Citation analysis to reconstruct the dynamics of Antarctic ozone hole research and formulation of the Montreal Protocol

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The ozone layer acts like a shield in safeguarding the Earth by preventing the harmful ultraviolet radiations from entering into the atmosphere. Reported damage to the ozone layer in 1985 was a significant milestone in Antarctic science research. The research work played a significant role in generating international socio-political debate on this great environmental crisis. This article aims to reconstruct the intellectual developments in the field and identify important scientific events which contributed to the formulation of the world's most successful multilateral treaty, the Montreal Protocol. The dynamics of the research field was mapped using a newly developed indicator – weighted direct citations (WDC). The WDC value indicates intellectual closeness between two citations in terms of co-citations and shared references. Direct citations were weighted with shared references and co-citations to derive WDC values. An attempt was made to decompose the citation network of articles to identify significant activity layers. The work of J. C. Farman et al. (1985) and S. Solomon (1986), which are the top two most cited significant papers in the subject accounts for top WDC values jointly.

Keywords: Bibexcel, ozone hole, policy research, protocol, scientometrics, weighted direct citation.

ALMOST 90% of ozone in the atmosphere is found in the stratosphere layer of the atmosphere that lies between 10 and 50 km above the Earth's surface. This thin layer of ozone acts as a shield by preventing harmful ultraviolet radiations from entering into the Earth's atmosphere. Without the ozone layer, most animals and plants would not survive, and significant depletion would cause cancer and other serious diseases in people. Hence it plays a significant role in protecting life on Earth. The reported damage to the ozone layer above the Earth's surface was the most significant discovery by scientists of the British Antarctic Survey (BAS) in 1985[1], which had attracted worldwide attention for its likely adverse effects on human health and the environment. Almost instantaneously, 'Save ozone layer' became an international movement. A series of negotiations taking into account technical and economic considerations and developmental needs of the developed and developing countries resulted in the Montreal Protocol, which was regarded as 'perhaps the single most successful international agreement to date', as quoted by Kofi Annan, former Secretary General, United Nations. It turns out that industrialization and lifestyle change throughout the world were the factors responsible for ozone hole damage. The Montreal Protocol was drafted to protect the ozone layer by phasing out the production of numerous substances believed to be responsible for ozone depletion[2]. The treaty entered into force on 1 January 1989 and has been ratified by more than 195 countries and generated worldwide campaign to meet this serious environmental disaster[2,3]. Furthermore, the phasing out of ozone depleting substances (ODS) has helped fight climate change since many ODS are also powerful greenhouse gases. The scientific community took up the issue as a challenge and saw a great upsurge in ozone hole research (Figure 1).

Ever since Eugene Garfield[4] proposed a new dimension in documentation through association of ideas in 1955, citations are being used regularly to delineate developments in any research field. It was underlined that it is more remarkable because citation-based system is a quantitative and objective algorithm that does not rely on subjective or qualitative enhancements[5].

It was found that careful citation mapping leads to the uncovering of small but important historical links overlooked by even the most diligent scholars[6–8]. Price[9] pointed out that the pattern of bibliographic references can be used to identify the nature of scientific research front. One way of mapping the dynamics of a field is to reduce the number of direct citation links by the citation time lag. With successive shortening of time lag, one or

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several components linked by papers published in the same year range can be reconstructed. As suggested by Persson[10,11], direct citations could be weighted by a number of indirect citations coupled to it. If paper A cites B, that citation would be stronger if both papers are co-cited by other papers or share citations to other papers, a measure called weighted direct citations (WDC; Figure 2).

In another study[12], citations were used to reconstruct significant events toward development of DNA theory. Co-citation data have been used routinely to identify research fronts. Citation linkages between groups of papers associated with any individual can be used to construct a map of core papers for any specialty[6,7]. In this article, we have attempted to reconstruct the development of Antarctic ozone research and identify milestone papers which contributed significantly in developing the field. The authors attempted to visualize how ideas are interconnected with each other contributing to a broad understanding of this problem.

Materials and methods

Direct citations, shared references and co-citations have been used as similarity measures to detect past and emerging research themes. Shibata *et al.*[13] found that direct citations performed better in detecting research themes earlier compared to co-citations, the main explanations being that it takes time to build co-citations. They also found that papers connected by direct citations had the strongest clustering tendency. Direct citation becomes stronger if the two papers are co-cited by other papers. Then, the strongest direct citation links would be those that share many references and are frequently co-cited. Persson[10,11] suggested a measure combining all three, direct citations, co-citations and shared references into one indicator; WDC (Figure 2).

Around 362 articles were retrieved from the *Web of Science* database by searching titles with search term 'Ozone* and Antarctic*'. The articles were downloaded for analysis. Bibexcel software[14] was used to arrange the citations year-by-year and WDC values among citation links were calculated. A citation network map with 1-year citation time lag with WDC values greater than 10, was drawn using Pajek software[15] (Table 1 and Figures 3 and 4).

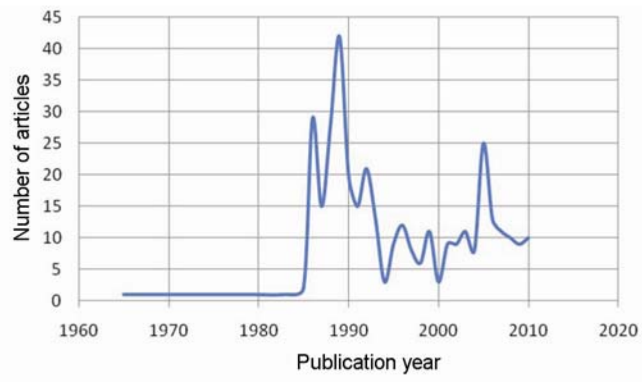

Figure 1. Growth of scientific research in Antarctic ozone hole research.

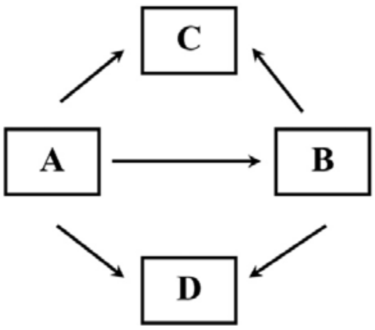

Figure 2. Computation of weighted direct citation values using shared and co-citation frequencies.

Results and discussion

In 1970, Crutzen[16] showed that the nitrogen oxides NO and NO_2 react with ozone to hasten its destruction without being destroyed themselves. It was research and awareness that played an important role to build an international movement and drafting of the Montreal Protocol[17]. In 1974, Molina, a postdoctoral fellow working in Rowland's laboratory at University of California at Irvin, showed the threat to ozone layer posed by chlorofluorocarbon (CFC) gases[18]. This landmark paper showed that CFC gases were used widely in spray cans, refrigerators and plastic foams. The authors pointed out that these chemically inert gases may remain in the atmosphere up to 150 years. Photo dissociation of these gases in the stratosphere produces significant amounts of chlorine atoms and leads to the destruction of atmospheric ozone.

Recognizing the significant contribution of their work, The Nobel Prize in Chemistry 1995 was awarded jointly to Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland 'for their work in atmospheric chemistry, particularly concerning the formation and decomposition of ozone'.

The Nobel Committee remarked that the scientists' work 'contributed to our salvation from a global environmental problem that could have catastrophic consequences'. Their research revealed much about the processes that regulate the ozone content of the atmosphere. The three winners of the Nobel Prize in Chemistry are the first ever to receive the award for atmospheric chemistry or environmental science.

Antarctic ozone hole monitoring started with the pioneering work of Gordon Dobson in establishing a global network for ozone monitoring in the International Geophysical Year with instruments installed at British,

Table 1. Weighted direct citation frequency of top 11 citing-cited articles

WDC	Citing article	Cited article
72	Solomon, 1986, **321**, 755	Farman, 1985, **315**, 207
58	Stolarski, 1986, **322**, 808	Farman, 1985, **315**, 207
56	Mcelroy, 1986, **321**, 759	Farman, 1985, **315**, 207
37	Stolarski, 1986, **322**, 808	Solomon, 1986, **321**, 755
36	Tung, 1986, **322**, 811	Farman, 1985, **315**, 207
35	Tung, 1986, **322**, 811	Solomon, 1986, **321**, 755
34	Stolarski, 1986, **322**, 808	Mcelroy, 1986, **321**, 759
33	Tung, 1986, **322**, 811	Mcelroy, 1986, **321**, 759
32	Hofmann, 1987, **326**, 59	Farman, 1985, **315**, 207
32	Crutzen, 1986, **324**, 651	Solomon, 1986, **321**, 755
32	Crutzen, 1986, **324**, 651	Farman, 1985, **315**, 207

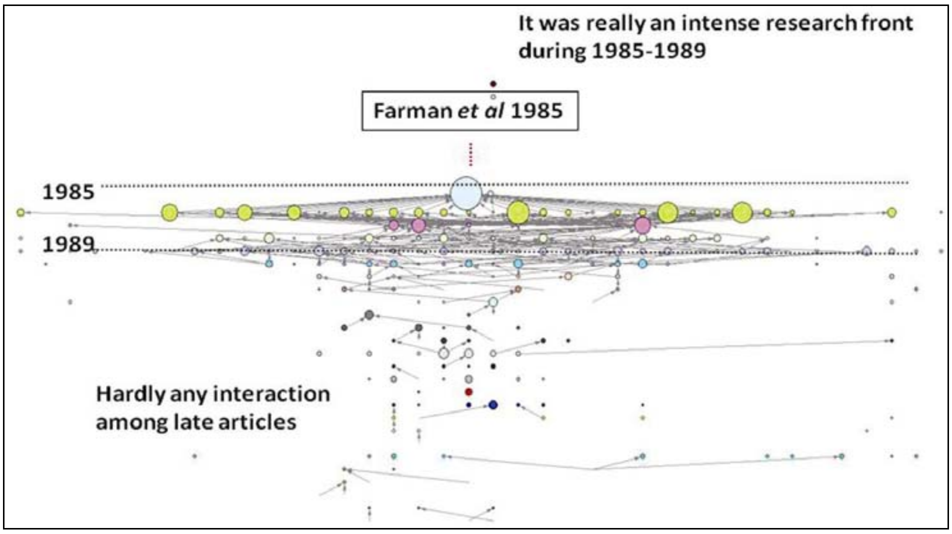

Figure 3. Citation network in year layers.

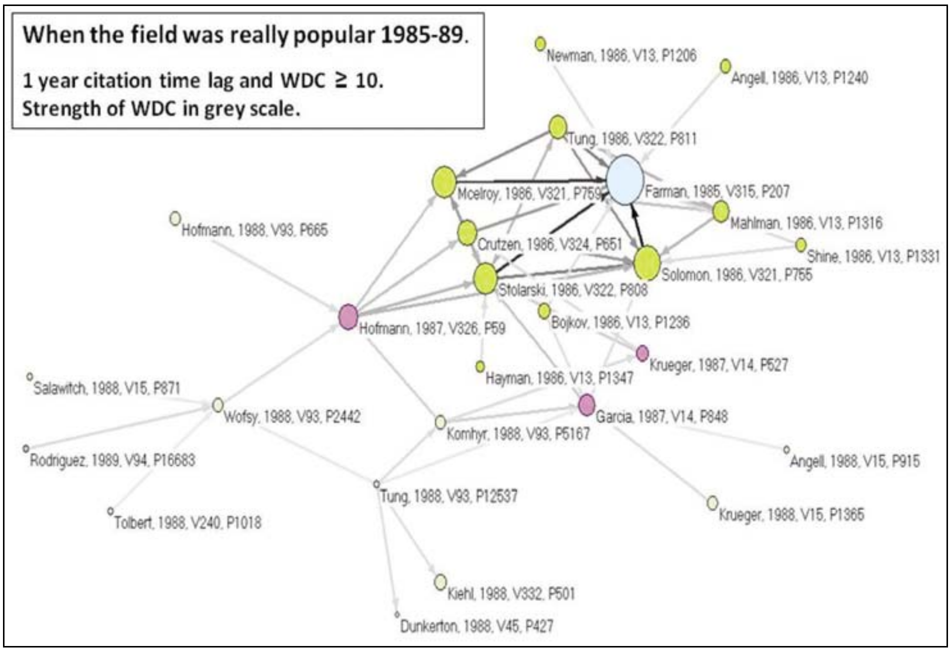

Figure 4. Citation network with 1-year citation time lag with weighted direct citation (WDC) values greater than 10. Strength of WDC is shown in grey scale.

Table 2. Most cited articles on ozone research in Antarctica (N = 4995)

Time cited			
Web of Science	*Scopus*	Paper detail	Type of the paper
162	976	Farman, J. C., Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction. *Nature*, 1985, **315**, 207.	Monitoring and survey
82	475	Solomon, S., On depletion of Antarctic ozone. *Nature*, 1986, **321**, 755.	Methods and theories
63	214	Mcelroy, M. B. *et al.*, 1986, Reductions on Antarctic ozone due to synergistic interactions of chlorine and bromine. *Nature*, 1986, **321**, 759.	Methods and theories
61	78	Stolarski, R. S., Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease. *Nature*, 1986, **322**, 808.	Methods and theories
43	232	Molina, L. T. and Molina, M. J., Production of Cl_2O_2 from the self-reaction of the ClO radical. *J. Phys. Chem*., 1987, **91**, 433.	Methods and theories
42	206	*Crutzen, P. J., Nitric acid cloud formation in the cold Antarctic stratosphere: A major cause for the springtime 'ozone hole'. *Nature*, 1986, **324**, 651.	Methods and theories
41	16	Hofmann, D. J., Balloon-borne observations of the development and vertical structure of the Antarctic ozone hole in 1986. *Nature*, 1987, **326**, 59.	Monitoring and survey
38	–	Tung, K. K. *et al.*, Are Antarctic ozone variations a manifestation of dynamics or chemistry? *Nature*, 1986, **322**, 811.	Methods and theories
34	–	Toon, O. B. *et al.*, Condensation of HNO_3 and HCl in the winter polar stratospheres. *Geophys. Res. Lett.*, 1986, **13**, 1284.	Methods and theories
29	–	Nash, E. R., An objective determination of the polar vortex using Ertel's potential vorticity. *J. Geophys. Res. Atmos*., 1996, **101**, 9471.	Methods and theories
29	–	Garcia, R. R., A possible relationship between inter-annual variability in Antarctic ozone and the quasi-biennial oscillation. *Geophys. Res. Lett.*, 1987, **14**, 848.	Methods and theories
28	–	Mahlman, J. D., Antarctic ozone decreases: a dynamical cause? *Geophys. Res. Lett.*, 1986, **13**, 1316.	Monitoring and survey
26	162	Solomon, S., The mystery of the Antarctic ozone 'hole'. *Rev. Geophys*., 1988, **26**, 131.	Methods and theories
24	306	*Molina, M. J., Antarctic stratospheric chemistry of chlorine nitrate, hydrogen chloride and ice: release of active chlorine. *Science*, 1987, **238**, 1253.	Methods and theories
23	–	Dezafra, R. L., High concentrations of chlorine monoxide at low altitudes in the Antarctic spring stratosphere: diurnal variation. *Nature*, 1987, **328**, 408.	Monitoring and survey
23	–	Mccormick, M. P., Polar stratospheric cloud sightings by SAM II. *J. Atmos. Sci.*, 1982, **39**, 1387.	Monitoring and survey
23	–	Solomon, S., Progress toward a quantitative understanding of Antarctic ozone depletion. *Nature*, 1990, **347**, 347.	Methods and theories

*Awarded Nobel Prize in 1995.

Japanese and American Antarctic stations in 1957. The publication of a significant paper by Farman *et al.*[1] reporting for the first time about ozone hole in the stratosphere became one of the global environmental issues of the 20th century. It played a crucial role in stimulating the onset of focused research into stratospheric ozone above Antarctica, moving the community from a purely monitoring role to one concerned with processes. Focus on studies about the science of ozone depletion and chemicals responsible for ozone depletion increased substantially[19,20].

Fundamental work on methods and theories along with monitoring and survey constituted major areas of research (Table 2). Eventually the research outcomes could significantly contain the ozone damage and this saw a gradual decline in research in the subject (Figure 1). Publication pattern clearly follows a geopolitical development associated with the subject.

Weighted direct citations vis-á-vis citation network

Direct citation indicates influence of a paper on subsequent research work; co-citation depicts the relatedness of papers at cited dimension with a tendency to be cited together. The shared references depict usefulness of papers at citing dimension. In WDC, all three indicators have been combined into one. Higher the WDC values more will be the influence of papers at cited and citing dimension.

One way of mapping the dynamics of the field is to reduce the number of direct citation links by successively minimizing the citation year lag. Another approach is to remove the weakest links from the citation network[11]. The year cross-section of citation networks in ozone layer research presents a nice picture of the dynamics of the field. Citation network depicts an intense research activity during 1985 and 1989, which reduced considerably in the following years. During this period an intense geopolitical activity to find scientific solution to this great environmental crisis was also developed.

WDC values provide currency status of research by quantitatively assigning values to citing-cited linkages. Table 1 gives the list of top 11 citing-cited papers in terms of WDC values arranged in descending order. It is evident that Farman *et al.*[1] have played a central role in initiating research momentum in the subject (Figure 3). The research front has registered intense activity during the initial years of 1985–1989.

Frequency distribution of WDC values in Table 1 shows the importance of the paper by Farman *et al.*[1] in influencing research activities on methods and theories. Citation network with 1-year citation lag with WDC values greater than 10 shows intense research activities where Farman *et al.*[1] is a dominant node (Figures 3 and 4).

Most cited papers in Antarctic ozone layer research in Antarctica

The most cited references reflect the influence of a research work on subsequent research activities. The top most-cited significant papers from a large corpus of 4995 research articles are given in Table 2. It is evident that the paper by Farman *et al.*[1] is the most influential one (most-cited) recorded both in *Web of Knowledge* and *Scopus*, world's two largest citation and abstracting databases[21,22]. The paper attracted wide scientific interest around the world as well as rapidly becoming of interest to politicians because of the related health and economic issues. Funding agencies responded rapidly and there was soon a rise in research papers (methods and theories) attempting not only to explain the processes but also with suggestions on how to mitigate the damage. The work of Paul J. Crutzen, Mario J. Molina and F. Sherwood Rowland to delineate the role of chlorine in stratospheric chemistry and identification of the industrial chemical CFC used as solvent, refrigerant, etc. resulted in the Nobel Prize in Chemistry in 1995. Solomon is also one of the most-cited authors in Antarctic science as a whole[23]. The significant discovery played an important role in drafting a multilateral treaty – Montreal Protocol[17], a force behind adopting long-term measures in combating this environmental disaster.

Most active countries in research

USA and UK account for more than 50% research in this area. USA is also the leading player in Antarctic science research as a whole, followed by UK, Germany and Japan (Table 3). USA was also the lead collaborator in Antarctic ozone hole research, followed by UK and Switzerland[23,24].

Table 3. Top-10 most productive countries in ozone research in Antarctica

Country	Productivity (number of articles)
USA	190
UK	48
Germany	24
Japan	24
France	21
New Zealand	19
Italy	17
India	16
Russia	14
Australia	12

Molina and Rowland from USA along with Crutzen from Germany bagged the Nobel Prize in chemistry in 1995 for their work on the formation and decomposition of ozone. Their research formed a scientific basis for the Montreal Protocol, which played an important role for combating ozone layer damage. In terms of productivity, UK stands only next to USA and played a significant role in Antarctic ozone research. Significant contribution to Antarctic ozone research by USA and UK can be attributed to the fact that until 1980, only UK, Japan and USA had ozone measuring programme from Antarctica[25]. And the first reported damage of the ozone layer was culmination of long-term ozone monitoring undertaken by the scientists of the BAS since 1957. This played an important role for the rise of ozone hole research in Antarctica, and indeed a geopolitical movement which saw the world's most successful multilateral treaty to control escalation of the crisis.

Conclusion

As a single indicator, WDC captured the influence of scientific articles in both cited and citing dimensions and was used to reconstruct the dynamics of Antarctic ozone hole research. It generated a geopolitical movement which was instrumental in formulating the Montreal Protocol on substances that deplete the ozone layer. The protocol spelt out a time limit for the production of nearly 100 chemicals responsible for ozone layer damage. The pivotal discovery of ozone hole by Farman *et al.*[1] of BAS played a crucial role in generating momentum in Antarctic ozone hole research. Perhaps this discovery arguably will remain as the most important scientific contribution of BAS in Antarctic science. Temporal cross-section of citations captured the growth dynamics. Most cited papers revealed the demand from the subject specialty to deal with this phenomenon. Three scientists were awarded the Nobel Prize in 1995 for their significant contribution to deal with this global environmental crisis.

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