 2) on both data sets, including co-country, co-occurrence, cluster, and thematic evolution analysis. The results and data were also visualized and manipulated, which helped discover hidden patterns and trends in the data.

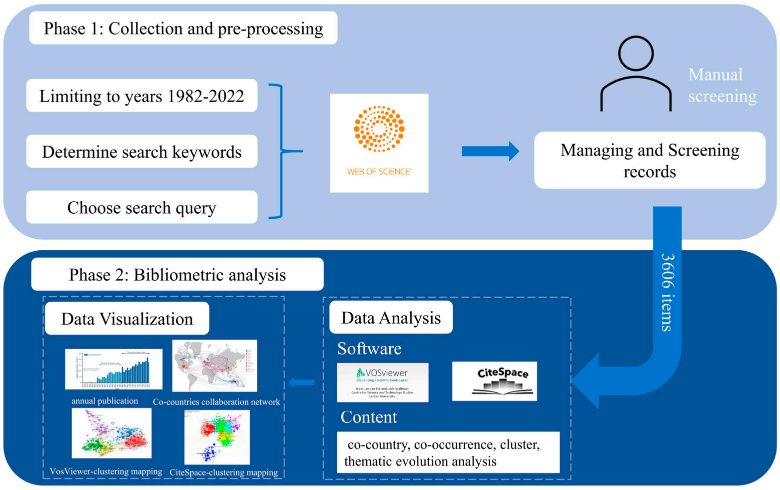

Figure 1. Bibliometric lines of research for Phases 1 (light blue) and 2 (dark blue).

2.1. Data Collection

Literature databases are online repositories that provide access to articles, books, and other publications from a range of academic disciplines. These databases allow researchers to search for and access the relevant literature to support their research. Some popular literature databases include WoS, Scopus, and ScienceDirect. Compared to the WoS, Scopus has lower quality control standards than the WoS, and its coverage is limited compared to that of the WoS, which includes over 12,000 journals. In addition, search results from the WoS allow to be exported to other software programs for additional post-processing. For these reasons, we selected the WoS as the database of peer-reviewed literature used in this research.

We considered those documents with a publication year between 1982 and 2022 and studies regarding geophysical research in the Antarctic. To retrieve complete and suitable publications data from the WoS, we constructed search queries based on two main research pillars, treating Antarctica and geophysics as two broad concepts. We used the advanced feature and selected the keywords "Antarctic", "Antarc", or "geophysics", which should appear in the title and/or abstracts. The search was supplemented by Antarctic-related geophysical and expedition station terms, such as "King George Island" and "Antarctic Peninsula", also combined with specific geophysical terms, such as "seismic", "gravity", "magnetic", "electrical", "electromagnetic", "radio", "echo sounding", and "RES". The documents retrieved by this search then underwent manual screening to avoid word ambiguity. After the process was complete and any duplicates had been eliminated, a final total of 3606 published works had been identified.

2.2. Analysis Methods

With the rapid development of computers and information technology, there are now several software tools available for bibliometrics analysis and scientific mapping [35,36]. The most widely used analytical software programs include HistCite [37], VOSviewer [38], and CiteSpace [39]. The software programs used in this article were VOSviewer and CiteSpace. VOSviewer is a commonly used free text-mining tool that runs software invented by Van Eck and Walterman in the Netherlands [38]. VOSviewer is used to create bibliometric networks of different items (e.g., authors, organizations, keywords, etc.) using various network analysis methods, such as co-citation, term co-occurrence, and bibliographic coupling [38]. CiteSpace is a multi-dimensional, time-sharing, and dynamic citation visualization analysis software that focuses on the potential knowledge contained in analytical scientific analysis [40,41]. The software has the capability to draw a knowledge map of a specific field, Utilizing intuitive and visual formats, this tool proficiently translates complex information. As a result, it not only presents the structure of disciplines within the field in an accessible manner but also analyzes the laws and distribution of these disciplines. Through this software, we effectively understand the visual presentation of the developing trend of a discipline or knowledge field within a specific period of time [42,43]. The results obtained via VOSviewer and CiteSpace using different algorithms will be different. In this paper, we synthesize the conclusions of both methods and reference highly cited literature to help us to obtain more accurate conclusions.

The number of publications, countries, institutions, titles, keywords, research hotspots, keyword clustering, and keyword abrupt are some of the markers used in this work to measure the volume of literature. VOSviewer and CiteSpace were used to read the information into the software, using multiple algorithms, and then recombine it according to type and intensity. The study analyzed the co-authorship between countries and institutions, which is defined as a cooperative relationship if they both appear in the same paper. These tools create a map employing colored clusters (such as countries and keywords) and connecting lines to denote specific parameters (such as the degree of cooperation between countries, which is quantified and represented by the clustering circle size). In co-country studies, the strength of the links between countries and institutions is reflected in the number of publications that are co-authored by them. Co-occurrence analysis is then used to analyze the frequency of occurrence of a set of words in the research literature, that is, words that co-occur in a somewhat related body of literature. Cluster analysis is based on the similarity of objects, wherein collections of physical or abstract objects are grouped into multiple clusters that consist of similar objects for analysis [44]. In addition, CiteSpace offers citation burst analysis, a technique that was used to identify the number of suddenly changing citations within a certain period. Utilization of the mutation detection algorithm designed by Kleinberg identify emergencies in the frontiers and extract explosive nodes from big data [45,46].

3. Results and Discussion

3.1. Characteristics of Publication Output

To present an overview of the literature regarding geophysical research, the annual number of articles published from 1982 to 2022 (3606 articles in total) is shown in Figure 2. It should be noted that since the Web of Science core data set can only be searched regarding literature published from 1982 to the present day, only the development of Antarctic geophysics from 1982 to the present day can be analyzed; however, this does not imply that the study and development of Antarctic geophysics began in 1982.

Observing the growth trend depicted in Figure 2, it is evident thatthe literature on Antarctic geophysical research has shown an overall growth trend over a period of more than 40 years between 1982 and 2022. The increase from 3–4 articles in the 1980s to 174 articles in 2022 indicates that geophysical research and investment in surveys of the Antarctic continent is increasing year by year. Antarctic geophysical studies are gaining increasing attention for two main reasons. On the one hand, research in Antarctica is important for understanding global climate change [47,48], geological evolution [49], understanding global sea level changes [50], etc. On the other hand, more than 99.6 percent of the continent's land mass is covered by an ice sheet that has accumulated over millions of years. The ice sheet is, on average, just over 2133.6 m thick, but in places, it is more than twice that thick. Geophysical and drilling research was used to understand the characteristics and evolution of subglacial geology [51] and provide important information on the englacial environment and bed conditions of the Antarctic ice sheet [52], as well as elucidating the histories of accumulation and ice flow [19,53,54].

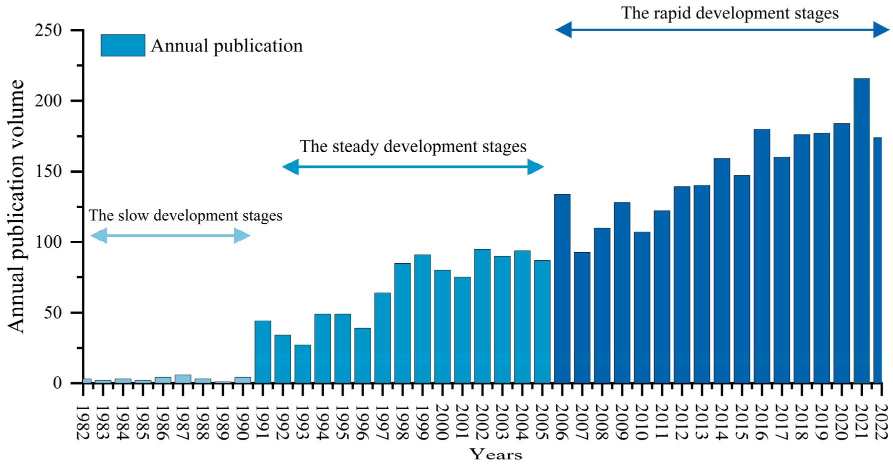

Figure 2. Time evolution of annual publications and the accumulated literature from 1982 to 2022.

In contrast, the development of these publications can be divided into three stages, the slow development stage (1980–1991), the steady development stage (1991–2005), and the rapid development stage (2006–2022). During the slow development stage, the annual output of Antarctic geophysics-related literature and its total volume was relatively small, with only a few studies published. The study area was mainly concentrated in East Antarctica [55,56] and near the marginal seas [57]. Dibble et al. studied the volcanic tectonics of Mount Erebus using seismic, infrasonic, and magnetic induction recordings [58]. During the steady development stage, the annual number of articles published shows an "N"-type distribution trend, with slight up- and downturned fluctuations. Compared with the previous stage, the annual number of publications in this period shows a rapid development trend, from 3–4 papers to more than 40 papers, indicating that international research on Antarctic geophysics was gradually gaining scientific importance. During this period, a total of 1003 papers on Antarctic geophysical research were published. The article "Geophysical studies of the West Antarctic rift system" was published in *Tectonics* in 1991 by Behrendt, LeMasurie, Cooper, et al. Elsewhere, the Bundesanstalt für Geowissenschaften and Rohstoffe (BGR), working alongside the United States Geological Survey (USGS), used aeromagnetic techniques to investigate the rift structure of the Ross Sea continental shelf. This article was cited 174 times [59]. During the rapid development stages, the number of articles issued shows a large fluctuation, with the annual average number of articles published rising to more than 100 papers. Since the Fourth International Polar Year (2007–2008), the annual number of publications has shown a rapid growth trend, indicating that international integrated geophysical programs have promoted the development of Antarctic geophysical research [60]. The number of publications peaked at 216 in 2021.

3.2. Research Influence and Cooperation Analysis

3.2.1. Major Countries and Institutions for Antarctic Geophysical Research

Antarctic geophysical research involves a total of 82 countries (regions), mainly in Europe, North America, and Asia. Figure 3 lists the top 15 countries with the highest levels of academic productivity and summarizes their total number of articles and centrality. Here, country centrality refers to key nodes with the greatest influence in the co-occurring network, or key nodes with larger intermediary bridging roles [61]. The higher the value of country centrality, the greater the importance of that country in the research area. The formula for centrality is as follows [62]:

$$C_B = \sum_{s \neq v \neq t \in V} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

where $\sigma_{st}(v)$ is the number of shortest path entries from s to t, passing through node v; and σ_{st} is the number of all the shortest paths from node s to node t.

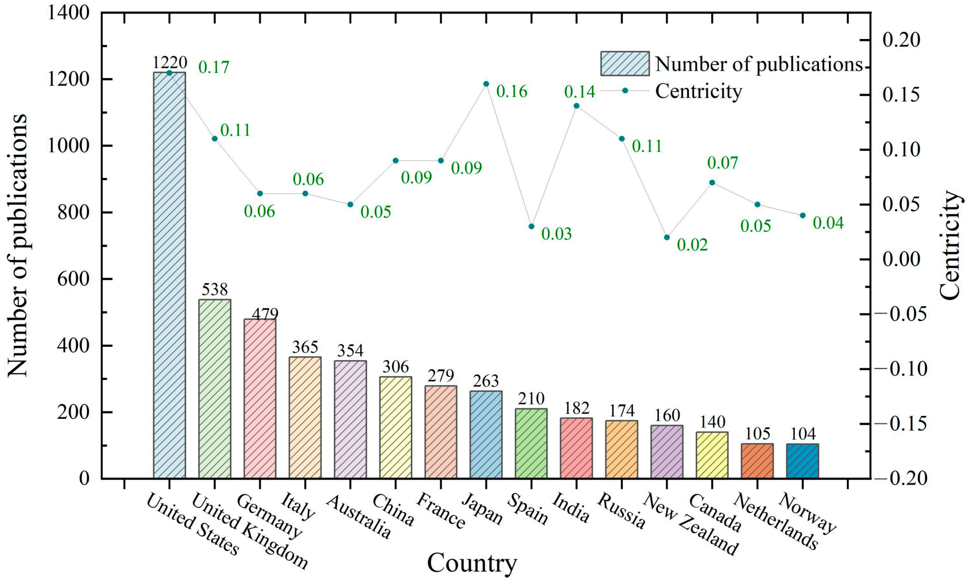

Figure 3. Distribution of the top 15 countries with publications in Antarctic geophysical research.

Among these fifteen countries, eight were European, three were Asian, two were Oceanic, and two were North American. Except for Canada, the other 14 countries are either original signatories to the Antarctic Treaty or consultative parties. The United States was responsible for the highest number of publications (1220), accounting for 25.5% of the total number of papers. Their centrality is also the highest, indicating that the United States is a world leader in Antarctic geophysical research. Eight European countries are among the top 15 countries/regions in terms of published Antarctic geophysical research. The United Kingdom and Germany are also among the top three publishers, indicating that Europe is also in a key position in the field of Antarctic geophysics. Other countries/regions are also at the top of the list of publications, such as Australia, China, and Japan, and have made significant contributions to Antarctic geophysical research. China has been conducting comprehensive geophysical surveys in Antarctica since its introduction to the field in 1984 [63,64]. Although China is a latecomer in the field of Antarctic research, it has made rapid progress. In less than 40 years, China has established four Antarctic research stations in Antarctica. In addition, the "Snow Eagle 601" airborne platform serves China's Antarctic expeditions [65,66]. Snow Eagle 601 was instrumented with ice-penetrating radar (IPR) along with a gravimeter, magnetometer, laser altimeter, and optical camera, and was employed in an investigation of Princess Elizabeth Land (PEL) in 2015 [66].

To date, 497 institutions have contributed to this area of research. The top 20 institutions with the highest number of publications in the field of ocean-based remote sensing research for the entire study period are shown in Figure 4. The Helmholtz Association tops the list with the largest number of publications (278) and a share of 7.71%. The Natural Environment Research Council published 274 papers (7.52%), while the British Antarctic Survey published 263 papers (7.63%). There is little difference between the productivity of the top institutions. Eight of these institutions are from the United States, three are from the United Kingdom, and two are from Germany, thus demonstrating the importance of the United States, the United Kingdom, and Germany in Antarctic geophysical research and the breadth of institutional involvement. Antarctic geophysical research in the United States developed early, with numerous and decentralized forces, showing a clear structure of systemic innovation. The National Science Foundation (NSF) operates the Antarctic basic equipment and organizes university and research institute involvement in Antarctic geophysics-related matters. The University of California and the University of Texas have their own characteristics, maintaining a leading position in Antarctic geophysical research. The University of California is characterized by its leadership in the field of ice-sheet research. In 2019, an Irvine-led team of glaciologists from the university unveiled the most accurate portrait yet created of the contours of the land beneath Antarctica's ice sheet, the results of which were published in the journal *Nature Geoscience* [6]. The University of Texas employed space-based, airborne, land-based, and marine geophysical methods to better understand ice sheet evolution, climate, and geologic processes in the polar regions. These efforts provided valuable insights into the dynamics of Antarctica's unique environment and contributed to the global understanding of climate change impacts [67]. The NSF invests USD 70 million annually into scientific research on Antarctica and the Southern Ocean, along with USD 255 million in the provision of related facilities [68]. The Helmholtz Association is the most prolific publisher of academic papers and is the largest research institution in Germany. It operates five ice-breakers and two polar planes, making it possible to obtain geophysical measurements in Antarctica [69]. As the largest investment institution in the UK, the Nature Environment Research Council (NERC) invested GBP 67.029 billion for polar research facilities in 2022 [70]. The British Antarctic Survey (BAS) has also carried out extensive scientific work and is a world leader in terms of Antarctic research [71]. Other institutions, such as the Centre National de la Recherche Scientifique (CNRS), the National Polar Research Institute, and the Chinese Academy of Sciences also play important roles in Antarctic geophysical research.

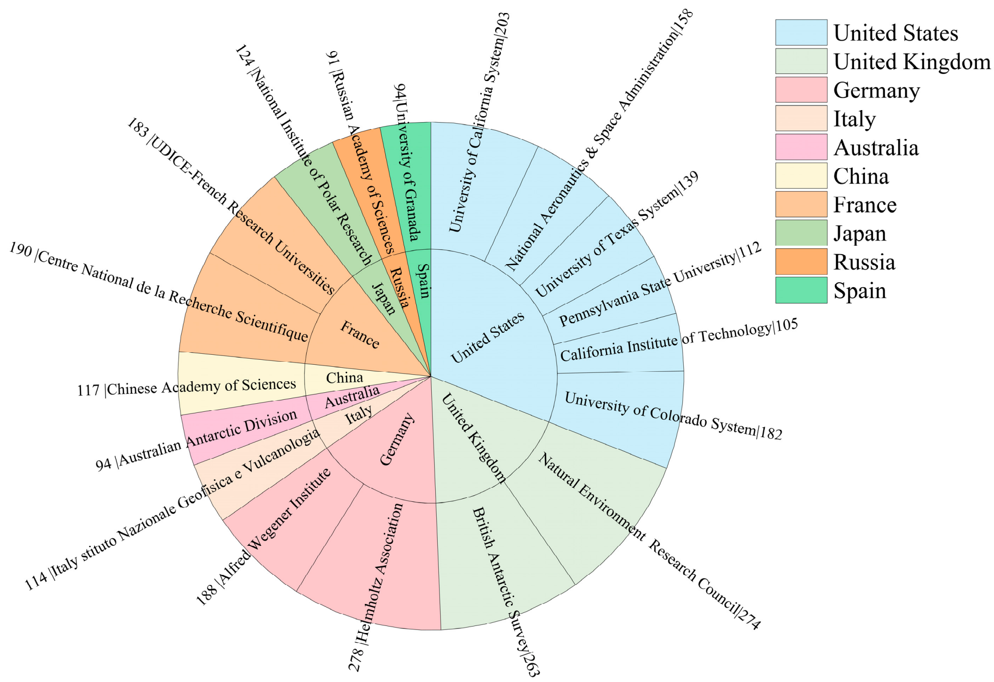

Figure 4. Distribution of major countries/institutions for Antarctic geophysical research.

3.2.2. Influence Distribution and Cooperation among Core Countries/Institutions

By promoting scientific cooperation among scientists in different disciplines, international cooperation has improved research productivity [72]. In particular, the Scientific Committee on Antarctic Research (SCAR), which was established in 1985, has played a key role in Antarctic cooperation [73,74]. SCAR, being a major international Antarctic research coordination body, supports and promotes various initiatives and projects, including the International Collaborative Exploration of the Cryosphere through Airborne Profiling program (ICECAP) [75–77], Instability and Thresholds in Antarctica (INSTANT) [78,79], RINGS [80], and AntArchitecture [81–83]. ICECAP is a significant and collaborative international research project involving the United States, the United Kingdom, Australia, France, and China. ICECAP fieldwork is led by the Polar Research Institute of China, using an equipment suite that includes radar and gravity measurements developed by the United States [84]. All these nations, along with the various institutions that are also linked to the program, collaborate on data analysis by offering scientific expertise in geophysics, geology, glacial history, and glaciology. This collaboration aims to gather data to help predict whether and how the East Antarctic Ice Sheet might collapse in the future [85]. These international cooperation projects operate under the umbrella of SCAR, furthering our understanding of Antarctica's role in the global environment. International cooperation has also made a range of geological and geophysical data sets available to the wider scientific community. Antarctic geophysical data sets, such as ADMAP (The Antarctic Digital Magnetic Anomaly Project), Bedmap (bedrock topography of the Antarctic), AntGG (Gravity and Geoid in Antarctica), and other data sets, are extremely useful for understanding the geological structure and evolution of the Antarctic continent and accelerating scientific discovery related to the Antarctic region [86–89].

To visualize this cooperation between countries and institutions, national and institutional cooperation networks were obtained via CiteSpace and VOSviewer, from which images were drawn using Scimago Graphic. The top 15 countries, listed in terms of their cooperation strength, are shown in Figure 5, where the nodes represent countries, the links join the various countries at their ends, and the size of the nodes indicates the centrality of the country. The more that the various countries cooperate, the larger their number of nodes. Figure 5 shows that those countries contributing to the field of Antarctic geophysical research have the following characteristics. (1) The largest node in Figure 5 is the United States. As can be seen from our mapping of the country's cooperation network, it has the largest nodes, representing cooperation links with many more countries compared to others on the map. The United States has led numerous international cooperation programs, such as Polar Earth Observing Network (POLENET) [90,91] and Antarctica's Gamburtsev Province (AGAP) [92], while Operation IceBridge (OIB) [93,94] is a partnership between NASA and its international partners, which include Canada, Germany, and the United Kingdom [93]. This mission has been ongoing since 2009 and has covered large areas of the polar regions, including Antarctica and the Arctic [95]. The OIB has been designed to bridge the gap between satellite observations and ground-based measurements, providing a more comprehensive and accurate picture of the polar regions [93,96,97]. (2) Due to the strong level of cooperation between European countries in terms of their geographical location and language exchange, the United Kingdom, Germany, Italy, Norway, France, and Russia have developed cooperative relationships and close ties. Russia has not been ranked among the top countries in terms of published literature but maintains close cooperative ties with several countries. The United Kingdom maintains its ongoing track record of successful exploration in remote and hostile frontier regions through major international collaborations, such as the AGAP project in the Gamburtsev Subglacial Mountains. (3) Asian countries are relatively less cooperative than their European counterparts. Japan, China, and India were more active and were closely linked to the United States, Norway, Russia, and others. China also actively participated in international cooperation in the field of Antarctic geophysics. In the fourth IPY, the Prydz Bay–Amery Ice Shelf–Dome A (the PANDA program) is led by China and also represents a core research plan [98].

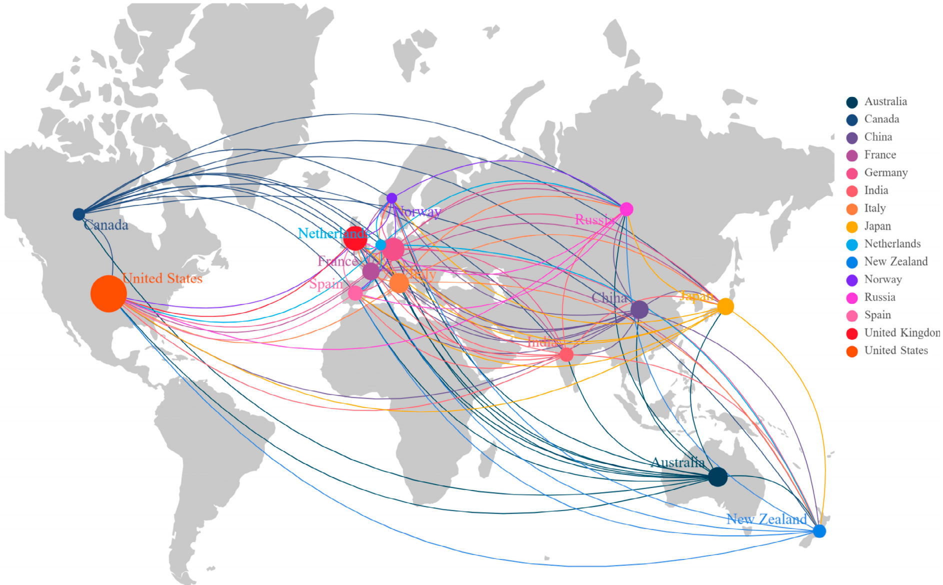

Figure 5. The cooperation network of the most productive countries, in terms of Antarctic geophysical research.

3.3. Focus on Antarctic Geophysical Research

Keywords are at the heart of academic papers and can highly refine their academic content [44]. By analyzing the co-occurrence patterns of keywords in scholarly articles and applying clustering algorithms, software programs such as CiteSpace can effectively identify the various research groups or clusters, based on their shared interests or thematic areas [99]. The main steps are as follows. First, the CiteSpace program collects data sets that have been obtained from the WoS, comprising scholarly articles or publications related to Antarctic geophysics. Second, CiteSpace performs a co-occurrence analysis of the keywords extracted from the data set; those keywords that frequently appear together are considered relevant and are likely to belong to the same research group. Third, CiteSpace uses a clustering algorithm to organize the co-occurrence network data, to identify the six most popular research groups [41]. These popular research groups comprise Antarctic ice sheet instability and sea level change, the Southern Ocean and sea ice, tectonic activity of the West Antarctic rift system, the paleocontinental rift and reorganization, magmatism and volcanism, and finally, subglacial lakes and subglacial hydrology. To ensure the accuracy of the groups exported from CiteSpace, these groups were critically evaluated and validated according to the most highly cited article and expert validation. By using these methods, we can assess whether the identified groups align with the existing Antarctic geophysical research areas and themes. Details of the six groups are as follows.

3.3.1. Antarctic Ice Sheet Instability and Sea Level Change

The Antarctic ice sheet is the largest in the world and, if it melts completely, the global mean sea level (GMSL) will rise by 60 m [100–102]. The Intergovernmental Panel on Climate Change (IPCC) published the Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC), which specifically identified the greatest challenge to accurately quantifying the rate and magnitude of sea level rise as being our limited knowledge of the mechanisms of ice sheet change [103].

Geophysical techniques can be used to accurately measure ice sheet characteristics, as well as their temporal and spatial variability [104,105], which has greatly promoted research on the progress of Antarctic ice sheet movement and research on its instability [106–108]. Based on the techniques of satellite altimetry and gravimetry, among others, the Antarctic ice-sheet mass balance can be estimated [109–111]. Since 2002, the measurements reported by the Gravity Recovery and Climate Experiment (GRACE) satellite program provide new and key observations for detecting, monitoring, and understanding ice-sheet mass balance [112–115]. However, the satellite has low resolution, and continuous time series detection is not possible in high-accumulation areas. The results yielded by the different analytical technologies are somewhat different [116,117]. Airborne and ground-based geophysical surveys provide critical data, more detailed information, and observations that can be used to calibrate and validate satellite retrieval results that cannot be measured from space. Ice thickness and near-surface density were measured via a reflection and refraction survey [17], while bedrock elevation was mapped using ground-based and airborne ice-penetrating radar [88]. These data are useful for fine-tuning information on the instability of the Antarctic ice sheet. Figure 6 shows the main geophysical methods used to probe the Antarctic ice sheet.

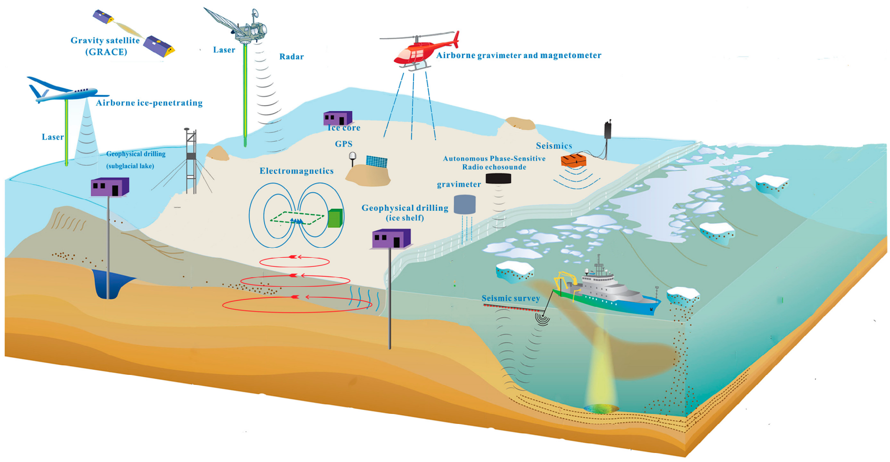

Figure 6. Geophysical observation methods applied to the Antarctic ice sheet (modified from [118]).

The recorded geophysical measurements indicate that the mass of the Antarctic ice sheet has been decreasing [100,118,119]. Since extensive measurement-taking began in 1992, the West Antarctic ice sheet (WAIS) and the Antarctic Peninsula have been losing mass [120–124]. Recent mass loss and an increase in the WAIS ice sheet are concentrated in the Amundsen Sea (ASE) and along the coast of the Bellingshausen Sea. These changes are consistent with the recorded observations of grounding line retreat [125] and a decline in the Pine Island Glacier [126,127]. From 2008 to 2015, Gardner et al. used Landsat 7 and 8 imagery, spanning the period from 2013 to 2015, to compare the physical observations to earlier estimates, and calculated a mass loss of -214 ± 51 Gt yr^{-1} for the WAIS [123]. In contrast, it is generally considered that the East Antarctic ice sheet (EAIS), which encompasses a larger ice mass, has been in a state of mass equilibrium or has had a slightly positive mass balance over the past two decades [100,128,129]. However, recent observations have detected thinning in some of the glaciers on the EAIS, resulting in a negative mass balance in the ice catchments [115,130]. Increased ice velocity and glacier terminal retreat in the EAIS outflow have been observed at Wilkes Land, which indicates mass loss [131]. However, increased EAIS mass on the Siple Coast and Dronning Maud Land have been reported [132]. All these findings suggest that the EAIS is highly dynamic in nature. However, the mass balance of the terrestrially dominated EAIS is still less clearly understood due to the lack of observational evidence.

3.3.2. Southern Ocean and Sea Ice

The Southern Ocean plays an extremely important role in the effective functioning of the Earth's systems and is a major regulator of planetary climate, acting as an important carbon sink for anthropogenic carbon dioxide from the atmosphere [133]. Antarctic Sea ice was formed when the surface of the Southern Ocean froze; it interacts in various ways with adjacent ice shelves and stranded ice [134]. The small-scale spatial properties of Antarctic Sea ice help to assess the stability and variability of global sea ice cover. Sea ice in the

Southern Ocean affects these important global functions; therefore, understanding how ocean–ice interactions occur is a high-priority scientific issue.

The factors of the sea ice itself make it difficult to obtain consistent and continuous data in field measurements; therefore, satellite remote sensing is required to obtain regional thickness distribution data on the circumpolar Antarctic Sea ice [135]. Satellite radar and laser altimetry are currently the most widely used and effective tools for the inversion of sea ice thickness [136]. These tools establish the range [137–140], thickness [141–143], and drift map [144,145] of sea ice, in order to deeply understand the impact of sea ice on the climate [146] and its impact on the ecosystem. Since the late 1970s, variations in the extent of Antarctic Sea ice have been charted regularly using passive microwave satellite imagery [137]. Until the mid-1990s, there was no significant trend in the annual mean total Antarctic sea ice extent or the extent at the annual minimum [147]. However, after reaching a record-high annual mean Antarctic Sea ice extent in 2014, the extent experienced a dramatic decline. In 2017, both the annual daily maximum and minimum extent, as well as the annual mean extent, reached record or near-record lows [148]) (Figure 7a). In February 2022, the annual minimum Antarctic Sea ice extent reached a historic low in the satellite era, with less than two million square kilometers recorded. This stands in stark contrast to the slightly positive trend in the Antarctic SIE observed before 2014 [149]. Based on satellite observations, from 1979 to 2015, the Antarctic sea ice area experienced a statistically significant growth rate that was roughly one-third the rate of the retreat observed in Arctic sea ice [150] (Figure 7b). Satellite Radar and Laser Altimetry are currently the most widely used and effective tools for inversion of sea ice thickness [136]. Kurtz et al. analyzed the basin-wide trends in Antarctic Sea ice thickness and volume over five years from 2003 to 2008, utilizing passive microwave observations and satellite laser altimetry data drawn from NASA's ice, cloud, and land elevation satellite (ICESat), shown in Figure 7c [142]. Satellite Radar and Laser Altimetry are currently the most widely used and effective tools for inversion of sea ice thickness [136]. Kurtz et al. analyzed basin-wide trends in Antarctic Sea ice thickness and volume over five years from 2003 to 2008 utilizing passive microwave observations and satellite laser altimetry data from NASA's Ice, Cloud, and Land Elevation Satellite (ICESat) [142]. Through analysis, it has been observed that there is a slight negative trend in sea ice thickness during the summer, but balanced losses in thickness, leading to small overall volume changes. However, estimating the thickness of Antarctic Sea ice from remote sensing data is still challenging. These measurements have linked airborne projects (e.g., NASA's Operation IceBridge, etc.), providing a vital component for understanding long-term changes in Antarctic Sea ice and its impact on the climate [94,95].

3.3.3. Tectonic Activity of the West Antarctic Rift System

Understanding the West Antarctic lithospheric structure is important for elucidating the dynamics and mass balance of the Antarctic ice sheet [151,152]. The West Antarctic rift system (WARS) is one of the largest continental rift systems on Earth [153]. Its size is comparable to that of the North American basin and the East African Rift Valley [59,154,155]. Unlike the stable East Antarctic Craton, the WARS has a complex tectonic history. From the Cenozoic era to the present day, West Antarctic tectonic activity has continued from time to time, and the area is prone to instability and potential collapse [156]. The West Antarctic ice sheet poses the most immediate threat of a large sea level rise [157]. Therefore, an in-depth understanding of the configuration and development of the West Antarctic rift system is essential for accurate mass balance [158,159] and glacial isostatic adjustment [160].

Direct knowledge of the rift system comes primarily from geological and geophysical surveys and drilling. Geophysical data have played a key role in defining the structure of West Antarctica [161]. Since 1980, such data have been collected in the form of about 35,000 km of marine common depth point (CDP) reflection profiles [162]. In 2006/2010, airborne magnetic and gravity measurements taken by the Polarstern helicopter affiliated with the Alfred Wegener Institute (AWI), which took readings in the Amundsen Sea Embayment, revealed important stages in the tectonic evolution of the region [163]. In 2012, the BAS used airborne ice-penetrating radar and magnetic and gravity measurements to identify a mile-deep rift under the ice in West Antarctica, which is assumed to be part of the WARS [164]. The 32,000-line km of aeromagnetic data collected near the Pine Island (PIG) catchment region [165] was used by researchers in the UK to interpret the dynamic partial stability of the West Antarctic ice sheet [86,166]. The seismic and geodetic networks deployed by the Polar Earth-Observing Network (POLENET-ANET) project, working in the Transantarctic Mountains (TAM), have played an important role in understanding the WARS [167,168]. As part of the Polar Earth Observing Network, Lloyd et al. employed the data from 13 temporary broadband seismic stations that were deployed from January 2010 to January 2012 to identify reduced seismic wave velocities in the uppermost mantle beneath the WARS, which are thought to be a residual thermal signature of Neoproterozoic rifting [169].

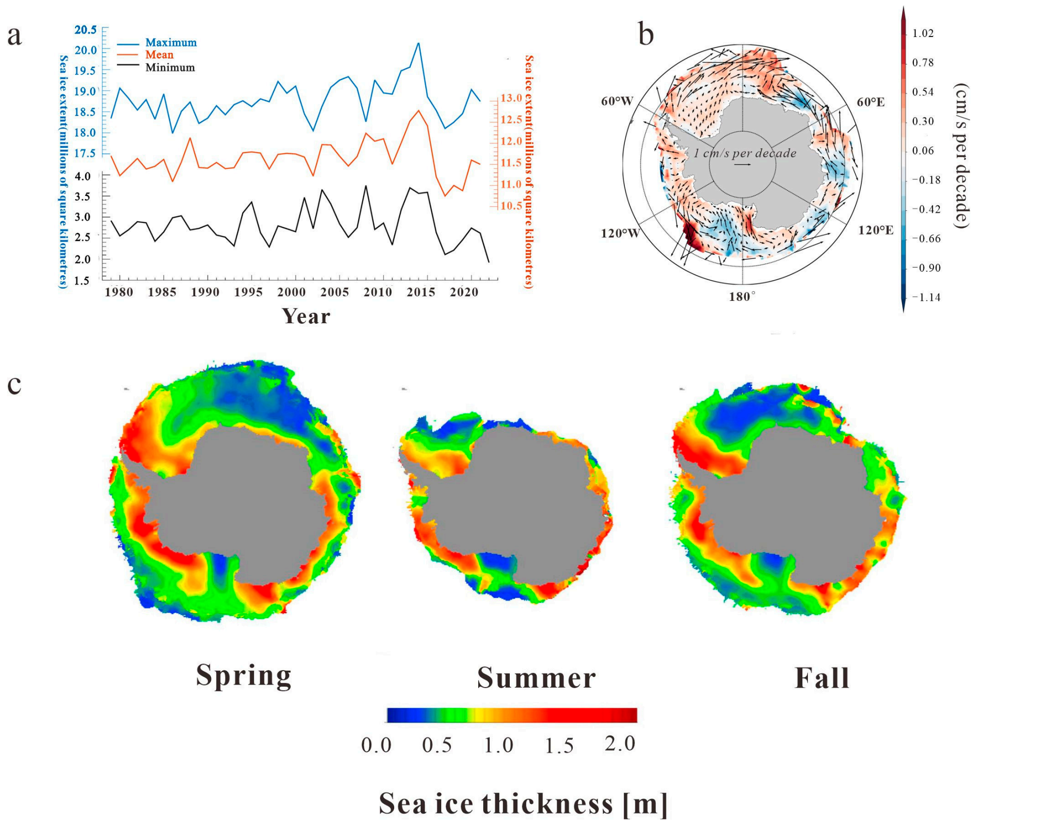

Figure 7. (**a**) The minimum daily sea ice extent (SIE) (10^6 km^2) for the Southern Ocean along with the daily maximum and annual mean for 1979–2022 [147]; (**b**) Antarctic sea ice drift velocity trend during 1992–2015 [150]; (**c**) Maps of the average sea ice thickness data for each season from 2003 to 2008 [142].

3.3.4. Paleocontinental Rift and Reorganization

Antarctica has played a crucial role in the study of the geological history and reconstruction of the supercontinents Rodinia and Gondwana [170–173]. The study of the lithosphere and the identification of geological boundaries in Antarctica and the neighboring continents are essential to an understanding of the geodynamic evolution of the planet, as revealed in the processes that led to the dispersal of Gondwana's constituent land masses [174]. However, due to the mostly ice-covered nature of Antarctica, the geometries of these blocks, the outlines of the moving bands, and the sutures between them are poorly known [175]. Airborne geophysical surveys, especially magnetic and gravity data, are the only tools that reveal subglacial geology in a regional sense [174].

The regional tectonic zones of Antarctica have become better understood as a result of the collection of 40 years of extensive airborne geophysical data from across the continent.

Eastern Dronning Maud Land (DML) in Antarctica represents a crucial area for enhancing our comprehension of the crustal fragments involved in the merging, amalgamation, and breaking up of Rodinia and Gondwana [175]. The BAS acquired 15,500-line km of data, based on high-resolution airborne magnetic measurements from the "Magmatism as a Monitor of Gondwana Break-up" (MAMOG) project conducted on the Jutulstraumen ice stream in western Dronning Maud Land. This provides new constraints on the magmatic and structural context of the DML's margins and aims to address the mantle processes that led to the initial breaking-up of Gondwana [176]. The AWI has also conducted several airborne geophysical surveys at the site. Early offshore surveys taken in an area north of the DML by the EMAGE project focused on the breaking-up history of Gondwana, specifically, the opening of the Weddell Sea and, thus, the dispersal of Antarctica and Africa/South America [177,178]. The VISA project, run by the AWI in collaboration with the Dresden University of Technology, focused on the East Antarctic Shield and the major structures on its continental margin to better understand the reconstruction of the paleocontinental region [179]. Airborne magnetic, gravity, and geological data from the Antarctic Peninsula have contributed to the scientific interpretation of Mesozoic arc magmatism and terrane accretion at the paleo-Pacific margin of Gondwana [180–182]. Overall, airborne gravity and magnetic data provide crucial evidence for revealing Antarctic geological and tectonic information, understanding the regional tectonic provinces of the continent, and providing insight into the breakup and assembly of the paleocontinental region.

3.3.5. Magmatism and Volcanism

Magmatism has played an important role in the geological evolution of Antarctica [183]. Magmatism in Antarctica has occurred in a variety of tectonic settings, resulting in diverse magma types and eruptive styles. Some of the volcanism behavior mirrors the type of magma that occurs [184]. Additionally, the enormous volume of ice cover in Antarctica and its interaction with volcanism have provided rare opportunities for scientists to use the volcanic record to understand past environmental conditions [183,185,186].

Geophysics researchers have inferred the presence of past active magma activity under the Antarctic ice sheet [187]. Lough et al. analyzed seismic data that were recorded by 37 seismic stations deployed in Marie Byrd Land. The observed seismic activity was interpreted as a sign of magma movement within an active subglacial magmatic system, demonstrating that volcanism continues to migrate southwards along the Executive Committee Range [188]. The aeromagnetic method has been the most useful geophysical tool for the identification of subglacial volcanic rocks. Short-wavelength, shallow-source, high-amplitude (100 to >1000 nT) magnetic anomalies were observed, ranging from 5 to 20 km in width at half-amplitude, located about 1 km above the 2–3 km thick moving ice. These magnetic anomalies are thought to be subglacial volcanic rocks [187,189,190]. Van et al. used aeromagnetic, gravity, and satellite imagery to identify 138 subglacial volcanoes in West Antarctica that are concentrated along the West Antarctic rift system [191]. High-resolution airborne magnetic surveys have successfully mapped the extent of Cenozoic magnetism along the arc/pre-arc boundary of the West Antarctic Peninsula, which straddles Adelaide Island [182,192]. Magnetotelluric investigations have provided significant evidence of volcanic activity. Using magnetotelluric data from the Erebus volcano, Hill et al. argued that the steep, melt-related low resistivity of the upper mantle defines the underlying magma system [193]. It has been suggested that the dynamical intersection of the Terror rift and the accommodation zone fracture structure may control the geometry and style of magma transport and storage in the Erebus volcanic system [193]. Gupta et al. also applied tomographic methods to detailed three-dimensional P-wave velocity imaging of the apocalyptic travel times that were recorded at 42 portable seismic stations in and around Mount Erebus, with a focus on understanding the deep structure and evolution of Mount Erebus [194].

3.3.6. Subglacial Lakes and Subglacial Hydrology

Ice-sheet hydrology has long been recognized as a crucial component in the understanding of ice sheets, their behavior, and their evolution [195]. The presence and distribution of water at the ice sheet bed are widely considered to control ice motion by facilitating basal sliding and substrate deformation [101,196]. In addition, as an enclosed special body of water under the ice, the subglacial lake may preserve primitive life forms and unique geological features, recording the evolution of life and changes in the climate and environment [197,198]. Therefore, the study of Antarctic subglacial hydrology has become a hot topic in Antarctic geophysical research.

Most of the identification and characterization of Antarctic subglacial hydrology has relied on remote geophysical observations (Figure 8a). Satellite data (e.g., ICESat, CryoSat-2 data sets) reveal the hydrological conditions present in the substrate. Satellite altimetry techniques have been used on numerous occasions to identify the presence of "active" subglacial lakes, along with their connectivity and their impact on ice dynamics (Figure 8b) [199–202]. At the same time, various geophysical methods can also be used to reconstruct the subglacial hydrological environment [203]. Radio-echo sounding (RES) is the most effective technique for detecting and characterizing subglacial water bodies (Figure 8c) [204,205]. The utilization of the scattering characteristics of returned bed echoes, such as the specularity content, trailing bed echoes, the bed-echo coherent index, and bed-echo variability, has advanced the quantitative identification of subglacial water and our understanding of subglacial drainage systems [206]. Subglacial lake drilling provides direct access to subglacial lake water and sediment samples, in a process that can extract valuable information on the paleoclimate and paleoenvironment [207,208]. Other geophysical methods, such as active seismic surveys (Figure 8d) and electromagnetic (EM) approaches, play important roles in revealing the geological and hydrological conditions prevalent in subglacial lakes [209–212].

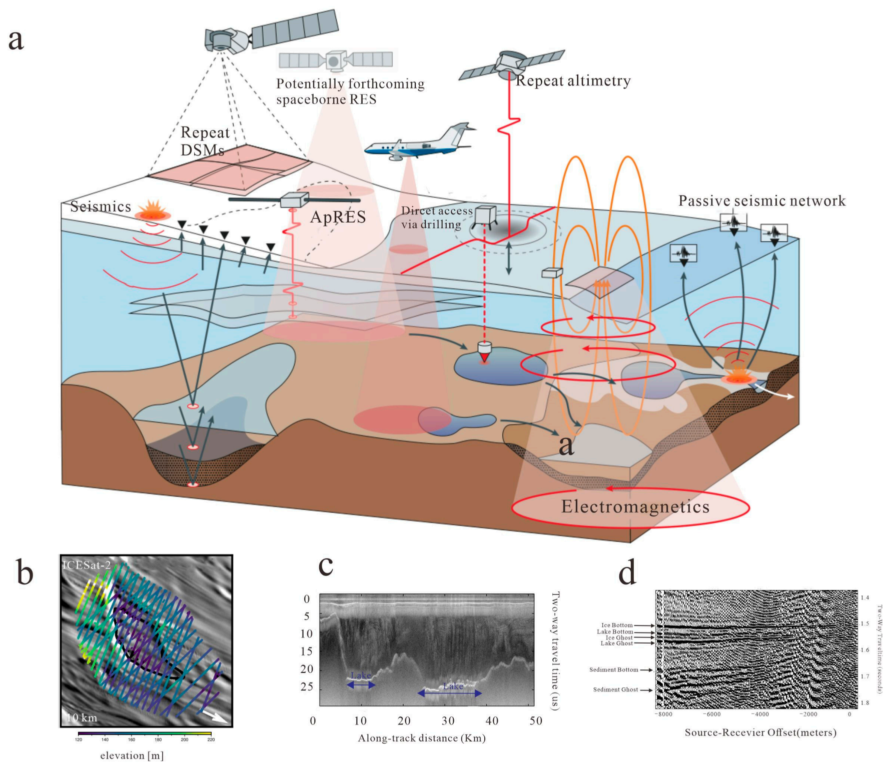

Figure 8. (**a**) Main geophysical methods for detecting subglacial hydrology [206]; (**b**) ICESat-2 altimetry coverage of active subglacial lakes in Antarctica [213]; (**c**) Radargrams of the Antarctic subglacial hydrological environment [214]; (**d**) The subglacial lake was imaged using seismic data [215].

Geophysical studies have greatly expanded our scientific understanding of subglacial hydrology. The first detection of Antarctic subglacial lakes using RES was achieved in the late 1960s [216]. In the 1970s, Oswald et al. analyzed RES data drawn from the "SPRI-NSF-TUD" database to find the largest subglacial lake ever discovered, Lake Vostok in Antarctica [217]. Subsequently, RES was widely applied in subglacial lake exploration in Antarctica. High-precision ERS-1 satellite radar altimetry data from 1997 to 1999 highlighted a drop in elevation of more than 2 m in the East Central Antarctic ice sheet, a change that was well above instrumental errors, representing evidence of a subglacial lake outburst [201]. This finding shed light on the highly active underlying hydrology of Antarctica and suggests that some subglacial lakes are not completely isolated. Continuous observations of ice surface changes made by the CryoSat [218] and ICESat/IceBridge projects [200] enable effective data capture, which was targeted to predict subglacial lakes and flow paths [219] and can be calibrated via the in situ measurement of these inferred lakes [220,221]. With the increasingly abundant satellite and RES data, the number, location, size, and depth of the Antarctic ice lake are constantly being corrected and updated [222]. Up until 2022, a total of 675 lakes have been discovered under the Antarctic ice sheet by utilizing airborne ice-penetrating radar and satellite altimetry [206] (Figure 9). Active seismic surveys, conducted in conjunction with radar surveys [223,224], can confirm the presence of liquid water beneath the ice and can be used to characterize the lake floor properties (i.e., hard bedrock, sediment, and till porosity) [215,225]. After conducting a thorough seismic field investigation of the lake near South Pole Station, it has been determined that the lake contains a sediment floor and reaches a maximum water depth of 32 m [215]. The "Vibroseis" technique employs snow flow receivers [226] to quantify the permeability, porosity, and groundwater content of rock formations within sedimentary basins at a high resolution [227,228]. Airborne electromagnetic techniques have also been used to image shallow groundwater areas that are 100 to 200 m below some of the thin glaciers and permafrost found in the McMurdo Dry Valleys. However, these techniques can only penetrate about 350 m of ice [229–231].

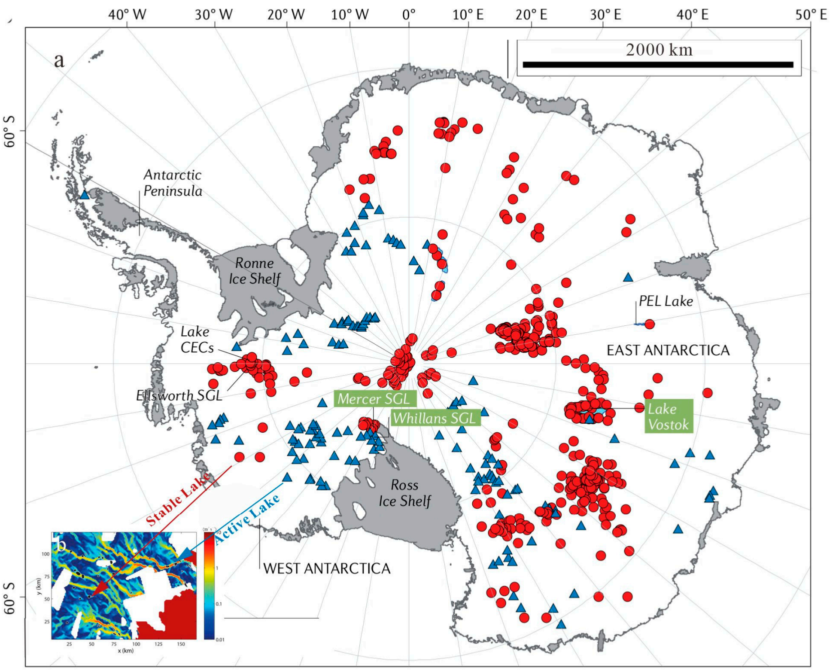

Figure 9. (**a**) Antarctic Inventory of subglacial lakes, Red circles represent stable lakes and blue triangles represent active lakes [206]; (**b**) subglacial water system of the Siple Coast in West Antarctica Major water-flow pathways connect subglacial lakes (in black) within a large-scale distributed system of subglacial till layers and linked cavities [107].

3.4. Theme Evolution in Antarctic Geophysical Research

An analysis of keyword bursts can identify the frontiers and hotspots of the different research periods seen during the evolution of Antarctic geophysical research, thereby revealing changes in the popularity of certain research directions. Statistical measurement functions available from the CiteSpace software were employed to create keyword intensity maps [232]. Table 1 shows 24 mutated keywords in the frontier region of Antarctic geophysics. The citation bursts represent the intensity of the sudden change calculated by CiteSpace. The year variable shows the duration of the mutation. The rise in research hotspots will lead to a burst of keywords occurring within a short time, where the mutation intensity is much greater than that for the common keywords. However, the number of articles published in the period from 1983 to 1990 was very small, with only 3–5 publications. The articles at this stage in the literature are insufficient in number to obtain keywords for strong mutations and clear research hotspots. Thus, the selection from the literature for the period 1991–2022 is not only representative but also provides valuable insights into the theme evolution found in Antarctic geophysical research. Between 1991 and 2022, there have been different studies at the edges of each period, with different focuses. These can be divided into three main phases.

Table 1. The top 24 keywords with the strongest citation bursts, from 1991 to 2022.

Rank	Keywords	Citation Bursts	Year
1	Margin	10.51	1991–2007
	Antarctic Peninsula	8.35	1991–2007
	Anomaly	5.17	1993–2017
	Marine sediments	5.31	1993–2002
	Weddell Sea	7.20	1994–2007
	Gondwanaland	5.06	1994–2002
	Reconstruction	4.97	1994–2007
	Plate	7.96	1994–2012
	Boundary	9.55	1995–2007
2	Seismic waves	6.31	1995–2007
	Magnetic anomalies	5.94	1996–2002
	Fracture zone	7.31	1998–2012
	Magmatism	6.17	1999–2012
	Plate tectonics	4.95	1999–2007
	Magnetic field	6.88	2003–2012
	Crustal	5.27	2003–2012
	Prydz Bay	5.18	2003–2012
3	Pacific margin	6.53	2008–2017
	West Antarctica	7.95	2009–2017
	Pine Island Glacier	5.75	2013–2022
	Ice shelves	5.14	2015–2022
	Amundsen Sea Embayment	6.44	2018–2022
	Antarctic glaciology	5.30	2018–2022
	Rayleigh wave	5.57	2019–2022

In 1990–1995, the keywords that appeared include “Margin”, “Antarctic Peninsula”, “Anomaly”, “Marine sediments”, “Weddell Sea”, “Gondwanaland”, “Reconstruction”, “Plate”, “Boundary”, and “Seismic waves”. This shows that the short-term popular areas for Antarctic scientific research were mainly concentrated in the areas of “Antarctic Peninsula”, “Weddell Sea”, “Marine”, etc. The reconstruction of Gondwana and plate tectonics are also popular research topics. “Margin” is the keyword with the greatest abrupt intensity of 10.51, indicating that geophysical research interest in the Antarctic continental margins and paleocontinental margins was high from 1991 until 2007. In addition to keywords about the object of study, there are also keywords regarding various geophysical detection techniques, such as "Seismic waves", indicating an increasing interest in seismic surveys in the period from 1999 to 2007.

In 1996–2005, the most popular keywords that appeared include "Magnetic anomalies", "Fracture zone", "Magmatism", "Plate tectonics", "Magnetic field", "Crustal", and "Prydz Bay". The keywords "Fracture zone" and "Magmatism" present high intensity and long duration in the literature from 1998 to 2012, indicating that Antarctic geophysical studies focused on rift tectonics and magmatism during this period. The bursting of "Crustal" indicates the increasing interest of scientists in the study of deep structures, such as the Antarctic mantle and the crust. The keyword "Magnetic field" was highlighted in this period, which lasted from 2003 to 2011, indicating that the magnetic method became a popular research direction in Antarctic geophysics at this time.

In 2006–2022, the most significant keywords that appear include "Pacific margin", "West Antarctica", "Pine Island Glacier", "Ice shelves", "Amundsen Sea Embayment", "Antarctic glaciology", and "Rayleigh wave". The keyword "West Antarctica" had the highest burst intensity of 7.95 and lasted from 2009 to 2017, indicating a strong focus on West Antarctica during this period. The abrupt mutation of "Pine Island glacier" also verifies this phenomenon. These keywords relate to recent research frontiers in Antarctic geophysics, such as the ice sheet mass balance, the Pacific margin, etc.

4. Conclusions

Since the early 1970s, it has been recognized that the field of geophysics has significant implications for Antarctic science. Therefore, a vast amount of research has been published on this topic. The main purpose of this paper was to provide a bibliometrics analysis of this vast body of literature using text-mining techniques and science mapping tools. The current study complements previously published reviews by mapping the existing science and providing a performance analysis. In addition, the overall conceptual evolution of the field is also explored. The specific conclusions are as follows.

(1) Regarding the publication trends, Antarctic geophysical research has consistently increased in terms of the number of papers that are published per year, suggesting a rise in global scientific interest in the subject. The trends can also be divided into three stages of development, based on the number of articles, the focuses of research directions, and major events (the IPY, etc.).

(2) Among the 82 participating countries/regions, the substantial investment and well-developed infrastructure developed by the United States, Germany, and the United Kingdom in Antarctica is a further indication of their leadership in Antarctic geophysical research. In terms of international cooperation, SCAR is a major international Antarctic research coordination body. It advocated for and led the development of the ICECAP, INSTANT, and RINGS programs, driving forward our understanding of Antarctica's role in the global environment. Research collaboration among the top 15 countries was quite frequent. ADMAP, OIB, AGAP, and other projects have contributed to the development and thematic evolution of geophysics.

(3) The science map reveals six popular research areas through a network analysis of keyword co-occurrences. By illustrating these six popular areas of research, we found that the wider use of satellite remote sensing to investigate sea ice, ice sheets, and subglacial lakes has greatly improved the identification and characterization of cryospheric features. Airborne geophysical methods are the most useful geophysical tools for identifying large-scale paleocontinental reconstructions, magma, and volcanism. Seismic and electromagnetic applications have played a crucial role in studying the subsurface structure and the evolution of the Antarctic ice sheet. Furthermore, radar surveys of the ice sheet, englacial, and basal environments have become increasingly important for evaluating the impact of climate change on Antarctica. In particular, ice radar techniques play a key role in identifying subglacial lakes.

(4) Evolutionary trends in Antarctic geophysical research can be obtained by an examination of the abrupt changes in keywords. It can be seen that the research area

gradually shifts from the Antarctic continental margin to the deep interior of the continent. This phenomenon is also inseparable from the progress of technology. In addition, because of global warming and rising sea levels, the mass balance of the Antarctic ice cap has become a hot topic among scientists in many fields. As research in Antarctic geophysics continues to evolve, it will be essential to integrate the latest technologies to further our understanding of this critical region.

Overall, Antarctica is a unique geographic focus for scientific endeavors, with a community of scientists from a variety of countries. The study of Antarctic geophysics is dedicated to advancing our understanding of the Antarctic continent and its ice sheet. The bibliometric study presented in this article used an essential research instrument to obtain a global perspective on developments and trends in the field of Antarctic geophysics research. This study will help researchers to realize the current state of Antarctic geophysics and provide promising directions for future research.

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