Jointly published by Akadémiai Kiadó, Budapest and Springer, Dordrecht

Scientometrics, Vol. 77, No. 3 (2008) 389–414
DOI: 10.1007/s11192-007-1947-x

Intellectual structure of Antarctic science: A 25-years analysis

PRABIR G. DASTIDAR,[a] S. RAMACHANDRAN[b]

[a] *Ministry of Earth Sciences, New Delhi (India)*
[b] *University of Madras, Chennai (India)*

To delineate the intellectual structure of Antarctic science, the research outputs on Antarctic science have been analyzed for a period of 25 years (1980–2004) through a set of scientometrics and network analysis techniques. The study is based on 10,942 records (research articles, letters, reviews, etc.), published in 961 journals/documents, and retrieved from the Science Citation Index (SCI) database. Over the years interest in Antarctic science has increased, as is evident from the growing number of ratified countries and research stations. During the period under study, the productivity has increased 3-times and there is a 13-fold increase in collaborative articles. Attempt has been made to identify important players like scientists, organizations and countries working in the field and to identify frontier areas of research that is being conducted in this continent. The highest 41% scientific output is contributed by the USA and the UK, followed by Australia and Germany. British Antarctic Survey (BAS), UK and Alfred Wegener Institute of Polar & Marine Research, Germany are the most productive institutes in Antarctic science. Maximum number of research articles on Antarctic science, have been published in the journal *Polar Biology,* indicating substantial work being done on the biology of this continent. The journals – *Nature* and *Science* – are the highly-cited journals in Antarctic science. The paper written by J. C. Farman et al., published in *Nature* in 1985, reporting depletion of ozone layer, is the most-cited article. Semantic relationships between cited documents were measured through co-citation analysis. J. C. Farman and S. Solomon are co-cited most frequently.

Received August 30, 2007

Address for correspondence:
PRABIR G. DASTIDAR
Ministry of Earth Sciences, Block No 9 & 12, CGO Complex
Lodi Road, New Delhi- 110003, India
E-mail: prabirgd11@gmail.com, prabirgd11@rediffmail.com

0138–9130/US $ 20.00

Introduction

Antarctica: A natural laboratory of science

Antarctica is the fifth largest continent in size, larger than Australia and the subcontinent of Europe. It was a part of Gondwanaland several million years ago and is today the only witness holding the imprints of events that took place on the earth during that period. This coldest, windiest, and highest continent is covered with an ice sheet of more than 2 km average thickness. The environment that has remained undisturbed and unpolluted for million of years, is a treasure trove of information of past events.

Antarctica plays a pivotal role in shaping the global environment. The North and South Poles maintain the heat budget of the world in balance. Its unique position makes it an ideal location to study the interaction between the earth's magnetic field and the charged particles from the sun. The Indian, Atlantic and the Pacific Oceans meet around Antarctica and the mixing process of cold and warm waters formulates a special regime of Antarctic convergence which has its own physical, chemical and biological characteristics. The Antarctic Ocean supports a few biological communities of commercial importance with large populations. It is among the richest biological provinces on the earth.

Governing Antarctica and Antarctic Treaty System

The Antarctic Treaty System (ATS) – one of the world's most successful multinational agreements – ensures that Antarctica remains a natural reserve for conducting scientific research. ATS provides a set of guidelines comprising a complex regime of conventions, decisions, protocols and measures for managing the vast continent. The Antarctic science is central to the ATS. It involves complex issues of political, environmental, legal and financial nature, as reflected in the Madrid Protocol [ANONYMOUS, 2002], which advocates principles of sustainable utilization of its resources adopting ecosystem-based management strategies, logistic cooperation; and safety and management of non-governmental activities like tourism [ANTARCTIC TREATY SECRETARIAT, 2006]. In 2003–2004 (01 July–30 June), Antarctic fisheries reported landing of 136,262 metric tons of fish (estimated fishing from the area covered by the Convention on the Conservation of Antarctic Marine Living Resources (CCAMLR), which extends slightly beyond the Antarctic Treaty area) [CIA, 2006]. International Association of Antarctic Tour Operators (IAATO) reported landing of 25,167 passengers in the Antarctic Treaty Area on 44 commercially-organized tour vessels and small sailing-vessels and/or yachts from October 2005 to March 2006 [IAATO, 2006].

The scientific enterprise is organized at various levels of aggregation. Each unit of analysis in scientific studies is a composite of, among other things, cognitions, text and scientists. These building blocks are different in nature [LEYDESDORFF, 2001]. In this work, an attempt has been made to analyze the structure of various dimensions of the Antarctic science specialty to visualize the intellectual structure of this discipline. Major players in Antarctic science have been identified and their research interests have been characterised. Some similar analyses have been reported before on Ocean Science and Technology [DASTIDAR, 2004], Ocean Technology [DASTIDAR & RAMACHANDRAN, 2005], and Antarctic science [DASTIDAR & PERSSON, 2005; DASTIDAR, 2007].

Notable instruments to the Antarctic Treaty System (ATS)

Notable instruments to the Antarctic Treaty System (ATS) are as follows:

● COMNAP (Committee of Managers of National Antarctic Program) was established in the year 1988 to improve the effectiveness of the activities pursuant to the Antarctic Treaty and associated Environmental Protocol (EP). COMNAP includes a permanent Standing Committee on Antarctic Logistics and Operations (SCALOP) and a number of task-oriented Working Groups and Networks. COMNAP also provides input to ATS discussions derived from its operational experience and carries out analyses in response to requests from the Treaty System.

● SCAR (Scientific Committee on Antarctic Research) is a committee of ICSU , the International Council for Science, and it is charged with the initiation, promotion and co-ordination of scientific research in Antarctica. SCAR also provides international, independent scientific advice to the Antarctic Treaty system. SCAR is the single international, interdisciplinary, non-governmental organization which can draw on the experience and expertise of an international mix of scientists across the complete scientific spectrum. For over 30 years SCAR has provided such scientific advice to the Antarctic Treaty System and made numerous recommendations on a variety of matters, most of which have been incorporated into Antarctic Treaty instruments. Foremost amongst these have been the advice provided for the many international agreements which provide protection for the ecology and environment of Antarctica. SCAR meets every two years to conduct its administrative business at the SCAR Delegates Meeting. They also elect an Executive Committee from among themselves which is responsible for the day-to-day administration of SCAR through its secretariat at the Scott Polar Research Institute in Cambridge, England.

● Agreed Measures for the Conservation of Antarctic Fauna and Flora, 1964

These measures were adopted in 1964 to protect endemic and native wildlife and plants. The provisions include a requirement for permits to capture birds and seals, and rules to prevent uncontrolled introduction of non-indigenous organisms. The sites having outstanding ecological interest are designated as 'Antarctica Specially Protected Areas (ASPA)'.

● Convention for the Conservation of Antarctic Seals, 1978

The Seal Convention was developed to provide a means to regulate commercial sealing. Although there is no indication of any interest in sealing, the Convention provides for such activities to be undertaken sustain ably. Some species of seals are totally protected, and catch limits are set for others.

● Convention on the Conservation of Antarctic Marine Living Resources, 1980

It stipulates that Krill and all other living resources of the Southern Ocean are treated as an integrated system where effects on predator, prey and related species are considered and decision on sustainable harvesting levels are made on the basis of sound scientific advice. Conservation measures under CCAMLR establish protected species, set catch limits, identify fishing regions, regulate when fishing may occur and what fishing methods can be used, and establish fisheries inspection procedures.

● Convention on the Regulation of Antarctic Mineral Resources Activities (CRAMRA), 1988

Though CRAMRA has not come into force, yet it is significant in paving the way towards the Protocol to the Antarctic Treaty on Environment Protection (1991), and subsequently influenced several provisions, specially the 50 year ban on mining exploration and activities.

● Protocol on Environmental Protection to the Antarctic Treaty, 1991

The protocol provides for wide ranging provisions relating to protection of the Antarctic environment that required to be harmonized in a comprehensive and legally binding form. It draws on and updates the agreed measures as well as subsequent Treaty meeting recommendations relating to protection of the environment.

Materials and methods

Though there are several indicators to study Science and Technology dynamics, research publications in peer-reviewed scientific journals are widely regarded as one of the most important indicators. The data for the study was culled from Science Citation Index (SCI) (CD-ROM) database. It provides a comprehensive coverage[1] of the world's research by covering research articles, reports, technical papers, news items, reviews, letters, communications, editorial materials, etc. The selected journal coverage of the SCI (CD-ROM) with more than 5000 international journals covering a wide range of

[1] Productivity in science follows well-defined mathematical regularities. Bradford's Law of journals productivity suggests concentration of core journals of a given subject specialty in a measurable central cluster. It simply suggests that if there are, say, 1,000 journals in a field, then one-third of the papers are to be found in each of three zones containing about 10, 100 and 1,000 journals, respectively. In a citation study it was shown that as few as 150 journals account for half of what is cited and one quarter of what is published. It has also been shown that a core of approximately 2,000 journals account for about 85% published articles, and 95% of cited articles [GARFIELD, 1996].

fields spanning science, engineering and technology, agriculture and medicine, etc. is able to capture a representative picture of the research dynamics of a multidisciplinary subject like Antarctic science. Besides the international coverage, editorial policies, citation analysis and other qualitative and quantitative aspects of the journals are also taken into consideration for journal selection [GARFIELD, 1990; ANONYMOUS, 2006]. Availability of data for a long period of time in a uniform format is also a pre-requisite for this kind of analysis.

Data downloading

Database search with 'Antarc*' in title, from the year 1980 through 2004 (25 years), retrieved 10,942 records. These articles formed the basis of the present analysis. To bring uniformity in the names of countries, Fed Rep Ger and Ger Dem Rep were merged into Germany, while USSR and Russia were clubbed together with Russia.

Network analysis

The attributes (author names, organization names and country names, etc.) were isolated separately and rank ordered [PERSSON, 2004]. The most productive units were chosen to form co-occurrence matrices to which a multidimensional scaling algorithm (a SYSTAT sub-routine) was applied to produce the network maps. The size of the circles in these maps was proportional to the size of the attributes, and the lines between the attributes indicated the presence of collaboration links while the width revealed the size of the frequency [DASTIDAR, 2004; DASTIDAR & RAMACHANDRAN, 2005; DASTIDAR & PERSSON, 2005; DASTIDAR, 2007]. For collaborative articles, each country was given a fraction-value where the sum of fractions equalled to the sum of documents. For example, in the case of a collaborative article written by two authors from the USA and the UK, each would get a value of 0.5 (1/2). The sum of the values of individual countries would denote the productivity of that country. UCINET software were used for doing Social Network Analysis [BORGATTI & AL., 2002].

Normalization of matrix

The data on cooperation links were tabulated in the form of valued adjacency matrix,

$$C = \left| C_{ij} \right|,$$

where C_{ij} denotes the number of cooperation links between the cell i and cell j Consequently one gets:

$$C_{ii} = 0\ .$$

In this study, the network analysis techniques were used to find the collaboration structure of the knowledge production units [BORGATTI & AL., 2002]. The entries in the matrix indicated the strength of cooperation links between the pairs of units. Since the links were bi-directional, the matrix was symmetric. Certain countries have strong links with many countries; their network of cooperation is quite extensive. In other words, they occupy a central position in the international network of science. Scientific cooperation between the countries is a function of their scientific size, while the pattern is not. The pattern of cooperation must be viewed without the confounding effect due to size. For controlling the effect of size, a special index, Salton Index, was computed by using the following formula:

$$\frac{C_{ij}}{\sqrt{\sum_i C_{ij} \sum_j C_{ij}}} .$$

Centrality of collaboration

Degree centrality refers to the position of the individual countries within the network, whereas, centralization is the characteristics of the entire network; raw data do not give a relative picture [WASSERMAN & FAUST, 1994]. Countries which have more ties with other actors may be in the advantageous positions. As they have many ties, they may have access to, and be able to call on more of the resources of the network as a whole. So, a very simple, but often very effective measure of an actor's centrality and power potential is their degree [HANNEMAN, 2006]. In this analysis Freeman's Degree Centrality [FREEMAN, 1979], where the number of vertices adjacent to a given vertex in a symmetric graph was the degree of that vertex. For a given binary network with vertices $V_1,...,V_n$ and maximum degree centrality, $C_{max,}$ the network degree centralization measure is S $[C_{max}–C_{(vi)}]$ divided by the maximum value possible, where $C_{(vi)}$ is the degree centrality of vertex V_i. The normalized degree centrality is the degree divided by the maximum possible degree expressed as a percentage [BORGATTI & AL., 2002]. Centralization is a group level index and it measures how variable or heterogeneous the actor centralities are. It records the extent to which a single actor has high centrality, and the others, low centrality [WASSERMAN & FAUST, 1994].

Results and discussion

The interest in Antarctic science has been rising continuously; it is visible through the increasing number of research stations, members of the Antarctic treaty system, and research articles in journals, etc. (Tables 1, 2 and Figure 2). During the study period, the publication of research articles on Antarctic science subject specialty grew more than 3-times (Table 1).

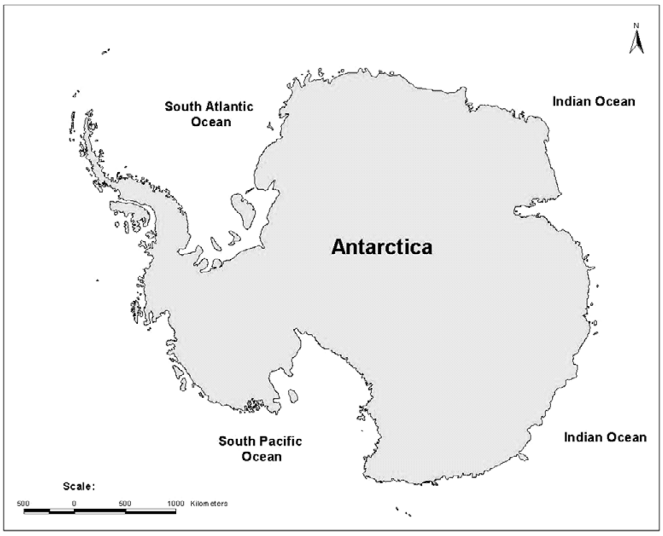

Figure 1. Map of Antarctica, surrounded by South Atlantic Ocean, Indian Ocean, and South Pacific Ocean

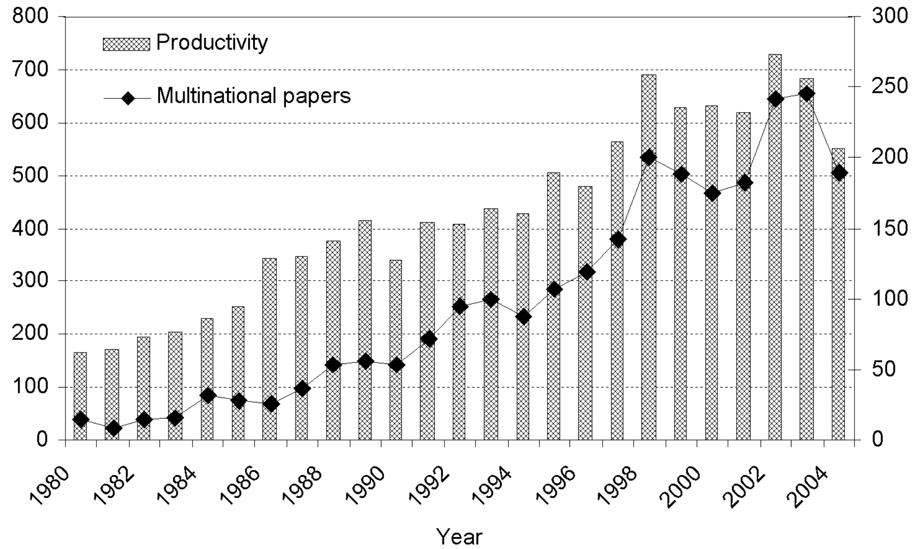

Figure 2. Growth of research activities (published papers) vs collaborative papers during 25 years (1980 to 2004)

Table 1. Year-wise distribution of outputs-number of papers (whole count) and number of collaborative articles (whole counts)

	Year	Total no. of papers	Collaborative articles	Percentage of collaborative articles
1	1980	165	15	9.09
2	1981	171	9	5.26
3	1982	194	15	7.73
4	1983	204	16	7.84
5	1984	230	31	13.48
6	1985	253	28	11.07
7	1986	342	26	7.60
8	1987	345	36	10.43
9	1988	377	53	14.06
10	1989	415	56	13.49
11	1990	339	54	15.93
12	1991	411	72	17.52
13	1992	409	95	23.23
14	1993	436	100	22.94
15	1994	428	87	20.33
16	1995	504	107	21.23
17	1996	480	119	24.79
18	1997	565	142	25.13
19	1998	691	201	29.09
20	1999	627	188	29.98
21	2000	630	175	27.78
22	2001	618	182	29.45
23	2002	729	242	33.20
24	2003	685	245	35.77
25	2004	552	190	34.42

Country productivity

The data revealed that around 80 countries showed their interest in Antarctic science, as is evident from the number (10,942) of articles they published in this area. The distribution is highly skewed. Scientific output in Antarctic science research during 1980–2004 in the world map is shown in Figure 3. Countries with smaller science-base like Nigeria, Slovenia, Sri Lanka, etc. have also shown interest in Antarctic science by way of participating in it. However, a major contribution (about 40%) in output was from the USA and the UK (Table 2). The highest individual share of 27% was contributed by the USA. There are 37 year-round stations maintained by 19 consultative countries, in which 7 countries have more than one station (Table 3). Besides, there are seasonal research stations run by the countries; 16 such type of stations are maintained by 15 countries.

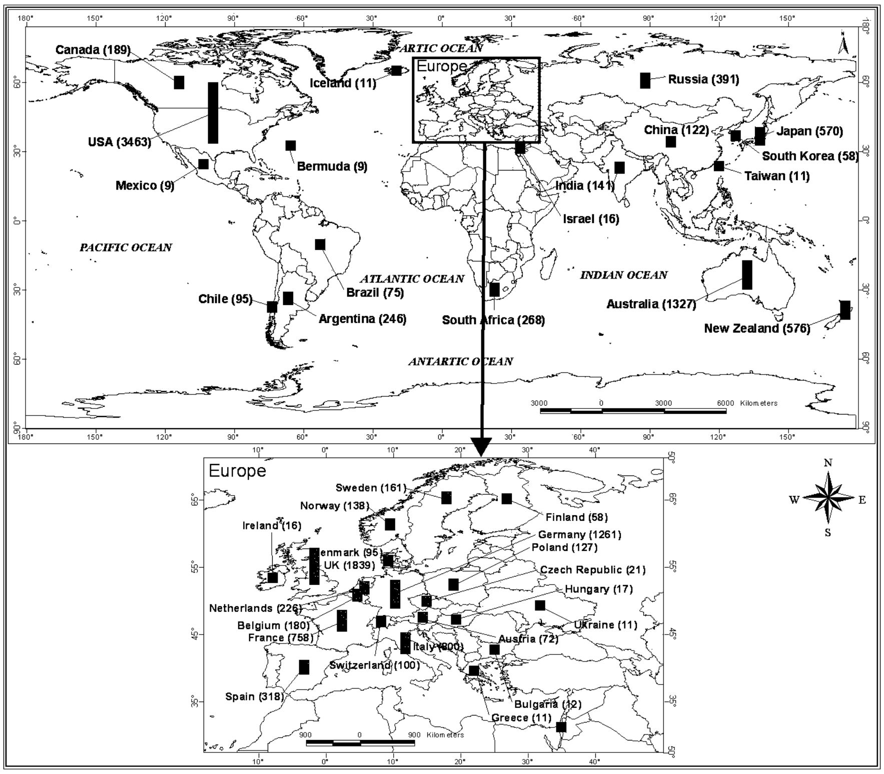

Figure 3. Scientific output of Antarctic research (1980–2004) in the world map

Country collaboration

Conducting science in collaborative mode is the main spirit of Antarctic science, as reflected in the Articles II and III of the Antarctic Treaty System (ATS) [ANTARCTIC TREATY SECRETARIAT, 2004]. To encourage the spirit of cooperation, XVI Antarctic Treaty Consultative Meeting (ATCM) declared 1991–2000 as the 'Decade of International Antarctic Scientific Cooperation' (*ATS Handbook 2002*). The data showed a sharp increase in the number of collaborative papers during 1990s (Figure 2). During the study period, the number of collaborative papers registered a 13-fold rise.

Table 2. Scientific output in Antarctic research using fraction count: 1980–2004 (N = 10,942)

Rank	Country name	Scientific output	% of world total	GERD (in PPP USD)
1	USA*	2886.90	26.7	954.0(2002)
2	UK*	1491.83	13.8	490.6(2002)
3	Australia*	1051.85	9.7	404.5(2000)
4	Germany*	948.87	8.8	686.0(2002)
5	Italy*	653.21	6.0	288.7(2001)
6	France*	526.08	4.9	611.2(2002)
7	Japan*	492.22	4.5	836.6(2002)
8	New Zealand*	430.22	4.0	246.1(2001)
9	Russia*	305.86	2.8	102.2(2002)
10	Spain*	241.37	2.2	222.4(2002)
11	South Africa*	232.99	2.2	68.7(2002)
12	Argentina*	188.37	1.7	44.0(2002)
13	Netherlands*	152.82	1.4	536.6(2001)
14	India*	126.29	1.2	20.5(2000)
15	Belgium*	117.06	1.1	614.7(2002)
16	Canada	109.65	1.0	588.4(2002)
17	Sweden*	107.30	1.0	1082.5(2001)
18	Poland*	107.00	1.0	62.7(2002)
19	Peoples R China*	90.74	0.8	–
20	Norway*	88.73	0.8	612.2(2002)
21	Chile*	63.16	0.6	51.9(2001)
22	Brazil*	58.49	0.5	76.9(2000)
23	Switzerland	50.78	0.5	740.4(2000)
24	Denmark	45.97	0.4	777.6(2002)
25	South Korea*	44.53	0.4	492.3(2002)
26	Austria	37.84	0.3	645.2(2002)
27	Finland*	35.99	0.3	905.2(2002)
28	Czech Republic	13.99	0.1	–
29	Bulgaria*	10.50	0.1	34.9(2002)
30	Hungary	9.16	0.1	135.3(2002)
31	Greece	9.08	0.1	115.8(2001)
32	Ukraine*	9.00	0.1	57.6(2002)
33	Ireland	8.91	0.1	369.2(2001)
34	Taiwan	8.50	0.1	–
35	Israel	7.91	0.1	997.2(2002)
36	Mexico	6.16	0.1	38.3(2002)
37	Turkey	4.50	0.0	42.6(2002)
38	Bermuda	4.33	0.0	27.4(1997)
39	Iceland	3.90	0.0	925.7(2002)
40	Jamaica	3.33	0.0	3.0(2002)
41	UKSSR	3.00	–	–
42	Pakistan	2.50	0.0	5.2(2002)
43	Estonia	2.25	0.0	98.9(2002)
44	Philippines	2.00	0.0	
45	Romania	2.00	0.0	24.9(2002)
46	Singapore	2.00	0.0	525.7(2002)
47	Antarctica	1.83	0.0	–
48	Monaco	1.83	0.0	–

Table 2. (cont.)

Sl. no.	Country name	Scientific output	% of world total	GERD* (in PPP$^{\phi}$USD)
49	Reunion	1.5	0.0	–
50	Ciskei	1.00	0.0	–
51	Colombia	1.00	0.0	10.5(2001)
52	Indonesia	1.00	0.0	–
53	Ivory Coast	1.00	0.0	–
54	Kenya	1.00	0.0	–
55	Papua N Guinea	1.00	0.0	–
56	Peru*	1.00	0.0	5.2(2002)
57	Portugal	1.00	0.0	170.2(2002)
58	Saudi Arabia	1.00	0.0	–
59	Vanuatu	1.00	0.0	–
60	Zimbabwe	1.00	0.0	–
61	Bolivia	0.50	0.0	6.9(2002)
62	Byelarus	0.50	0.0	35.1(2002)
63	Comoros	0.50	0.0	–
64	Costa Rica	0.50	0.0	34.5(2000)
65	Latvia	0.50	0.0	42.8(2002)
66	Luxembourg	0.50	0.0	961.1(2000)
67	Morocco	0.50	0.0	–
68	Namibia	0.50	0.0	–
69	New Caledonia	0.50	0.0	–
70	Niger	0.50	0.0	–
71	Nigeria	0.50	0.0	–
72	Qatar	0.50	0.0	–
73	Slovenia	0.50	0.0	286.2(2002)
74	Sri Lanka	0.50	0.0	5.1(1996)
75	Uruguay*	0.50	0.0	20.6(2002)
76	Venda	0.50	0.0	–
77	Vietnam	0.50	0.0	–
78	Yugoslavia	0.50	0.0	–
79	Fiji	0.33	0.0	–
80	Fr Polynesia	0.33	0.0	–
81	French Guiana	0.33	0.0	–
82	Venezuela	0.20	0.0	20.7(2002)

GERD = Per Capita Gross Domestic Expenditure on R&D
– = Data not available
* = Consultative Parties [Ecuador is not listed above]
$^{\phi}$PPP = Purchasing Power Parity
Note: Figures within the brackets denote the year.

Table 3. Number of stations and manpower deployment by the countries

	Country	No. of stations (oldest station)	Man power deployment (Peak)
1	USA	3(1955)	1140
2	UK	2(1956)	195
3	Australia	3(1954)	200
4	Germany	1(1981)	50
5	Italy	1(2005) (jointly with France)	45
6	France	2(1956)	145
7	New Zealand	1(1957)	85
8	Japan	1(1957)	110
9	Russia	5(1956)	379
10	Spain	–	–
11	South Africa	1(1962)	80
12	Argentina	6(1904)	417
13	Netherlands	–	–
14	Canada	–	–
15	Belgium	–	–
16	Sweden	–	–
17	India	1(1989)	65
18	Norway	1(2005)	40
19	Poland	1(1977)	40
20	P. R. China	2(1985)	70
21	Switzerland	–	
22	Denmark	–	–
23	Chile	3(1948)	197
24	Brazil	1(1984)	40
25	Austria	–	–
26	Finland	–	–
27	South Korea	1(1988)	60
28	Czech Republic	–	–
29	Hungary	–	–
30	Ireland	–	–
31	Israel	–	–
32	Taiwan	–	–
33	Ukraine	1(1996)	24
34	Bulgaria	–	–
35	Greece	–	–
36	Mexico	–	–
37	Bermuda	–	–
38	Turkey	–	–

– = Data not available
Note: Figures within the brackets denote years.

More productive countries tended to have more collaborative projects. It opened up new opportunities to address the complex issues in a collaborative manner. The network of collaboration among top 38 countries is given in Figure 4. The USA was found to be the most networked country in Antarctic science, followed by Germany, the UK, France and Australia. The values of degree centrality ranged from 0.107 (Bulgaria) to 3.055 (USA), with a mean value of 1.06 and standard deviation of 0.751. The network centralization was found as 14.3% (Table 4).

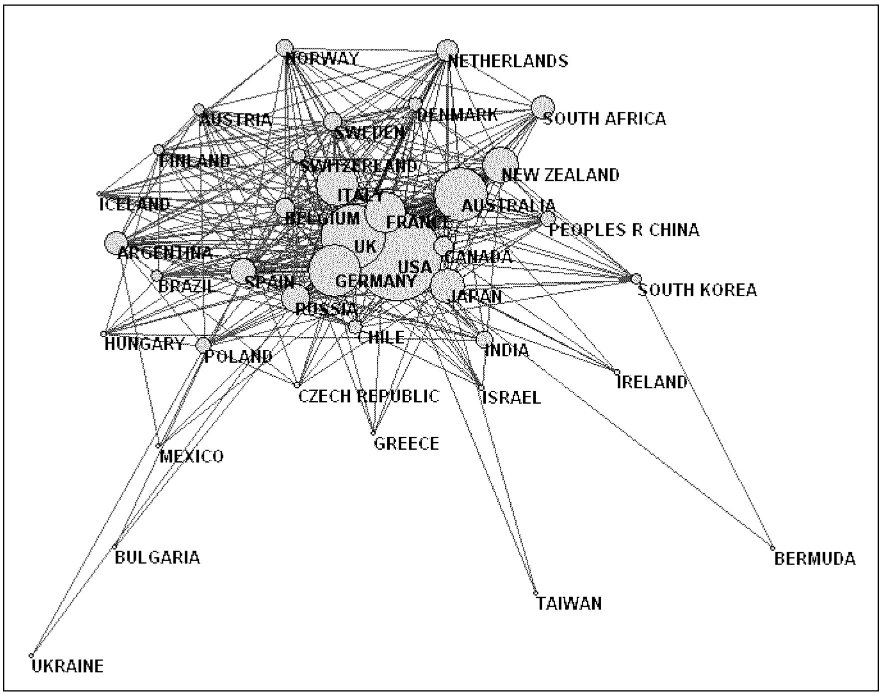

Figure 4. Network of collaboration of top 38 countries (N = 82)
Note: The thickness of the lines and proximity of the circles indicate collaboration intensity between the countries. Size of the circles depicts productivity of the countries

Organizational productivity and collaboration

Around 2726 organizations contributed to Antarctic research during the past 25 years (1980–2004). The top 39 most-productive organizations were taken up for producing the network map (Figure 5). Among all the institutes, British Antarctic Survey (BAS) was observed to be the most-productive institute in Antarctic science, followed by Alfred Wegener Institute of Polar and Marine Research, National

Aeronautics and Space Administration (NASA), University of Tasmania, and Australian Antarctic Division (Table 5). The organizational collaboration did not show any core-periphery. Every third organisation participating in the Antarctic science research belonged to the USA, 75% of them were universities. For Australia and Germany, both institutes and universities were contributing to the Antarctic science. In the UK, institutes were the major contributors.

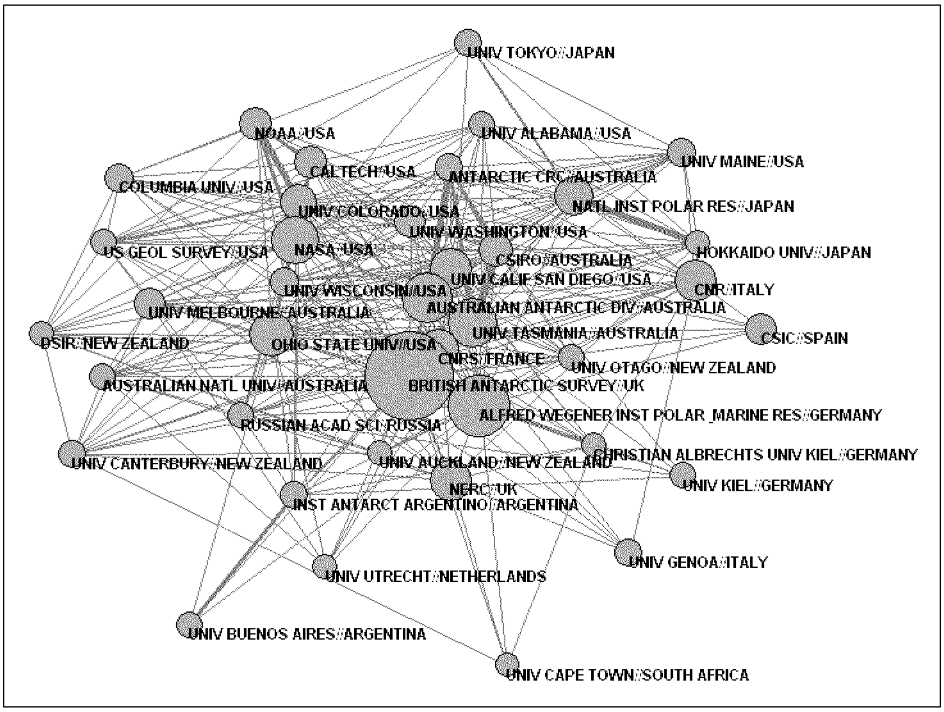

Figure 5. Collaboration network among 39 most-productive organizations in Antarctic research (N = 2726)
Note: The thickness of the lines and proximity of the circles indicate collaboration intensity between the organisations. Size of the circles depicts productivity of the organisations

Table 4. Freeman's degree centrality measures

	Country	Degree centrality	Normalised degree centrality	Share	Multinational papers
1	USA	3.055	20.850	0.075	1059
2	Germany	2.855	19.485	0.070	515
3	UK	2.603	17.765	0.064	637
4	France	2.438	16.639	0.060	412
5	Australia	2.141	14.612	0.053	507
6	Italy	1.731	11.814	0.043	265
7	Japan	1.500	10.238	0.037	141
8	Argentina	1.458	9.953	0.036	108
9	Russia	1.416	9.664	0.035	127
10	Spain	1.350	9.214	0.033	141
11	New Zealand	1.310	8.941	0.032	264
12	Belgium	1.276	8.709	0.031	111
13	Sweden	1.272	8.681	0.031	92
14	Denmark	1.256	8.572	0.031	80
15	Netherlands	1.152	8.545	0.031	130
16	Canada	1.158	7.903	0.029	145
17	Norway	1.125	7.678	0.028	85
18	Switzerland	0.095	7.473	0.027	83
19	Austria	0.968	6.607	0.024	59
20	Finland	0.968	6.607	0.024	40
21	Brazil	0.804	5.490	0.020	31
22	Chile	0.776	5.296	0.019	61
23	Poland	0.751	5.126	0.019	40
24	Peoples Republic of China	0.723	4.934	0.018	59
25	South Africa	0.693	4.730	0.017	65
26	Hungary	0.681	4.648	0.017	15
27	India	0.595	4.061	0.015	27
28	South Korea	0.567	3.870	0.014	23
29	Iceland	0.540	3.686	0.013	10
30	Czech Republic	0.399	2.723	0.010	13
31	Israel	0.341	2.327	0.008	13
32	Greece	0.293	2.000	0.007	3
33	Ukraine	0.276	1.884	0.007	4
34	Mexico	0.234	1.597	0.006	5
35	Ireland	0.222	1.515	0.005	13
36	Taiwan	0.146	0.996	0.004	5
37	Bermuda	0.139	0.949	0.003	10
38	Bulgaria	0.107	0.730	0.003	3

Table 5. Rank-list of the top highly-productive institutes involved in Antarctic Research

	Organization	No. of articles
1	British Antarctic Survey, UK	972
2	Alfred Wegener Institute of Polar & Marine Res, Germany	475
3	Australian Antarctic Div, Australia	312
4	University of Tasmania, Australia	305
5	NASA, USA	293
6	Ohio State Univ, USA	244
7	Univ Calif, San Diego, USA	220
8	NERC, UK	216
9	CNR, Italy	214
10	CNRS, France	205
11	Natl Inst Polar Res, Japan	196
12	Univ Colorado, USA	163
13	CSIRO, Australia	146
14	NOAA, USA	137
15	CALTECH, USA	135
16	Univ Washington, USA	127
17	CSIC, Spain	124
18	Univ Melbourne, Australia	123
19	Columbia Univ, USA	103
20	Univ Wisconsin, USA	102
21	Univ Maine, USA	101
22	Univ Genoa, Italy	100
23	Antarctic Crc, Australia	98
24	Inst Antarct Argentino, Argentina	95
25	Univ Tokyo, Japan	94
26	Univ Canterbury, New Zealand	94
27	US Geology Survey, USA	92
28	Russian Acad Science, Russia	91
29	Univ Kiel, Germany	89
30	Univ Alabama, USA	88
31	Univ Otago, New Zealand	88
32	Univ Buenos Aires, Argentina	85
33	Australian Natl Univ, Australia	84
34	Christian Albrechts Univ Kiel, Germany	83
35	DSIR, New Zealand	82
36	Hokkaido Univ, Japan	82
37	Univ Auckland, New Zealand	81
38	Univ Utrecht, Netherlands	76
39	Univ Cape Town, South Africa	75
40	Texas A&M Univ, USA	72
41	Univ Cambridge, UK	72
42	Univ Calif, Santa Barbara, USA	71
43	Univ Illinois, USA	71
44	Univ Calif, Santa Cruz, USA	71
45	Lab Glaciol & Geophys Environm, France	70
46	Univ Texas, USA	69
47	Arctic & Antarctic Res Inst, Russia	69
48	Macquarie Univ, Australia	68

Table 5. (cont.)

	Organization	No. of articles
49	Woods Hole Oceanog Inst, USA	67
50	Univ Paris 06, France	67
51	Polish Acad Sci, Poland	66
52	Univ Siena, Italy	65
53	Univ Alaska, USA	64
54	Univ Bremen, Germany	62
55	Natl Inst Water & Atmospher Res, New Zealand	60
56	Univ Wyoming, USA	60
57	Univ Copenhagen, Denmark	60
58	Univ Pretoria, South Africa	60
59	Consejo Nacl Invest Cient & Tecn, Argentina	60
60	Univ Hawaii, USA	59
61	Chinese Acad Science, Peoples Republic of China	58
62	Oregon State University, USA	58
63	Acad Science, Russia	57
64	Monash University, Australia	56
65	University of Calif, USA	54
66	University of Bern, Switzerland	54
67	Univ Calif, Los Angeles, USA	53
68	Univ Waikato, New Zealand	53
69	Department Science, Australia	52
70	Univ Liege, Belgium	52
71	Montana State Univ, USA	52
72	Victoria Univ, Wellington, New Zealand	52
73	Univ New S Wales, Australia	49
74	Natl Ctr Atmospher Res, USA	48
75	Univ Bristol, UK	47

Highly-productive authors and author collaboration network

The rank list of the highly-productive authors is led by J. B. Mc Clintock, followed by C. Wiencke and G. Diprisco (Table 6). Around 12,990 authors participated in the knowledge–production exercise. The network map is sparsely networked with isolated dyadic clusters. The top 47 authors were chosen for producing the network map (Figure 6). The top 10 most productive scientists did not have collaboration with any member of this group.

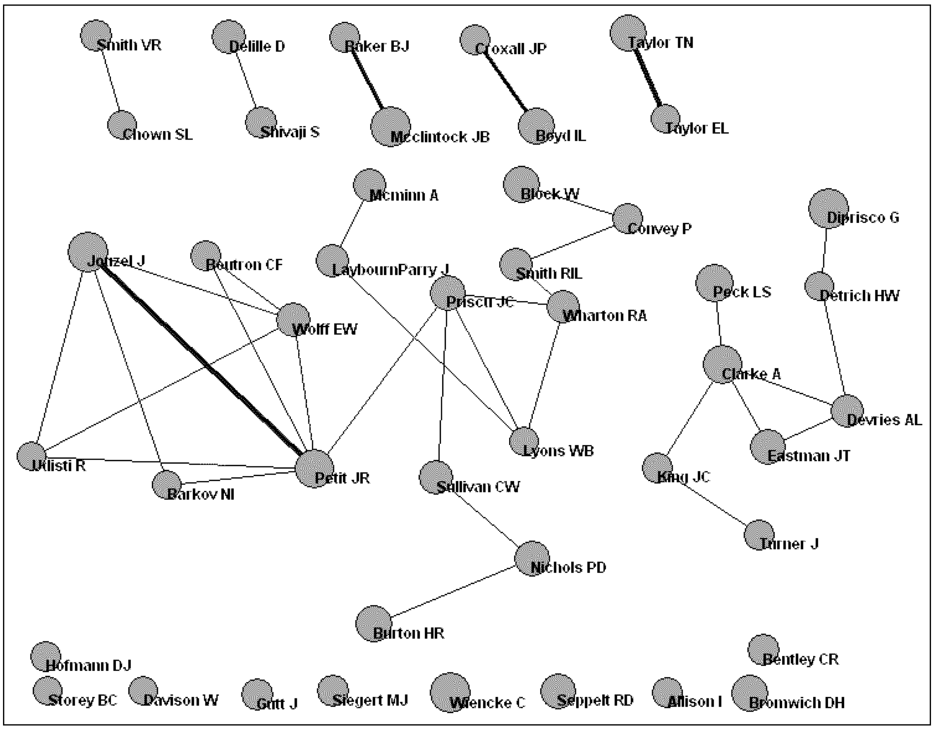

Figure 6. Research collaboration among top 47 most productive authors (N = 14,429)
Note: The thickness of the lines and proximity of the circles indicate collaboration intensity between the authors. Size of the circles depicts productivity of the authors

Highly-cited articles and cutting edge research

The highly-cited articles are the important indicators of their degree of influence, and their work points to the direction of research dynamics. A total of 3,69,045 citations through 18,506 references produced 10,942 articles, with an average of around 34 references per article. The top 20 highly-cited articles have global or commercial significance. The most-cited article of Farman & al. (1985) provides clue to the chemical basis for the depletion of the ozone layer, followed by the articles on glaciology of Antarctic ice sheet. Articles dealing with topics of scientific and commercial interests like Antarctic krill and fish biology, etc. are also prominent in this list. The reporting of 'destruction of ozone' layer in the year 1985 generated the global concern about its protection and several measures were initiated to reduce emissions of greenhouse gases. Out of top 20, 16 articles belonged to the 1980s. The major R&D work was being done in the areas of polar biology, followed by geophysical sciences (Table 7).

Table 6. Rank list of the highly-productive authors in Antarctic research (1980–2004)

	Author name	Productivity (No. of articles)
1	JB McClintock	56
2	C Wiencke	56
3	G Diprisco	53
4	J Jouzel	53
5	A Clarke	52
6	JR Petit	50
7	LS Peck	48
8	W Block	45
9	HR Burton	45
10	DH Bromwich	45
11	TN Taylor	45
12	IL Boyd	45
13	RD Seppelt	42
14	PD Nichols	42
15	JC Priscu	42
16	JT Eastman	41
17	EW Wolff	40
18	CW Sullivan	39
19	D Delille	39
20	A Mcminn	37
21	J Laybournparry	36
22	AL Devries	36
23	RIL Smith	36
24	RA Wharton	36
25	C Gerday	35
26	MJ Siegert	35
27	VR Smith	34
28	J Gutt	33
29	S Shivaji	33
30	CR Bentley	33
31	P Convey	32
32	JP Croxall	31
33	CF Boutron	31
34	J Turner	31
35	I Allison	30
36	BJ Baker	30
37	DJ Hofmann	30
8	JC King	30
39	HW Detrich	29
40	NI Barkov	29
41	EL Taylor	29
42	G Feller	29
43	R Udisti	29
44	WB Lyons	29
45	BC Storey	29
46	W Davison	29
47	SL Chown	29

Table 7. Highly-cited documents in Antarctic science (articles/books) during 1980–2004

	Name of the articles/books	Times cited
1	Farman JC, Gardiner BG & Shanklin JD, 1985: Large losses of total ozone in Antarctica reveal seasonal ClO_X/NO_X interaction, *Nature,* 315, 207.	258
2	Drewry DJ, 1983: The surface of the Antarctic ice sheet, Antarctica: glaciological and geophysical Folio.	185
3	Marr JSW, 1962: The natural history and geography of the Antarctic krill *(Euphausia superba* Dana), 32, 33, Discovery Rep.	170
4	Eastman JT, 1993: *Antarctic Fish Biology* (Academic, San Diego).	144
5	Solomon S, Garcia RR, Rowland FS & Wuebbles DJ, 1986: On the depletion of Antarctic ozone. *Nature*, 321, 755–758.	141
6	Dayton PK, Robilliard GA, Paine RT, Dayton LB, 1974: Biological accommodation in the benthic community at McMurdo Sound, Antarctica. *Ecol. Monogr.*, 44, 105.	133
7	King JC. 1994: Recent climate variability in the vicinity of the Antarctic Peninsula. *Int. J. Climatol*. 14, 357–369	102
8	Clarke A, 1983: Life in cold water: the physiological ecology of polar marine ectotherms. *Oceanogr Mar Biol Annu Rev* 21, 341–453.	101
9	HolmHansen O & Mitchell BG, 1991: Spatial and temporal distribution of phytoplankton and primary production in the western Bransfield Strait region, *Deep-Sea Res.*, 38, 961–980.	100
10	Petit JR, 1999: Climate and atmospheric history of the past 420000 years from the Vostok ice core, Antarctica. *Nature*, 399. 429–436.	100
11	Bromwich DH, 1988: Snowfall in high southern latitudes. *Rev. Geophysics*, 26(1), 149–168.	96
12	Parish TR & Bromwich DH, 1987: The surface windfield over the Antarctic Ice Sheets. *Nature*, 328, 51–54.	95
13	Dayton PK & Oliver JS, 1977: Antarctic soft-bottom benthos in oligotrophic and eutrophic environments. *Science,* 197, 55–58.	94
14	Vincent WF, 1988: *Microbial Ecosystems of Antarctica.* Cambridge University Press, Cambridge.	94
15	McElroy MB, Salawitch RJ, Wofsy SC & Logan JA, 1986: Reductions of Antarctic ozone due to synergistic interactions of chlorine and bromine. *Nature*, 321, 759–762.	113
16	Stuiver M, Denton GH, Hughes TJ & Fastook JL, 1981: History of the marine ice sheet in West Antarctica during the last glaciation: A working hypothesis: In Denton, G. H., and Hughes, T. J., Eds., *The Last Great Ice Sheets*, New York, Wiley-Interscience, 319–439.	113
17	Smith WO & Nelson DM, 1985: Phytoplankton bloom produced by a receding ice edge in the Ross sea – spatial coherence with the density field. *Science*, 227, 163.	112
18	Schwerdtfeger W. 1984: *Weather and Climate of the Antarctic: Developments in Atmospheric Science*, 15, Elsevier, Amsterdam, 261 p.	111
19	Orsi AH, Whitworth T & Nowlin WD Jr, 1995: On the meridional extent and fronts of the Antarctic Circumpolar Current. *Deep-Sea Res*., 42, 641–673.	111
20	White WB & Peterson R, 1996: An Antarctic circumpolar wave in surface pressure, wind, temperature, and sea ice extent. *Nature*, 380, 699–702.	108

Core-journals in Antarctic science

The 10,942 articles of our database were published in 961 journals/documents. A majority of them were published in the journal, *Polar Biology.* Study revealed that 'biology' was the most popular area of research in Antarctic science. It was followed by geophysics. The journal *Antarctic Science* was the fourth most-productive journal in terms of publishing research articles on Antarctic science (Table 8). Significant percentage (around 40%) of the papers in the area of Antarctic science are published in these 16 journals (1.66%).

Highly-cited journals in Antarctic science

18,506 journals/documents carrying 369,045 citations were used to produce 10,942 articles. Multidisciplinary journals *Nature* and *Science*, published from the UK and the USA respectively, were the most-cited journals. These were followed by *Polar Biology*, *Journal of Geophysical Research* and *Antarctic Science* (Table 9).

Table 8. Most productive journals publishing articles on Antarctic science (N = 961)

Sl. no	Journals title	Publishing country	No of articles
1	*Polar Biology*	USA	987
2	*Geophysical Research Letters*	USA	372
3	*Journal of Geophysical Research – Atmospheres*	USA	345
4	*Antarctic Science*	UK	316
5	*Annals of Glaciology*	UK	273
6	*Marine Ecology – Progress Series*	Germany	224
7	*Nature*	UK	206
8	*Journal of Glaciology*	UK	202
9	*Journal of Geophysical Research – Oceans*	USA	163
10	*Marine Biology*	USA	156
11	*Earth and Planetary Science Letters*	Netherlands	134
12	*Meteoritics & Planetary Science*	USA	126
13	*Deep-Sea Research Part II – Topical Studies in Oceanography*	UK	125
14	*Science*	USA	113
15	*Hydrobiologia*	Netherlands	109
16	*Geology*	USA	101

Table 9. Highly-cited journals in Antarctic science

Sl no.	Journals title	Publishing country	Times cited
1	*Nature*	UK	4634
2	*Science*	USA	3351
3	*Polar Biology*	USA	2722
4	*Journal of Geophysical Research*	USA	2570
5	*Antarctic Science*	UK	1995
6	*Geophysical Research Letters*	USA	1670
7	*Marine Biology*	USA	1629
8	*Antarct Journal of US*	USA	1586
9	*Marine Ecology – Progress Series*	Germany	1513
10	*Antarctic Research Series*	USA	1459
11	*Deep Sea Research*	England	1397
12	*Limnology & Oceanography*	USA	1320
13	*Earth Planet Science Letters*	Netherlands	1292
14	*Annals of Glaciology*	UK	1202
15	*Journal of Glaciology*	UK	1178
16	*Journal of Geophysical Research – Oceans*	USA	1131
17	*Geochim Cosmochim Ac*	UK	1085
18	*Geology*	USA	1071
19	*Journal of Geophysical Research–Atmosphere*	USA	1001
20	*Journal of Experimental Marine Biology and Ecology*	Netherlands	829

Highly-cited authors in Antarctic science

The highly-cited authors in Antarctic research have been listed in Table 10. A. Clarke has been found as the most-cited author in Antarctic science, followed by A. L. Gordon and O. Holmhensen. A. Clarke and O. Holmhensen both work in the areas of Polar biology and ecology. For A. L. Gordon the research areas are glaciology and physical oceanography of Antarctic waters.

Co-citations in Antarctic science

SMALL [1973] proposed ‘co-citation’ as a measure to model the intellectual structure of scientific specialties If A is the set of papers that cite document X and B is the set of papers that cite document Y, then $A \cap B$ is the set of documents that cite both X and Y. The number of elements in $A \cap B$, denoted as $\# A \cap B$, is the co-citation frequency of X and Y. Essentially, co-citation frequency is defined as the frequency with which two documents are cited together [EGGHE & ROUSSEAU, 2002].

Table 10. Rank-list of the highly-cited authors in Antarctic science

	Most cited authors	Times cited
1	A Clarke	596
2	AL Gordon	364
3	O Holmhensen	339
4	DJ Drewry	335
5	SZ Elsayed	328
6	PK Dayton	313
7	RIL Smith	313
8	SS Jacobs	310
9	JT Eastman	307
10	JP Croxall	301
11	I Everson	300
12	WF Vincent	296
13	PJ Barrett	291
14	S Solomon	286
15	WO Smith	283
16	PF Barker	280
17	GH Denton	279
18	JC Farman	270
19	DH Bromwich	269
20	WF Budd	265
21	W Schwerdtfeger	262
22	HJ Zwally	257
23	J Jouzel	250
24	RB Alley	249
25	JP Kennett	248
26	JB Anderson	243
27	JC King	241
28	J Priddle	227
29	AC Palmisano	226
30	DG Vaughan	225
31	DL Garrison	222
32	JR Petit	217
33	IWD Dalziel	213
34	RB Heywood	211
35	DH Elliot	211
36	M Stuiver	210
37	TR Parish	205
38	CR Bentley	202

Co-citation blocks represent the semantic relationships between the cited elements, authors with similar or compatible research interests form the co-citation blocks and together they define a 'research front'. In this analysis an attempt has been made to visualize the research fronts, and to draw its profile structure through author co-citation analysis. Apart from defining research fronts, it is a useful retrieval tool to identify authors with similar research interests. The distribution of the co-citation blocks is similar to the citedness profile. Authors with higher level of co-citedness are also the most-cited authors individually (Tables 10 and 11). This phenomenon was also observed in the study on ocean engineering [DASTIDAR & RAMACHANDRAN, 2005]. The highest co-citation frequency was formed by J. C. Farman and S. Solomon. Both work on ozone depletion and are highly-cited individually. The co-citation map of top 39 most-cited authors did not show any core-periphery structure.

Table 11. Highly co-cited first authors in Antarctic science

	Cited author 1	Cited author 2	Co-citation frequency (1 + 2)
1	JC Farman	S Solomon	171
2	SZ Elsayed	O Holmhensen	147
3	SZ Elsayed	WO Smith	111
4	O Holmhansen	WO Smith	109
5	DH Bromwich	TR Parish	105
6	A Clarke	JT Eastman	100
7	TR Parish	W Schwerdtfeger	100
8	J Jouzel	JR Petit	97
9	A Clarke	PK Dayton	94
10	DI Garrison	AC Palmisano	89
11	A Clarke	IEverson	86
12	GH Denton	M Stuiver	84
13	<Anon>	JC Farman	84
14	GH Denton	DJ Drewry	80
15	GH Denton	DJ Drewry	89
16	DH Bromwich	W Schwerdtfeger	79
17	AI Gordon	SS Jacobs	76

Conclusion

There are around 37 year-round stations in Antarctica maintained by 20 consultative parties, out of which 7 countries are having more than one station. The USA has the largest research complex in Antarctica. It has by far sent the maximum manpower to the Antarctica, followed by Argentina, Russia, Australia and the UK [COMNAP, 2005, TABLE 3]. The US Antarctic Programme (USAP) also hosts visiting scientists from other Antarctic Treaty countries. The USA is the lead country in Antarctic science research. Its sound policies, higher per capita domestic expenditure on R&D, making both universities and research institutions equal partners in research and development activities, and emphasis on collaborative projects have made it the leader in the Antarctic science research. Only eighteen countries have shown productivity of more than 100 papers during the study period. The network map of highly-productive countries shows a distinct core-periphery structure; the countries in the central cluster are the most-productive countries and occupy an influential position in the Antarctic science research (Figure 4).

Productivity in science is investment-dependent. As has been seen in the case of ocean science and ocean engineering [DASTIDAR, 2004], the most-productive countries in Antarctic science also have higher GERD (Gross Domestic Expenditure on R&D) than the less-productive countries. The social and political objectives of the nations also play a significant role in shaping the scientific enterprise of the nations (UNESCO, 2005). The GERD of the USA was 954 USD and that of the UK was 491 USD, in 2002, whereas for a middle-level country, it was quite low. For example, for India and the Chile, it was only 21 USD and 52 USD respectively (Table 2). The result is visible in their respective outputs. The consultative parties were the major players in the field. The top 22 countries were the consultative parties, except Canada, which in spite of being not a consultative party, was active in Antarctic science research. Non-treaty countries also showed their interest in Antarctic science. In all, more than 80 countries of the world showed scientific interest in this continent (Table 2). Consultative parties like Ecuador, Peru and Uruguay did not show much evidence of scientific productivity on Antarctic science [DASTIDAR & PERSSON, 2005].

There are small clusters of collaboration at the individual level. It indicates formation of smaller interest groups. There are many small dyadic clusters in the author collaboration network. These smaller units can be grown into bigger collaboration networks. The isolates may be encouraged to participate in collaborative projects to address bigger multidisciplinary issues collectively.

Limitations of the study

Data used in the analysis were culled from Science Citation Index (CD-ROM) database. To many countries, research in Antarctic science is a matter of national pride. Therefore, some countries publish their research findings in their own national periodicals which might not be covered in SCI database. Chile, for example, until 2001, used to bring out two publications – a "Scientific Series" and a "Bulletin". Similarly, India also publishes its scientific findings in "Scientific Reports". Thus, the results published in several journals or documents were not included in the analysis. Retrieval methodology used in this analysis could also leave out some articles.

*

The authors express their gratitude to Prof. Olle Persson, Head, Sociology Department, Umeå University, Sweden, for his guidance and constructive suggestions. The authors are thankful to Dr. Jose Retamales, Director, Instituto Antártico Chileno, Punta Arenas, Chile for his suggestions and showing keen interest in the work. The authors are also thankful to Dr. B.S. Aggarwal for editing the manuscript.

Note: The opinion expressed in the article is of the authors, not necessarily of the institute where they belong.

References

ANONYMOUS (2002), *Handbook of the Antarctic Treaty System (ATS) (2002)*, July: U S Department of State, Washington DC, July.

ANONYMOUS (2006), *Journal Selection Process*, retrieved on 19 July, 2006 from: http://scientific.thomson.com

ANTARCTIC TREATY SECRETARIAT (2006), accessed on June 23, 2006 from: http://www.ats.aq/uploaded/SIGNEDINWASHINGTON.pdf

ANTARCTIC TREATY SECRETARIAT (2004), *Final Report of the Twenty-Seventh Antarctic Treaty Consultative Meeting (ATCM)*, 14 May–4 June, Cape Town.

BORGATTI, S. P., EVERETT, M. G., FREEMAN, L. C. (2002), *UCINET for Windows: Software for Social Network Analysis*. Harvard: Analytic Technologies.

CIA (2006), *World Fact Book*, retrieved on18th July, 2006 from: http://www.cia.gov/cia/publications/factbook

COUNCIL OF MANAGERS OF NATIONAL ANTARCTIC PROGRAMS (COMNAP) (2005), *COMNAP report to Antarctica Treaty Consultative Meeting (ATCM) XXVIII*.

DASTIDAR, P. G., PERSSON, O. (2005), Mapping the global structure of Antarctic research *vis-à-vis* Antarctic Treaty System. *Current Science* 89 (2) : 11552–11554.

DASTIDAR, P. G. (2004), Ocean Science & Technology research across the countries: A global scenario. *Scientometrics*, 59 (1) : 15–27.

DASTIDAR, P. G., RAMACHANDRAN, S. (2005), Engineering research in ocean sector: An international profile. *Scientometrics*, 65 (2) : 199–213.

DASTIDAR, P. G. (2007), National and institutional productivity and collaboration in Antarctic science: an analysis of 25 years of journal publications (1980–2004), *Polar Research* (forthcoming).

EGGHE, L., ROUSSEU, R. (2002), Co-citation, bibliographic coupling, and a characterization of lattice citation network. *Scientometrics* 55 (3) : 349–361.

FREEMAN, L. C. (1979), Centrality in social networks: Conceptual clarification. *Social Networks*. 1 : 215–239.

GARFIELD, E. (1990), How ISI selects journals for coverage: quantitative and qualitative Considerations. *Current Contents*, May 28.

GARFIELD, E. (1996), The significant scientific literature appears in a small core of journals. *The Scientist*, 10 (17), Sept. 2.

HANNEMAN, R. (2006), *Introduction to Social Network Methods*, http://www.faculty.ucr.edu/~hanneman/, accessed on 22 June 2006.

INTERNATIONAL ASSOCIATION OF ANTARCTICA TOUR OPERATORS (IAATO) (2006), *IAATO Overview of Antarctic Tourism 2005–2006 Antarctic Season*, Information Paper Submitted by the IAATO to XXIX ATCM, Edinburgh.

LEYDESDORFF, L. (2001), The sociology of science, In: *The Challenges of Scientometrics: The Development, Measurement and Self-organization of Scientific Communications*, Universal Publishers, pp. 15–35.

PERSSON, O. (2004), *BIBEXCEL, A Tool-Box for Scientometric Analysis*, retrieved on 25th December from: http;//www.umu.se/inforsk/Bibexcel.

SMALL, H. (1973), Co-citation in the scientific literature: A new measure of the relationship between two documents, *Journal of the American Society for Information Science*, 24 : 265–269.

UNESCO INSTITUTE OF STATISTICS (2005), *Human Resources in R & D*.

WASSERMAN, S., FAUST, K. (1994), *Social Network Analysis, Methods and Applications*. Cambridge, Cambridge University Press.