Antarctic Science 36(5), 379–397 (2024) doi:10.1017/S0954102024000324

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A bibliometric analysis of research on the variability of precipitation over the Antarctic Peninsula

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Abstract: Regional warming rates experienced in the Antarctic Peninsula since the mid-twentieth century, linked to global climate change, have been amongst the world's fastest. The majority of studies of change in this region have focused on temperature, and while precipitation is also predicted to change (both in form and quantity) in the models, fewer studies have set out to document and test this prediction. In this study, we examined trends in research publications on precipitation variability over the Antarctic Peninsula from 1990 to 2023 using the Web of Science Core Collection database. A total of 86 relevant papers were retained and used to identify patterns in scientific outputs. *VOSviewer* and *Bibliometrix* software packages were used to illustrate the subject content of and trends in publications retrieved by key word analysis. Our findings revealed a positive trend in the number of papers published by year. Within the analysed period, research on precipitation variability in the Antarctic Peninsula region was initiated by a study of Turner and colleagues from 1997. The UK and US research communities were the two largest contributors to this field of Antarctic research globally, with their researchers also holding strong positions within international collaborative networks.

Received 21 February 2024, accepted 16 August 2024

Key words: *Bibliometrix*, precipitation variability, rainfall, snowfall, *VOSviewer*

Introduction

The Antarctic Peninsula (AP) is one of the most intriguing and extreme regions on Earth. It is the northernmost part of Antarctica, and it stretches more than 1300 km into the Southern Ocean, in the direction of the southern tip of South America (Ducklow *et al.* 2013, Silva *et al.* 2020, Xu *et al.* 2021). This region is both scientifically valuable and unmatched in its beauty. With its massive ice shelves and high mountains, the AP provides an insight into the intricate dynamics of the polar regions of our planet.

The AP hosts crucial ecosystems, supporting a broad range of marine vertebrates such as penguins, whales, seals and seabirds, as well as Antarctic krill and complex and diverse benthic communities (Trathan *et al.* 2022, Kawaguchi *et al.* 2024). Its nutrient-rich waters maintain marine life and support global fisheries, contributing to the delicate balance of the Southern Ocean environment (Bestley *et al.* 2020). The region's glaciers and ice shelves are critical markers of climate change, with rapid ice melt and glacier retreat providing significant insights into the effects of global warming (Cook *et al.* 2016). Understanding the dynamics of the AP is therefore critical for understanding larger environmental processes and managing their consequences.

Apart from its environmental importance, the AP also provides exceptional opportunities for scientific research in various fields, including ecology, biodiversity, climatology, glaciology and terrestrial and marine biology. Its distinct environment provides researchers with significant insights into Earth's climatic history, contributing to the reconstruction of historical climates and forecasting of future trends (Cook *et al.* 2016, Tewari *et al.* 2022). Furthermore, the AP's remote location and extreme climatic conditions make it an ideal environment for researching adaptation mechanisms in diverse organisms such as animals, plants and microorganisms, with applications in fields such as medicine and biotechnology (Clarke *et al.* 2007, Fountain *et al.* 2014, Peck 2018).

The role that the AP plays in global climate and ocean systems is often underappreciated. The ice sheets and

https://doi.org/10.1017/S0954102024000324 Published online by Cambridge University Press

seasonal sea ice formed on the surface of the surrounding Southern Ocean are integral parts of Earth's cooling system, reflecting solar radiation away from Earth's surface and helping stabilize the global climate, allowing temperatures to remain within a range that is suitable for most life (Khare 2022). In the absence of this ice, the planet would absorb more solar radiation, increasing atmospheric temperatures, as has happened in past geological epochs. Studies have highlighted teleconnections between the climate of Antarctica and lower-latitude regions as far as the tropics (Schneider *et al.* 2012, Purich & England 2019, Lee & Jin, 2021, Li *et al.* 2021).

The ice shelves also operate as ocean buffers, limiting ice flow from the continent into the surrounding ocean and thereby moderating Antarctic contributions to rising sea levels (Smith *et al.* 2020). The Antarctic Circumpolar Current (ACC), which circulates the Antarctic continent in a clockwise (west to east) direction, is the largest and most powerful of Earth's ocean currents, driving the circulation system of all of the oceans (Koenitz *et al.* 2008, Thompson 2008). The ACC underpins water exchange throughout the global oceans, as well as having a significant impact on regional and global climates (Barker *et al.* 2007, Thompson 2008, Rintoul *et al.* 2010).

However, the AP cannot escape the effects of human activities despite its pristine environment and remoteness. The AP is increasingly at risk from anthropogenic stressors including climate change, pollution, national research operations and tourism, which are impacting the physical environment and its ecosystems and biodiversity (Convey & Peck 2019, McCarthy *et al.* 2019, Siegert *et al.* 2019, 2023, Chown *et al.* 2022). Increased greenhouse gas and chlorofluorocarbon emissions since the Industrial Revolution and particularly since the mid-twentieth century have altered its climate system (Convey *et al.* 2009, Turner *et al.* 2009). As a result, the AP has been recognized as one of the world's fastest-warming regions between the 1950s and early 2000s, with regional warming of up to 0.56°C per decade (Bromwich *et al.* 2013).

The dramatic changes in climate experienced over the AP during the last century have had severe impacts including temperature increases, glacial retreat and changes to precipitation patterns. Regional warming also significantly increases annual mean precipitation as a result of the increasing capacity of air to hold water vapour with these rising temperatures (Frieler *et al.* 2011, Salzmann 2016). These variations in temperature and precipitation over the AP can significantly change oceanographic conditions and sea-ice extent. In fact, Antarctic sea ice has been anomalously low for 3 consecutive years, with 2023 breaking the record for having the lowest sea-ice summer (Liu *et al.* 2023). Such changes can severely affect the functioning and services of ecosystems through direct impacts on the biotic populations inhabiting this region.

Key effects of climate change on the AP are as follows:

1) Regional warming: the AP has experienced dramatic warming over the last few decades, with temperatures rising by ~2.5°C since the 1950s, as confirmed by numerous scientific studies (Vaughan *et al.* 2003, Turner *et al.* 2005, 2009, Bozkurt *et al.* 2021). This warming trend exceeds the global average, having far-reaching consequences for the region's climate system.
2) Sea-ice decline: while sea-ice extent in Antarctica has fluctuated, the AP has seen a decrease in sea-ice cover, notably during the summer months (Turner *et al.* 2015, 2020). Reduced sea ice impacts marine ecosystems, especially krill abundance, which are important components of the Southern Ocean food web (Murphy *et al.* 2007, Stammerjohn *et al.* 2008). The changing sea-ice dynamics will also greatly affect the availability of terrestrial breeding and moulting habitats for marine vertebrates such as penguins and seals.
3) Retreat of glaciers and ice shelves: regional warming and ocean forcing in the AP are resulting in increased thinning and retreat of glaciers and ice shelves (Cook *et al.* 2016). Rising air and sea temperatures enhance the melting and collapse of ice shelves, such as that of the Larsen B Ice Shelf in 2002 (Glasser & Scambos 2008), and glacial retreat, particularly in the northern and western parts of the AP (Davies *et al.* 2012, Cook *et al.* 2016). Loss of land-based ice contributes to rising sea levels, and there are also implications for ocean circulation (DeConto & Pollard 2016).
4) Southern Ocean acidification: as atmospheric carbon dioxide levels increase, acidification of the Southern Ocean will occur, and this scenario poses dangers to some Antarctic marine organisms (Hancock *et al.* 2020), particularly krill, phytoplankton and calcifying organisms (Kawaguchi *et al.* 2011, Trimborn *et al.* 2017, Figuerola *et al.* 2021).
5) Ecosystem shifts: climate change experienced in the AP region impacts both marine and terrestrial ecosystems, directly impacting habitat availability and species distributions. Cimino *et al.* (2016) concluded that approximately one-third of existing Adélie penguin colonies may decline by the year 2060. Such changes can impact the breeding success and survival rates of these organisms (Saraux *et al.* 2011). Ocean warming and sea-level rise endanger the fragile equilibrium of Antarctic ecosystems, with significant consequences across the food web (Ducklow *et al.* 2007).

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6) Variability of precipitation: weather systems over the AP are also affected by climate change, including changes to precipitation regime. Numerous studies have reported variability in precipitation events over the AP, with most studies reporting or predicting an increasing trend under future climate change projections (Carrasco & Cordero 2020, Bozkurt *et al.* 2021, Vignon *et al.* 2021). Precipitation variability influences ecosystems, populations, sea-ice dynamics and glaciological processes.

Studies on climate variability over the AP have been prominent owing to the strong regional warming conditions that have affected this region. However, the same cannot be said about variability of precipitation in this region. We hypothesize that the number of publications relating to the AP is increasing owing to the fact that Antarctic climate change has gained considerable attention in recent years. Therefore, this study aims to investigate the trends in research on the variability of precipitation over the AP based on the outcomes of a bibliometric analysis.

Materials and methods

Bibliometric analysis

An accepted and widely used approach for exploring and interpreting extremely large amounts of scientific data is bibliometric analysis (Donthu *et al.* 2021). This approach is used for a variety of reasons, including identifying developing trends in article and journal performance, collaboration patterns and research elements, as well as investigating the intellectual structure of a particular discipline or research area in the available literature (Ellegaard & Wallin 2015, Verma & Gustafsson 2020). The data at the centre of bibliometric analysis are typically massive (hundreds if not many thousands of individual items) and objective in nature (e.g. numbers of citations and publications, occurrences of key words and topics), but its interpretation frequently relies on both objective (e.g. performance analysis) and subjective (e.g. thematic analysis) evaluations established through informed techniques and procedures.

Bibliometric analysis can help decode and map the cumulative scientific knowledge and evolutionary developments in well-established domains by rigorously interpreting vast amounts of unstructured data. As a result, well-conducted bibliometric studies can lay solid foundations for advancing a field in novel and meaningful ways – it enables and empowers scholars and researchers to 1) gain a one-stop overview, 2) identify knowledge gaps, 3) develop novel ideas for investigation and 4) position their intended contributions to the field.

In this study, bibliometric analysis was conducted to identify research and conclusions relating to trends in precipitation patterns over the AP region. Scientific output data were extracted from the Web of Science Core Collection (WoSCC), one of the most widely used, daily updated databases in academic and bibliometric studies, allowing the download of full citation records. WoSCC is considered to be the largest abstract and citation databases of peer-reviewed scientific articles, books and conference proceedings, covering a wide range of disciplines across the natural sciences, technology, social sciences, medicine and humanities. Using such a well-established database is important to limit the risk of overlooking significant documents in the field search.

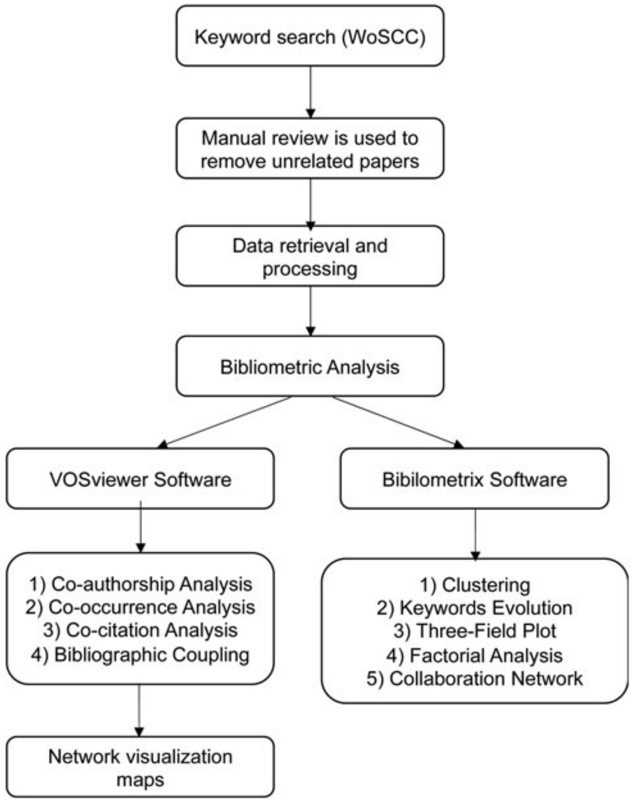

Figure 1. Research design for bibliometric analysis. WoSCC = Web of Science Core Collection.

Data collection

Literature was retrieved from the WoSCC on 19 January 2024. To ensure the completeness of the literature on precipitation variability over the AP, the search query was widened to include phrases with comparable meanings to 'precipitation' and 'variability'. Hence, the terms used for the search strategy for the data were topic (TS) = (('Antarctic Peninsula') AND ('precipitation' OR 'rainfall' OR 'snowfall') AND ('increas*' OR 'decreas*' OR 'change*' OR 'pattern' OR 'trend' OR 'variability')). The time period was set to 1990–2023 and the language was restricted to English only. The databases used were the Science Citation Index Expanded (SCI-E) and the Social

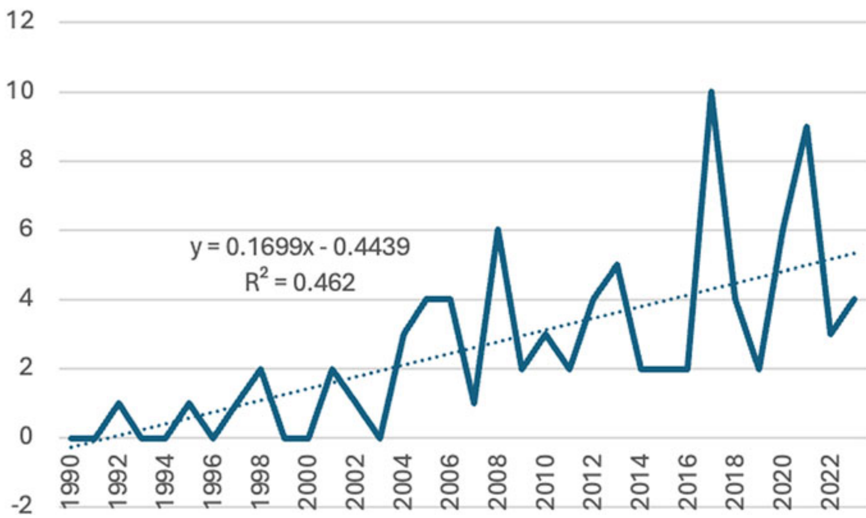

Figure 2. Trends and numbers of published articles retrieved from the Web of Science Core Collection database in the period 1990–2023, by year of publication.

Sciences Citation Index (SSCI). To compare the annual production of papers relating to climate variability and precipitation variability over the AP, a further key word search was performed where the terms TS = ('precipitation' OR 'rainfall' OR 'snowfall') were replaced with TS = ('warming' OR 'climat*' OR 'temperature').

A total of 261 records containing articles, proceedings papers and reviews were initially acquired. Further inspection of this publication set revealed that it included many non-relevant publications. The following are some contributing factors identified:

- Most publications discuss the impacts of the Antarctic Oscillation (AAO) on precipitation of other regions beyond the AP (or Antarctica).
- Some publications discussed climatology and climatic conditions of the AP but only mentioned variability of precipitation casually.
- Isoelectric solubilization/precipitation is discussed as a technique used to extract Antarctic krill protein isolates.
- Some publications deal with energetic electron precipitation.
- Some studies investigate the isotopic composition of the precipitation and do not discuss the variability of precipitation.
- Some were geological and hydrological studies of snowpacks, glaciers and ice-mass balance, which may be influenced by precipitation, but these studies did not discuss the variability in precipitation.
- Some studies deal with snow accumulation and not snowfall variability.

Further refinement of the search query was not promising, as the search query we used was complete, and so further limiting the search options could lead to the exclusion of relevant papers from the literature database. Therefore, the only option was to manually select the papers dealing primarily with variability in precipitation over the AP. We manually selected 86 papers that were relevant to our topic of interest. The consideration of only these 86 papers for bibliometric analysis ensures a high degree of consistency and accuracy.

The data were obtained and exported as a bibliographic flat-file database file (BibTex) using tab-delimited file formats, with full records and cited sources. All data were exported on 19 January 2024 to avoid deviations arising from the daily updates of this database.

Data analysis tools

The data were then analysed using bibliometric mapping techniques, which are quantitative approaches to visually representing scientific information using bibliographic data. The analysis of precipitation data was conducted using *VOSviewer* (Visualization of Similarities; https://doi.org/10.1007/s11192-009-0146-3) and *Bibliometrix* software. The bibliometric analysis conducted here focused on studies of precipitation over the AP and its trends of change. The assessments covered the annual production of scientific publications in this field, the most productive countries and their collaborators, key word occurrences and research development by theme.

This mapping technique is particularly beneficial for displaying large bibliometric maps in an accessible manner, as well as for creating and exploring maps based on bibliometric network data. The output results are displayed in clusters to help visualize the links between the studied data. The software creates distance-based maps in which the distance between two elements represents the strength of their relationship, with a greater distance indicating a stronger association. Figure 1 depicts the research strategy for bibliometric analysis using both software packages. Bibliometric network analysis using *VOSviewer* comprises co-authorship, co-occurrence, co-citation and bibliographic coupling.

Bibliometrix was used for clustering, key word evolution, three-field plots, factorial analysis and collaboration networking.

Results and discussion

Trends in scientific publication

A total of 86 papers relating to precipitation variability studies were identified from the WoSCC database in the period 1990–2023 (Fig. 2), with an overall positive trend of papers being published each year, suggesting greater research interest over time into AP precipitation variability in concert with recent climatic changes in this region. However, the trend observed only increases moderately ($R = 0.68$), indicating that publication in this field is still not vigorous. A large majority of the papers identified ($n = 82$; 95.3%) were research articles, indicating that this is the primary approach for scientific communication in this field. In addition, proceedings papers ($n = 3$) and review articles ($n = 1$) contributed only a small proportion to the overall number of publications, accounting for 3.5% and 1.2%, respectively.

Papers published earlier than 1999 focused more on precipitation changes over specific regions within the AP. However, one article in particular stood out among these papers, and we believe this is the paper that initiated research relating to precipitation variability over the AP. Turner *et al.*'s (1997) study investigated the spatial and temporal variability of precipitation along the western coastal side of AP using synoptic data from Faraday and Rothera weather stations. To date, this paper has been cited 109 times, of which 17 were among the 86 relevant papers identified in the present study. From 2004 onwards, paper production has accelerated, suggesting developing concern and continued interest from the scientific community.

The initial search identified 2201 papers on climate variability studies over the AP from the WoSCC database in the period 1990–2023. Of the 86 relevant papers identified relating to precipitation variability over the AP, 62 (72.1%) were also present in this pool of papers relating to climate variability over the AP. This shows that most papers on AP precipitation variability are closely related to studies on the climate variability in this region. In addition, all of the 86 identified papers cited at least one of the 2201 papers on climate variability over the AP. The earliest paper on climate variability over the AP was published in 1976, whereas the first paper on precipitation variability was published nearly 2 decades later in 1992.

The Coupled Model Intercomparison Project Phase 1 (CMIP1) was formally initiated in 1995 (Meehl *et al.* 2000). Meanwhile, the first generation of the European Centre for Medium-Range Weather Forecasts Re-Analysis (ERA15) dataset was introduced in 1991 (Uppala *et al.* 2005). Studies that employed climate modelling and the use of re-analysis datasets for precipitation variability over the AP started in 1998 (Turner *et al.* 1998). This combination of factors could be a contributor to the spike in the number of papers produced in 1998 ($n = 9$), which is triple the average number of papers produced within the first decade of the current study (1990–1999). The first two papers that we identified amongst the relevant papers to use the ERA15 re-analysis dataset were both contributed by Turner and colleagues in 2 consecutive years (Turner *et al.* 1998, 1999).

Table I. Top 12 research areas of the 86 identified published papers relating to precipitation changes over the Antarctic Peninsula over the time period 1990–2023 (minimum number of papers is 2).

No.	Subject category	Papers	%
1	Meteorology & Atmospheric Sciences	33	38.4
2	Geosciences	32	37.2
3	Physical Geography	11	12.8
4	Oceanography	10	11.6
5	Ecology	9	10.5
6	Environmental Sciences	8	9.3
7	Multidisciplinary Sciences	4	4.7
8	Biology	3	3.5
9	Geochemistry & Geophysics	3	3.5
10	Biodiversity Conservation	2	2.3
11	Geology	2	2.3
12	Plant Sciences	2	2.3

After 2005, the number of papers published per year slowly increased. One contributing factor to this trend is likely the introduction of ERA40, which is an updated version of the previously mentioned re-analysis dataset that extended coverage from 1957 to 2002. The reports of Turner *et al.* (2005), Van de Berg *et al.* (2006) and Marshall (2009) are all studies that used the ERA40 dataset. The latest version of the Coupled Model Intercomparison Project (CMIP) is CMIP6, which contributed to two papers published in 2023 (Zhu *et al.* 2023a, 2023b).

Of the 86 papers relating to precipitation variability over the AP, 37 used climate model simulations, 25 used re-analysis data, 4 used remote sensing and only 3 used surface observations. This suggests that climate models and re-analysis data are amongst the popular methods for studying precipitation variability, as is the case with other meteorological and atmospheric science phenomena over the AP (e.g. climate variability, regional warming and snow accumulation).

In terms of location, most of the studies represented the western AP (40 out of 86 papers), while 34 papers mentioned the eastern AP. Only nine studies mentioned 'Maritime Antarctica'. This may be due to the western AP having more weather stations (e.g. Rothera Station, Palmer Station, González Videla Station and Vernadsky Station) compared to the eastern AP.

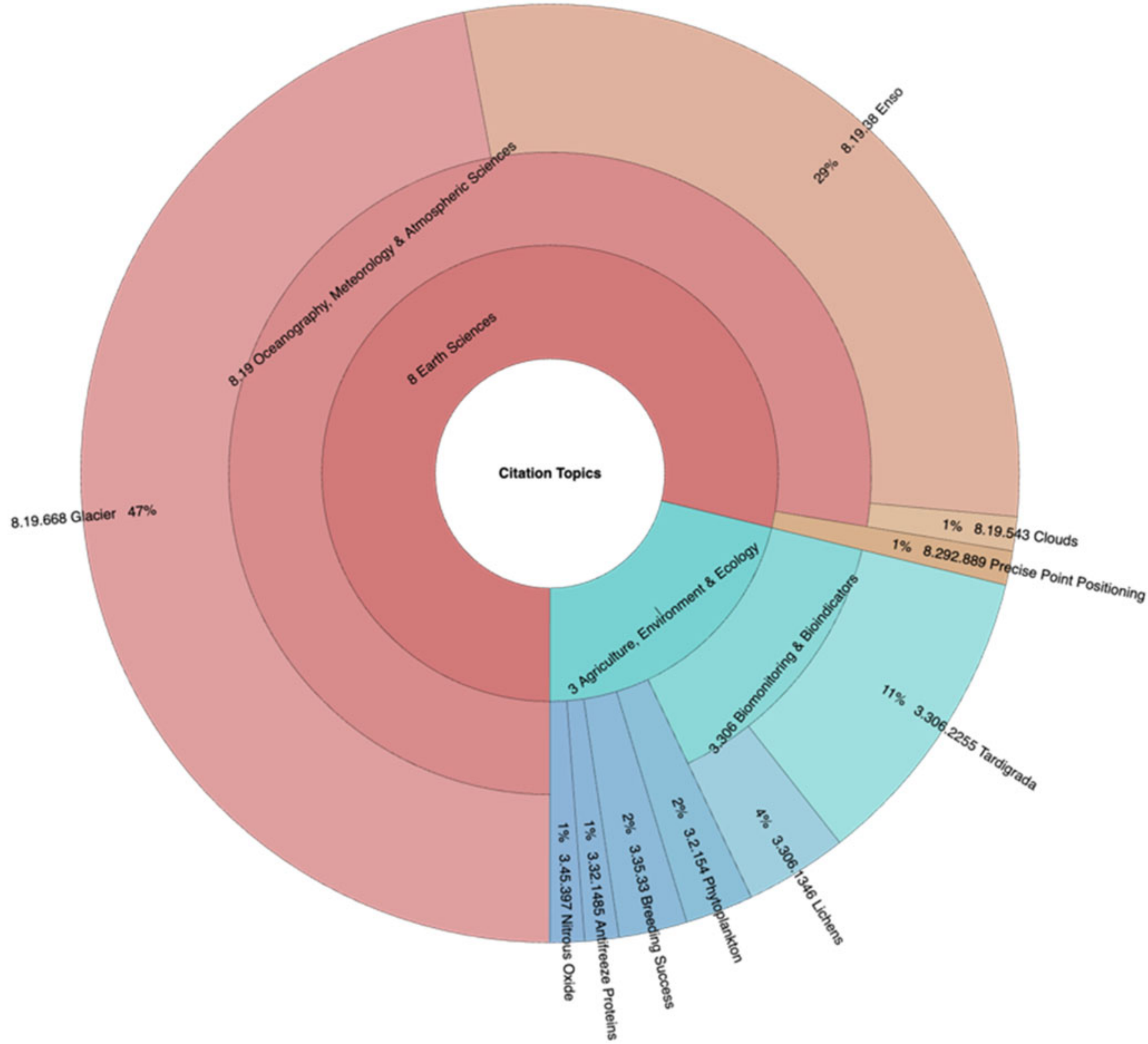

Figure 3. Citation topics for the 86 papers on precipitation variability over the Antarctic Peninsula, as assigned by the InCites algorithm.

Subject categories and citation topics

The papers on precipitation variability over the AP focus on 23 research areas, with only 4 of these research areas having at least 10 papers devoted to them. Table I summarizes the 12 most popular research areas. The majority of the papers were in the 'Meteorology & Atmospheric Science' and 'Geosciences' categories, accounting for 38.4% and 37.2% of the total publications, respectively. This is unsurprising as precipitation studies are primarily associated with climatology and atmospheric sciences. In polar regions, precipitation variations are frequently associated with glacial retreat and ice-sheet changes (Boening *et al.* 2012, Steig *et al.* 2013, Pattyn & Morlighem 2020), representing the 'Geosciences' area of interest.

'Physical Geography', 'Oceanography', 'Ecology' and 'Environmental Sciences' (accounting for 12.8%, 11.6%, 10.5% and 9.3% of papers identified, respectively) contributed a lower proportion of the papers published but emphasize the interests of physical scientists, marine scientists and biologists in investigating the relationship between Antarctic precipitation patterns of the environment, local ecosystems and the Southern Ocean. Studies in these categories have identified that precipitation variability has a significant impact on freshwater budgets, biogeochemical processes, glaciers, ice

https://doi.org/10.1017/S0954102024000324 Published online by Cambridge University Press

sheets and the responses of organisms (Zwally *et al.* 2005, Convey & Smith 2006, Meredith *et al.* 2021).

The papers were also accurately assigned into citation topics as macro-topics ($n = 2$), meso-topics ($n = 7$) and micro-topics ($n = 10$). Citation topics are citation groupings generated using an algorithm developed by CWTS (Leiden). The citation topics, as assigned by the InCites algorithm, are illustrated in Fig. 3. The two macro-topics identified were 'Earth Sciences' ($n = 67$ papers) and 'Agriculture, Environment & Ecology' ($n = 18$), accounting for 77.9% and 20.9% of papers identified, respectively. The majority of the papers ($n = 40$) were on 'Glaciers', particularly discussing the effects of precipitation variability on Antarctic glaciers (i.e. glacial retreat). Approximately one-third of the papers on precipitation variability over the AP belonged to the citation topic 'Enso' ($n = 25$ papers). 'Enso' here refers to the El Niño-Southern Oscillation (ENSO) climate phenomenon, which comprises two opposing El Niño and La Niña phases that represent periods of warming and cooling (Timmermann *et al.* 2018). ENSO influences atmospheric circulation patterns and significantly impacts precipitation variability over the AP region.

Amongst the biology papers, only one micro-topic stood out: 'Tardigrada' ($n = 9$ papers; 10.4%). Tardigrades (also known as water bears or moss piglets) are micro-fauna that are both water-dwelling and found in terrestrial environments associated with lichens and bryophytes (Andersson 2017, Glime 2017). These micro-fauna are amongst the most important and diverse types of invertebrates in Antarctic terrestrial ecosystems (Tsujimoto *et al.* 2015). Cannone *et al.* (2013) and Amesbury *et al.* (2017) both suggested that some bryophyte populations in the AP region may decline under rapid warming and possibly under variable precipitation patterns. Any such decline in bryophyte populations can endanger the survival and reproductive success of tardigrades and other associated invertebrates as well as disrupt their function in Antarctic ecosystems.

While precipitation variability studies were originally a strictly climatological topic, they have expanded to include a variety of topics as the drivers and impacts of precipitation changes have become more prevalent and apparent. However, the bulk of the papers on precipitation variability over the AP are still skewed towards the physical sciences. More extensive research relating to the biological aspects of precipitation variability over the AP is required to improve our understanding of the responses of organisms to such changes.

The InCites algorithm can also sort publications by their relevant Sustainable Development Goals (SDGs). The 86 identified papers assigned were to four SDGs: 'Climate Action' (SDG 13), 'Life On Land' (SDG 15), 'Life Below Water' (SDG 14) and 'Zero Hunger' (SDG 2). 'Climate Action' was the most popular SDG, accounting for 82 papers and 95.3% of total publications. This suggests that the bulk of the studies discuss precipitation in the context of climate change and global warming. Next, 'Life Below Water' and 'Life On Land' contributed similar weightings of 14 and 13 papers (accounting for 16.3% and 15.1% of total papers). This illustrates the interest of biologists in researching the effects of precipitation changes over the AP on the biodiversity and ecosystems of both marine and terrestrial biota.

Table II. Top 10 journals in terms of publications relating to precipitation changes over the Antarctic Peninsula in the time period 1990–2023.

No.	Journals	Papers	%
1	*Geophysical Research Letters*	8	9.3
2	*Journal of Geophysical Research Atmosphere*	7	8.1
3	*Journal of Climate*	5	5.8
4	*The Cryosphere*	4	4.7
5	*International Journal of Climatology*	4	4.7
6	*Journal of Glaciology*	4	4.7
7	*Annals of Glaciology Series*	3	3.5
8	*Antarctic Science*	3	3.5
9	*Climate Dynamics*	3	3.5
10	*Deep Sea Research Part II Topical Studies in Oceanography*	3	3.5

Table III. Top 10 countries in terms of publications relating to precipitation changes on the Antarctica Peninsula in the time period 1990–2023.

Rank	Countries	Papers	%
1	UK	40	46.5
2	USA	24	28.0
3	The Netherlands	15	17.4
4	China	13	15.1
5	Spain	8	9.3
6	Australia	6	7.0
6	Chile	6	7.0
8	New Zealand	5	5.8
9	France	4	4.7
9	Germany	4	4.7

Dominant journals

Table II shows the top 10 publishing journals for papers relating to studies on precipitation changes over the AP. The 10 listed journals collectively contributed a total of 44 papers, accounting for 51.2% of the total papers identified. The top three publishing journals were *Geophysical Research Letters* ($n = 8$ papers), *Journal of Geophysical Research Atmospheres* ($n = 7$ papers) and *Journal of Climate* ($n = 5$ papers), consistent with precipitation being an aspect of meteorological and

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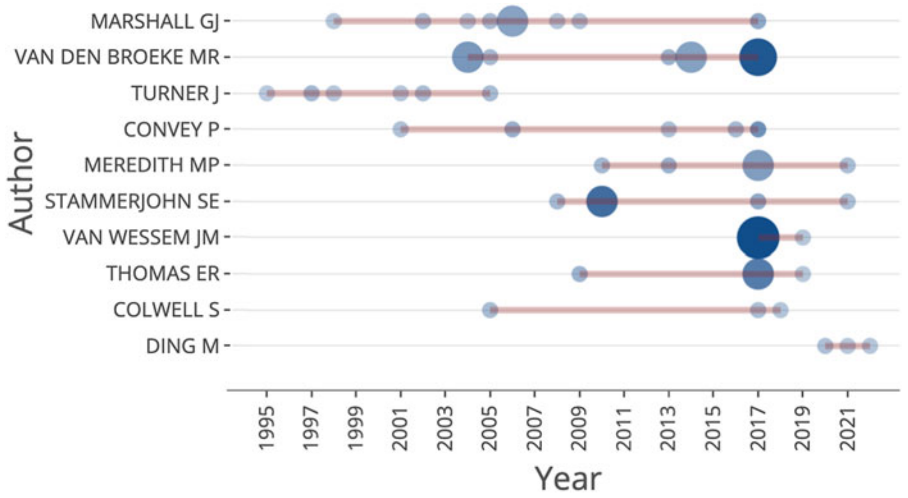

Figure 4. Top 10 authors in terms of paper production over time in this area during the period 1990–2023.

climatic science. These three journals are Q1 journals, meaning that their impact factors are in the top quartile (25%) of scientific publications. This illustrates that the authors working on research connected to Antarctic precipitation changes have a strong reputation in the field, and that studies of Antarctic precipitation changes produce similarly impactful results. Surprisingly, *Antarctic Science*, also a Q1 journal that is multidisciplinary, publishing on all aspects of scientific research in Antarctica, was not included amongst the top three publishing journals, with only three papers published in this area.

Research output by country, affiliation and author

Table III shows the top 10 countries producing papers relating to AP precipitation variability. Ranking by national output, papers originating from the UK ($n = 40$) dominated, followed by the USA ($n = 24$), the Netherlands ($n = 15$) and China ($n = 13$). The majority of the publications from the UK were contributed by the British Antarctic Survey (BAS; $n = 34$ papers) and British Geological Survey ($n = 6$). BAS emerged as the top research institute leading studies in precipitation changes over the AP. BAS is a component of the Natural Environment Research Council (NERC) and is presently the UK's primary polar research institute. BAS's research remit is primarily focused on Antarctica, and it operates two research stations in the AP (Rothera and Signy).

The substantial output of the USA can be attributed to contributions from its universities, most notably the University of Colorado ($n = 6$ papers), the University of California ($n = 5$ papers) and NASA ($n = 4$ papers). Both the University of Colorado and the University of California are public research universities operating several campuses. The contribution of NASA to precipitation variability research over the AP predominantly involved studies on snowfall and snow accumulation (Boening *et al.* 2012, Thomas *et al.* 2017). The USA operates one research station in the AP (Palmer Station).

All 15 publications from the Netherlands were contributed by researchers at Utrecht University. Papers from China were contributed primarily by the Chinese Academy of Sciences ($n = 5$ papers), the China Meteorological Administration ($n = 4$ papers) and Nanjing University ($n = 3$ papers). One possible contributory factor for the interest of the Chinese research community in studying precipitation patterns in the AP may relate to the strong teleconnections between the Chinese region and the AP (e.g. Fan & Wang 2004, Fang *et al.* 2019, Zhang & Duan 2023). Analogous teleconnections have also been identified between the Indian Ocean and Ross Sea (Swathi *et al.* 2023), the Himalayan mountains and Antarctic ice shelves (Kumar *et al.* 2015), the Atlantic and Southern oceans (Morozov *et al.* 2008) and the Pacific and Southern oceans (Mayewski *et al.* 2009). These teleconnections highlight the wide international interest in research into precipitation patterns in the AP region.

Australia and Chile ranked sixth despite these regions being relatively close to Antarctica. In addition, numerous studies have shown teleconnections between these regions and Antarctica (Rondanelli *et al.* 2019, Li *et al.* 2021, Reboita *et al.* 2021), yet it seems that precipitation variability over the AP is not a field of interest amongst Australian and Chilean researchers. The Australian Antarctic Division is dedicated to scientific research relating to Antarctica and the Southern Ocean, while Chile has its own permanent research station in the AP: Base General Bernardo O'Higgins Riquelme. There are no Dutch research stations in the AP, only a research laboratory near Rothera (which belongs to BAS). However, the Netherlands was ranked much more highly in this area compared to Australia and Chile.

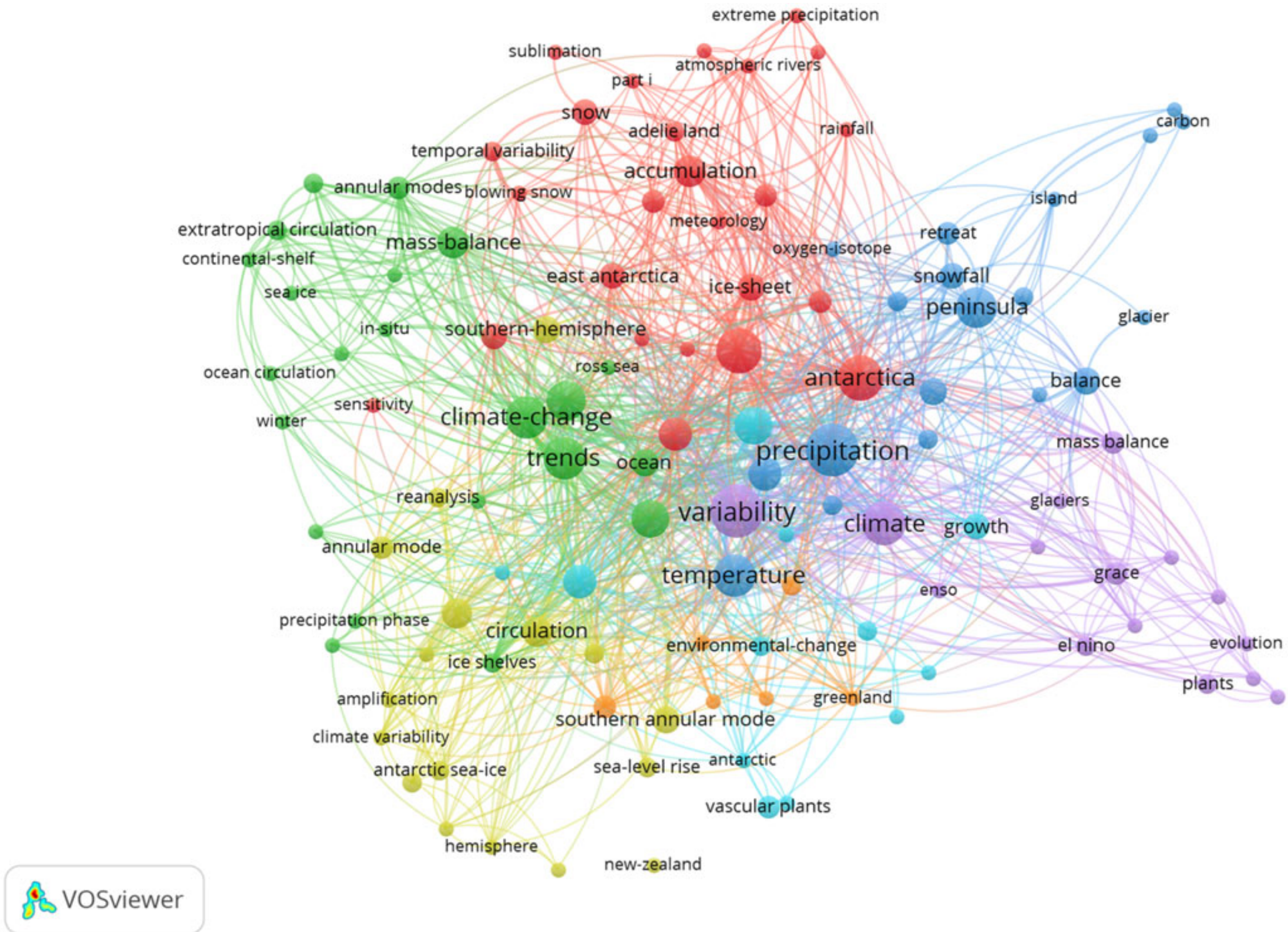

Figure 5. Co-occurrence network of key words from 86 papers on precipitation variability over the Antarctic Peninsula published in 1990–2023 (the minimum number of occurrences of a key word is two).

Figure 4 shows the 10 most productive authors in this field. The earliest researcher to study precipitation variability over the AP was J. Turner, whose 1995 and 1997 papers played an important role in initiating this research field. In the 2000s, more researchers started producing papers in this field (e.g. M.R. van den Broeke, P. Convey and S. Colwell), and towards the late 2000s, S.E. Stammerjohn, E.R. Thomas and M.P. Meredith became notable researchers in this field. Papers published by M.R. van den Broeke are amongst the most cited per year. G.J. Marshall is the longest-standing author in this field, having published for nearly 2 decades (1998–2017), hence why these papers have the greatest link strengths (LSs) in the co-citation analysis and explaining why they are seminal within the field.

Key word analysis

Co-occurrence network of key words. Figure 5 depicts a key word map constructed using the *VOSviewer* software from the 86 identified papers on precipitation changes in the AP region. *VOSviewer* found 488 key words; however, only 116 were used at least two times. The nodes in Fig. 5 represent the key words, and the links between them reflect their similarity (relatedness in terms of co-occurrence). Key words closer together (with shorter linkages) have a greater co-occurrence rate. The size of the nodes corresponds to their occurrence (number of papers that include a specific key word). Nodes in the map are organized into clusters (different colours). These clusters locate closely related key words, with each key word given to a single cluster.

Based on the co-occurrence network, there are seven clusters, indicated by different colours in Fig. 5: red, green, yellow, light blue, dark blue, purple and orange. The clusters are heterogeneous as they are loosely structured, but there is some distinction in terms of what they represent. For example, the red cluster contains key words related to Antarctica such as 'antarctica', 'west antarctica', 'east antarctica', 'surface mass balance', 'ice sheet' and 'snow accumulation'. The blue cluster has key words related to precipitation such as 'precipitation',

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Table IV. Top 10 key words relating to research on Antarctic precipitation changes (arranged in descending order of occurrence).

Rank	Key word	Occurrence	Total link strength
1	'variability'	22	164
2	'precipitation'	21	142
3	'antarctica'	16	130
4	'climate'	15	116
5	'surface mass-balance'	16	112
6	'trends'	14	98
7	'climate-change'	14	84
8	'temperature'	14	79
9	'atmospheric circulation'	9	78
10	'sea-ice'	12	74

'snowfall' and 'model'. Key words referring to specific parts of Antarctica ('peninsula' and 'south shetland islands') and glaciers ('glacier' and 'retreat') were also included in the blue cluster. This may relate to precipitation being primarily studied in the AP region, where one major impact of precipitation variability is the retreat of glaciers. The purple cluster contains key words associated with climate such as 'climate', 'variability', 'enso', 'el nino' and 'southern oscillation'. This shows that changes in climate such as the rapid warming experienced in the AP region are linked with precipitation variability. The key word 'variability' had a greater LS with 'climate' (LS = 8) compared to 'precipitation' (LS = 7), consistent with there being more studies on climate variability than on precipitation variability.

The key word 'climate-change' was assigned to the green cluster along with 'antarctic peninsula' and key words relating to sea-ice dynamics ('sea ice', 'mass balance', 'ocean' and 'ocean circulation'). This may indicate that climate change is experienced to a more significant degree in the AP compared to in other regions of Antarctica, with there being rapid warming and the greatest climate variability over the region. Climate change also has a direct influence on sea-ice dynamics and sea-level rise.

Two of our search terms, 'precipitation' and 'variability', were among the most frequently encountered key words (centre of Fig. 5). This also demonstrates that authors preferred the term 'precipitation' over 'snowfall' and 'rainfall', as well as 'variability' over 'changes', 'pattern' and 'trend'. 'Climate-change' was another frequently encountered key word, indicating that many studies of precipitation patterns are driven by links with climate change. Numerous publications have addressed how regional warming caused by climate change has a direct impact on variation in precipitation over the AP (Bozkurt *et al.* 2021, Tewari *et al.* 2022, Nicola *et al.* 2023). Although the term 'antarctic peninsula' was one of our search terms, it was less frequently encountered, despite the fact that all of the papers identified addressed precipitation variability over the AP. This is because some papers included other parts of Antarctica, explaining the appearance of terms such as 'antarctica', 'east antarctica' and 'west antarctica' in Fig. 5.

Dominant key words. Table IV shows the top 10 key words relating to papers on studies of precipitation changes over the AP. The total link strength (TLS) indicates the number of papers in which two key words occur together (Guo *et al.* 2019). The key words 'variability', 'precipitation', 'antarctica' and 'climate' had amongst the highest numbers of occurrences of 22, 21, 16 and 15, respectively (accounting for 25.6%, 24.4%, 18.6% and 17.4% of the papers identified, respectively). These are key words that are central to the field. Key words such as 'surface mass-balance' and 'sea ice' illustrate how precipitation changes relate to ice-sheet dynamics. Key words such as 'trends', 'climate-change', 'temperature' and 'atmospheric circulation' indicate that climatic factors strongly influence changes in precipitation over the AP. Key words relating to modelling and re-analysis datasets were not amongst the top 10, indicating that studies on precipitation variability using climate modelling software and re-analysis datasets such as CMIP and ERA are currently less frequently conducted.

Figure 6 shows the frequency of the top 10 key words over time. The earliest term relating to precipitation variability to emerge was 'temperature' in 2001. This suggests that most papers in the early 2000s reported the warming experienced rather than referring to climate change. Slowly, the use of the key word 'temperature' increased, but at present it still ranks lower than other key words related to the field, with studies now being more varied and focusing on ice mass balance, atmospheric circulation patterns, precipitation patterns and ecosystem responses. The key word 'climate-change' was more dominant than 'precipitation' until the early 2010s. After 2013, the frequency of 'precipitation' increased, and it currently ranks second. The frequency of the key word 'variability' increased considerably after 2011.

Thematic map of key words. Figure 7 shows the thematic map of studies related to precipitation variability over the AP. The thematic map provides insight into current themes in the field as well as the potential for future research progress in specific thematic areas. The themes are characterized by density and centrality. Density measures the development of a certain topic, while centrality measures the relevance of a certain topic. Centrality is the degree of linkage across different themes; density reflects the cohesion between the nodes (Cobo *et al.* 2018). In Fig. 7, the thematic map is divided into four quadrants (Q1, Q2, Q3 and Q4).

The upper left quadrant (Q1) refers to niche (or specific) themes, the upper right quadrant (Q2) refers to motor (or driving) themes, the lower left quadrant (Q3) refers to

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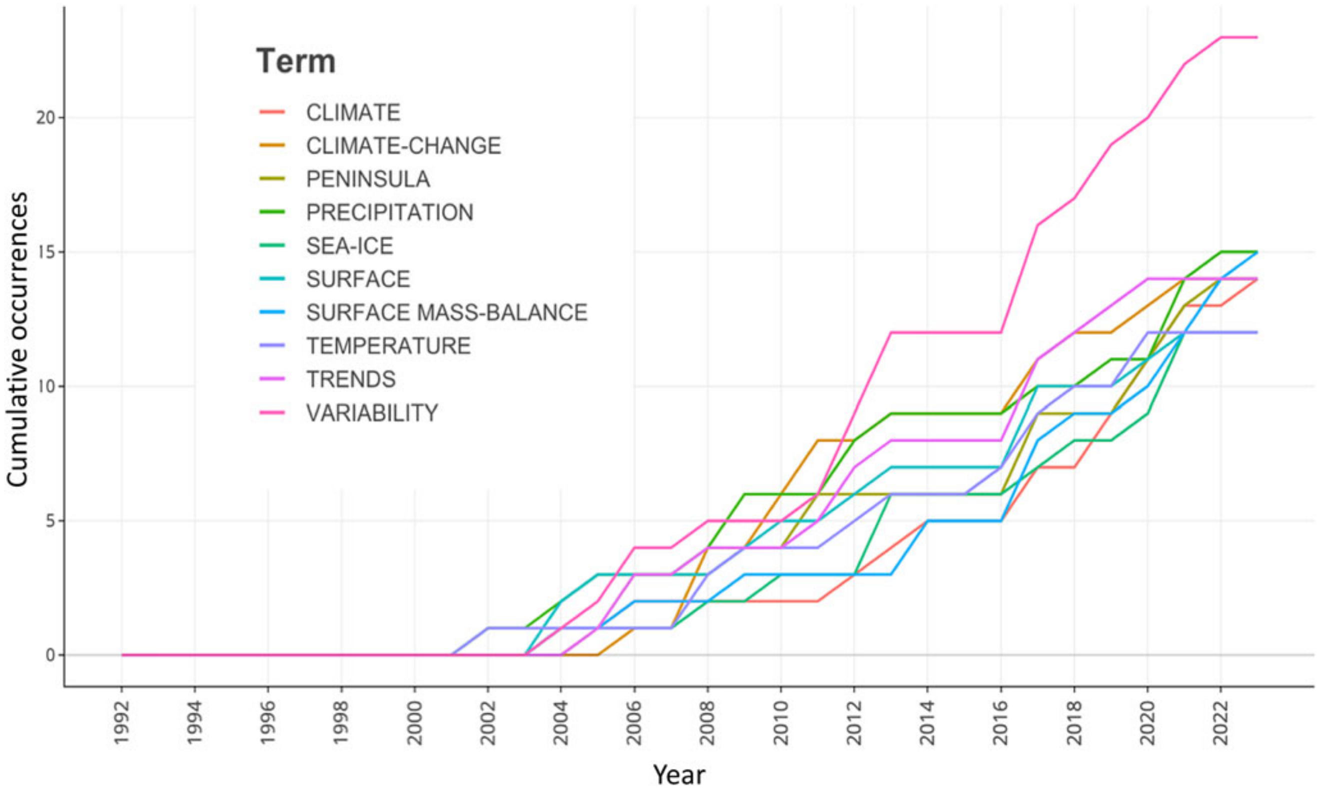

Figure 6. The frequency of key words relating to precipitation variability research over the Antarctic Peninsula in the period 1990–2023.

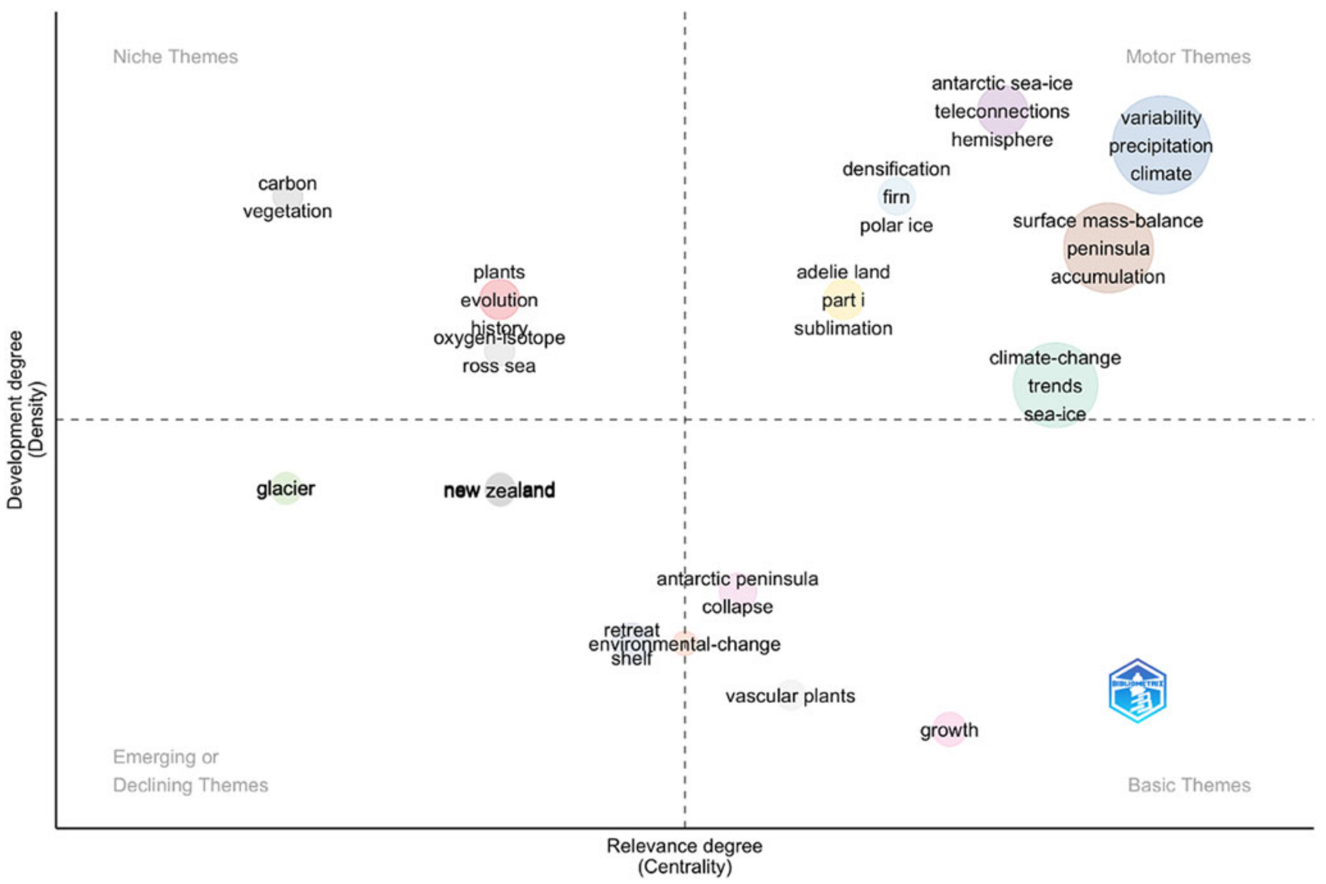

Figure 7. Thematic map of research on precipitation variability over the Antarctic Peninsula.

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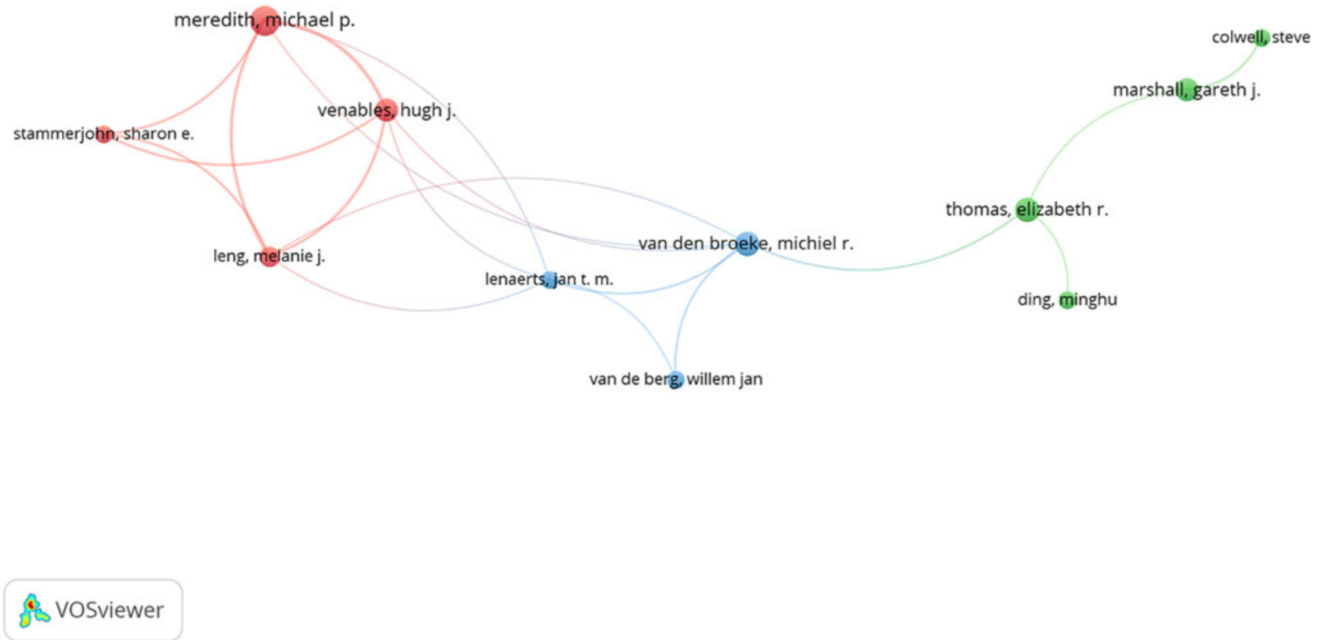

Figure 8. Co-authorship network amongst the top authors from the 86 identified papers on precipitation variability over the Antarctic Peninsula published in the period 1990–2023 (the minimum number of papers published is five).

emerging or declining themes, while the lower right quadrant (Q4) refers to basic (or underlying) themes. The themes 'variability', 'precipitation' and 'climate', representing studies on precipitation variability and climate variability, are driving this field. Themes such as 'antarctic sea-ice', 'surface mass-balance', 'accumulation' and 'teleconnections', which refer to ocean and atmospheric processes, are also drivers in this research field. 'Climate-change' is only a secondary driver of research on AP precipitation variability, as papers on climate change are often cited to explain the prevalence of precipitation variability over the AP, but as an underlying theme.

Biology-related topics such as 'vegetation', 'carbon' and 'plants' are specialized and appear as niche themes, with researchers studying the responses to precipitation variability of organisms and ecosystems. Such studies do not contribute to the understanding of how and why precipitation changes over the AP but rather to the understanding of the impacts of precipitation changes on Antarctic biota. Themes relating to glacial retreat, as shown by 'glaciers', 'shelf' and 'retreat', are emerging topics, and many recent studies on precipitation variability over the AP are focused on the impacts of increased/decreased precipitation patterns on glaciers and ice shelves.

Co-authorship analysis

A co-authorship analysis was performed for authors, affiliations and countries. There were 1027 authors identified, with outputs ranging from 1 to 10 papers. Therefore, we have chosen five papers as our median for this analysis, with only 14 authors having published at least five papers (Fig. 8). There are three clusters in this network. Van den Broeke (blue cluster) was the author appearing at the centre of the network. He has produced the most papers ($n = 10$) and also has the highest number of citations ($n = 420$ citations). He is a professor of polar meteorology at Utrecht University, and his research is primarily on ice mass balance and precipitation.

Although Stammerjohn (red cluster) had published five papers relating to precipitation variability studies over the AP and ranks second in terms of number of citations ($n = 404$), her name was not emphasized in the network. She is a researcher based at the University of Colorado, and her recent her work has focused on coastal western AP ecosystems and their responses to changes (climate change, ocean forcing, ice mass balance, etc.). This is evidenced by four of her papers being amongst the relevant papers that focus on the western AP. Interest in studying precipitation variability over the western AP may be linked with the prediction that Antarctic coasts in the western AP region will experience both warming and more frequent and intense rainfall by the end of the current century (Vignon *et al.* 2021).

In terms of contributions by affiliations, 51 out of 147 organizations have published at least two papers relating to precipitation variability over the AP. Figure 9 shows the co-authorship network of the organizations involved.

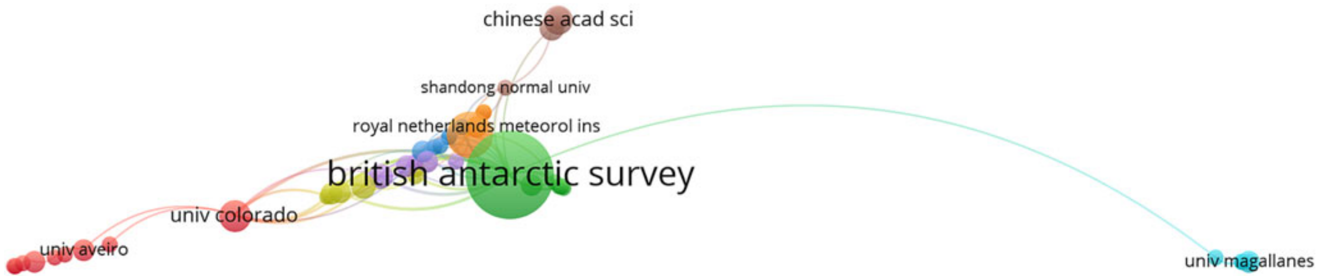

Figure 9. Co-authorship network of the organizations of authors from the 86 identified papers on precipitation variability over the Antarctic Peninsula published in the period 1990–2023 (the minimum number of papers published is two).

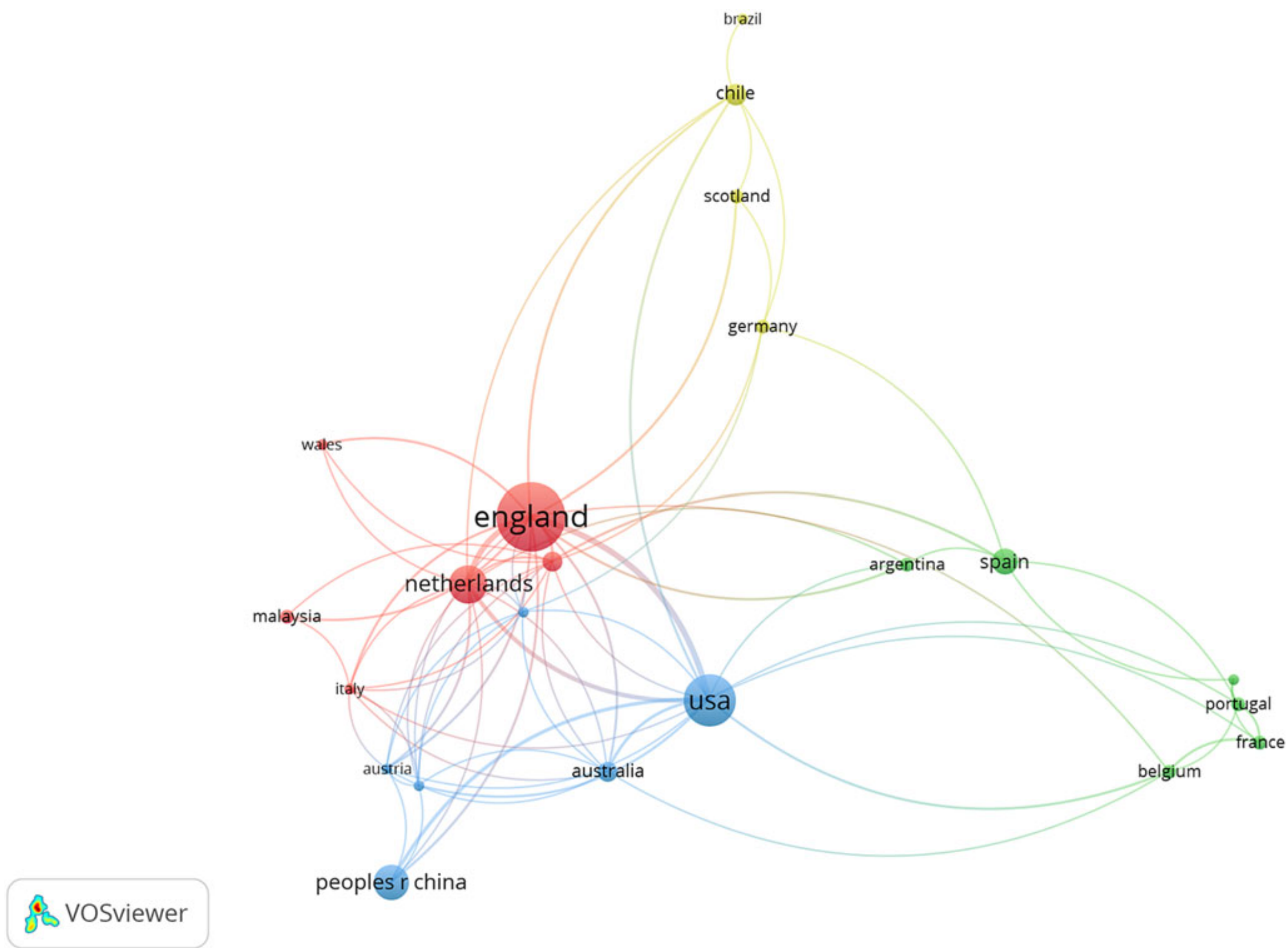

Figure 10. Co-authorship network of countries from 86 papers on precipitation variability over the Antarctic Peninsula published in 1990–2013 (the minimum number of papers published is two).

Two of the most common affiliations were BAS and Utrecht University (The Netherlands). This is consistent with the contributions of both of these affiliations in terms of numbers of papers published. BAS had 28 links, with affiliations from China (e.g. Chinese Academy of Science and Shandong University), the UK (e.g. University of Birmingham, University of Leicester and University of Leeds), Australia (e.g. Australian Antarctic Division), South America (e.g. University of Chile and Instituto Antártico Argentino), the USA (e.g. Columbia University and University of California) and Asia (e.g. Universiti Malaya, Malaysia). These findings confirm that BAS is the leading research institute with regard to precipitation studies over the AP.

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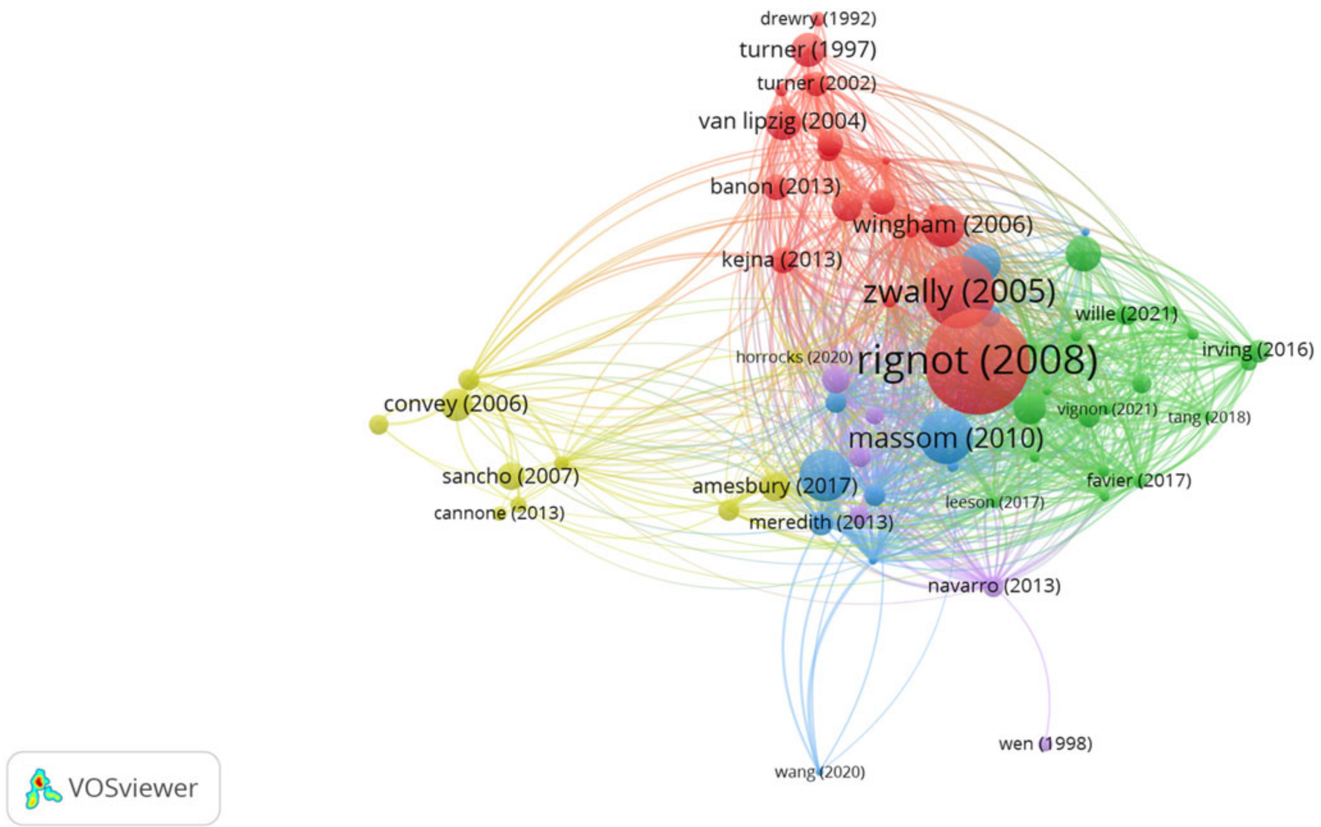

Figure 11. Bibliographic coupling of publications on precipitation variability over the Antarctic Peninsula published in the period 1990–2023 (the minimum number of citations of a paper is five).

In terms of national output, 26 countries have been involved in publishing papers on precipitation variability over the AP (Fig. 10). No key words were clearly highlighted, but papers originating from the UK ($n = 38$ papers; 2233 citations) dominated, followed by the USA ($n = 24$ papers; 2352 citations) and the Netherlands ($n = 15$ papers; 1465 citations). The main contributor to the dominance of the UK is the output from BAS. Outputs by the US universities and Utrecht University contributed to the positions of the USA and the Netherlands, respectively. While China published multiple papers ($n = 13$), citations of these papers were much lower ($n = 124$). Most papers published by the Chinese research community in this field are related to the strong teleconnections between the Chinese region and Antarctica (e.g. Fan & Wang 2004, Fang *et al.* 2019, Zhang *et al.* 2023). The links shown in Fig. 10 highlight the wide international interest and international collaboration in research into precipitation patterns in the AP region.

Bibliographic coupling

When two papers cite a common third document, this results in a bibliographic coupling (Mas-Tur *et al.* 2021). Figure 11 shows the bibliographic coupling for papers on precipitation variability over the AP with a minimum of five citations. The paper with the most citations was that of Rignot *et al.* (2008). This is a study on Antarctic ice mass loss that can be accounted for by precipitation variability over the AP. In this study, Rignot *et al.* used radar interferometry data, which accurately track changes in the surface elevation of the ice sheet, to estimate ice mass loss rates across Antarctica. They also used regional climate models to predict the ice sheet's surface mass balance, taking into account aspects such as snow accumulation and melt. They reported that the Antarctic Ice Sheet is rapidly losing mass, contributing to rising global sea levels. Between 1996 and 2006, Antarctica lost an estimated 196 ± 92 gigatonnes of ice per year (Rignot *et al.* 2008). Increased ice loss is considered one of the major implications of increased precipitation over the AP, underlying why many studies on precipitation variability over the AP have cited this paper to explain the effects of precipitation increase on the Antarctic Ice Sheet.

Another paper with a high number of citations ($n = 377$) was that of Zwally *et al.* (2005). This paper also addressed changes in the mass of ice sheets across Antarctica as well as their contributions to sea-level rise. Studies of Antarctic

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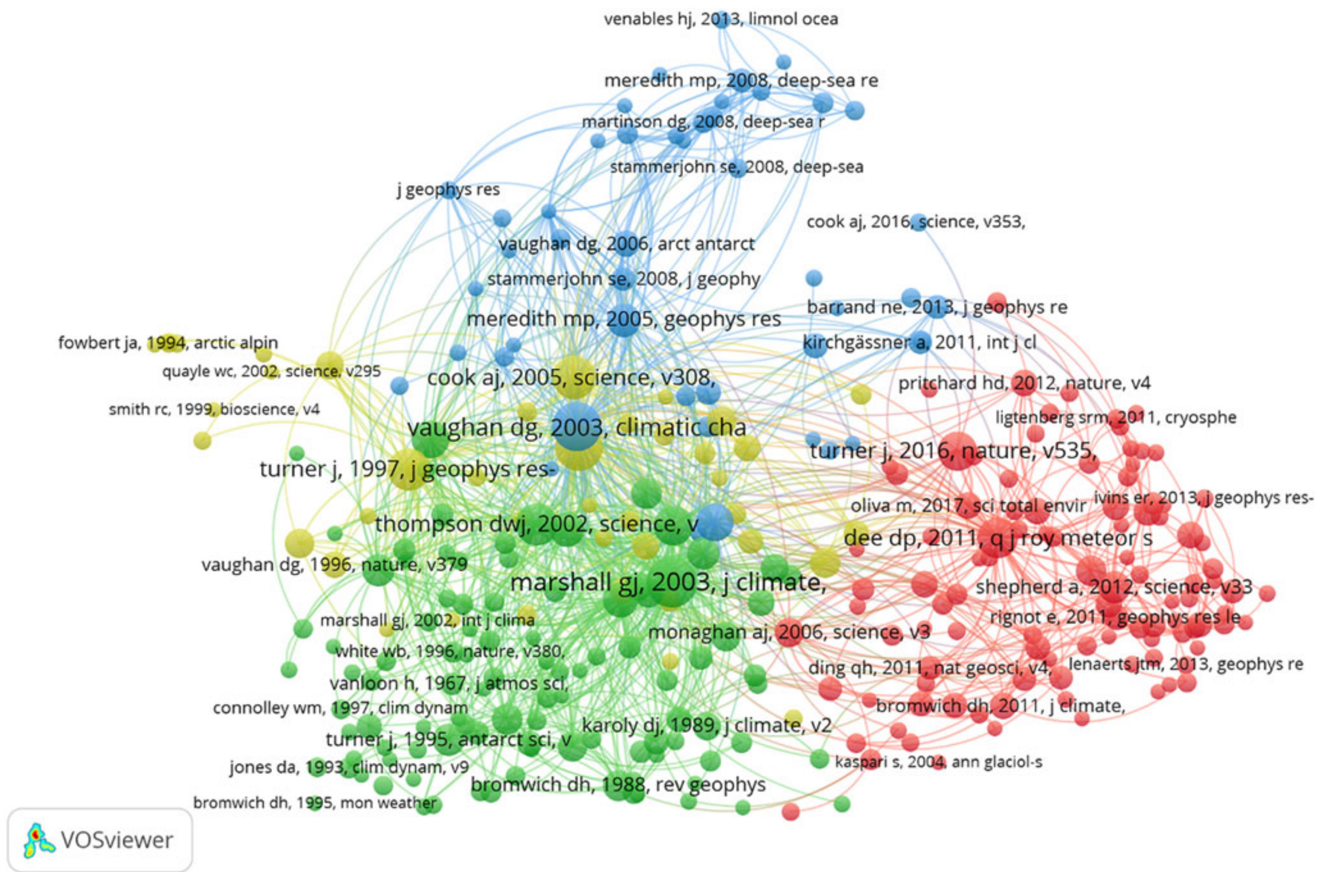

Figure 12. Co-citation network of publications on precipitation variability over the Antarctic Peninsula in the period 1990–2023 (the minimum number of citations of a paper is five).

sea-ice dynamics are also amongst the most cited. Conversely, Meredith *et al.* (2017), although having only 52 citations, had the greatest TLS of 315. This study explores the distribution of precipitation in the western AP using observational data and climate models, finding that changes to precipitation distribution (meteoric water) over the western region of the AP are linked to sea-ice dynamics, atmospheric circulation patterns and precipitation regimes. Other studies by Meredith and colleagues also emerged amongst those with the greatest links and TLS (e.g. Meredith *et al.* 2010, 2013, 2021). Meredith is a senior researcher at BAS, and the studies mentioned above are primarily on freshwater budgets over the AP region. Changes in precipitation patterns can alter the freshwater inputs into regions of the AP, with important implications for ecosystems, sea ice and glaciers.

Co-citation analysis

Co-citations can show similarities in theme between papers that are cited together, with the assumption being that papers cited together are often thematically similar (Mas-Tur *et al.* 2021). The papers were assigned to five heterogeneous clusters coloured red, green, yellow, blue and purple as shown in Fig. 12. No papers were particularly at the centre of the network, but one paper by Marshall (2003) was cited the most number of times ($n = 22$). That study investigated the Southern Annular Mode (SAM) using observational and re-analysis data. The SAM describes the north-south movement of the southern westerly wind belt around Antarctica (Mariani & Fletcher 2016). The SAM is correlated with precipitation variability in West Antarctica, with positive SAM trends favouring increased precipitation events in the AP region (Clem *et al.* 2016, Wille *et al.* 2021). Marshall (2003) was cited 2236 times, with 22 of these being papers identified in the present study. The paper was also strongly linked to other papers dealing with climate change and warming over the AP region (e.g. van den Broeke & van Lipzig 2004, Turner *et al.* 2016, Marshall *et al.* 2017). From the co-citation analysis, it can be seen that the field of research in precipitation variability over the AP is closely related to that of climate variability.

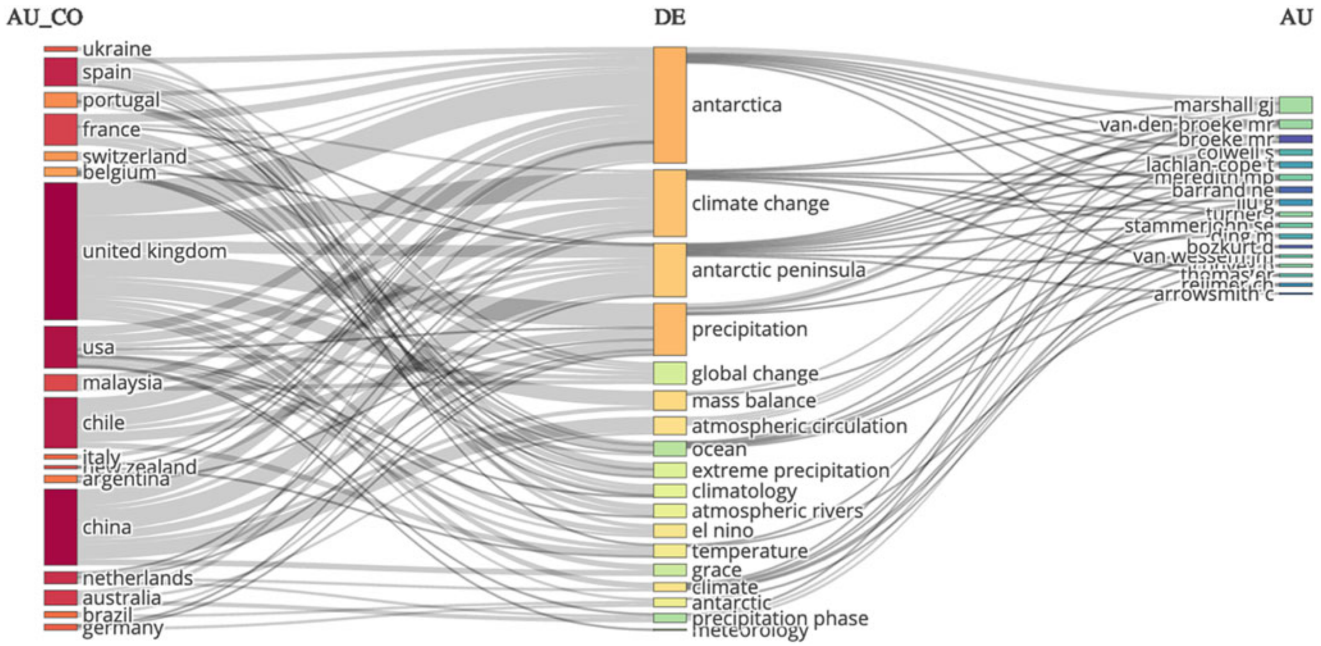

Figure 13. Three-field plot showing authors' countries (AU_CO), key words (DE) and authors (AU) associated with research on precipitation variability over the Antarctic Peninsula in the period 1990–2023.

Conclusions

Due to increased concerns about global warming and climate change, interest within the scientific community in studying changes in meteorological patterns such as precipitation variability is increasing. Antarctica, being such a pristine ecosystem, can be affected severely by the impacts of climate change, which could significantly affect local physical, oceanic and biological systems, as is also reflected globally. Changes in precipitation will influence the role of the AP in mediating global climatic and oceanic processes.

Overall, our bibliometric analyses found that research on precipitation variability over the AP has steadily increased, and there is clear potential for future development in this area. To date, the research field has been dominated by the UK and US research communities. Studies have primarily been contributed by the physical sciences community, with studies on the biological responses of organisms and ecosystems to precipitation changes having received less focus. Figure 13 provides a three-field plot summarizing this field in terms of dominating countries, most frequent key words and active researchers.

Particular focus is now required on ensuring that global climate change mitigation measures are implemented before current AP precipitation patterns are further disrupted. This study has highlighted both the bibliometrics and science behind increasing precipitation in the AP region, and urgent conservation measures are necessary to minimize the impacts that this phenomenon will have on the functioning of Antarctic ecosystems. Our findings also emphasize the importance of this region as a hub for scientific inquiry and collaboration through international research cooperation.

Financial support

This project was supported by the Ministry of Higher Education (Tindakbalas Kulat Terhadap Interaksi Antara Parameter (Environmental Stressors) Melalui Pendekatan Omiks, HICoE IOES-2023E), Yayasan Penyelidikan Antartika Sultan Mizan (Impact of Increasing Rainfall Trend on Atmospheric Reactive Gasses and Microbiota Over the Maritime Antarctic Region, GA008-2022) and Universiti Malaya through the Universiti Malaya Scholarship Scheme (UMSS). P. Convey is supported by NERC core funding to the British Antarctic Survey's 'Biodiversity, Evolution and Adaptation' team. W. Cheah is supported by the FIO-UM Joint Centre for Marine Science and Technology. S.N. Chenoli is supported by Universiti Malaya research project UMG013J-2023.

Competing interests

The authors declare none.

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https://doi.org/10.1017/S0954102024000324 Published online by Cambridge University Press