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Explaining International Co-Authorship in Global Environmental Change Research

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Abstract

This paper maps the domain of earth and environmental sciences (EES) and investigates the relationship between cognitive problem structures and internationalisation patterns, drawing on the concepts of systemic versus cumulative global environmental change (GEC) and mutual task dependence in scientific fields. We find that scientific output concentration and internationalisation are significantly higher in the systemic GEC fields of Meteorology & Atmospheric Sciences and Oceanography than in the cumulative GEC fields Ecology and Water Resources. The relationship is explained by stronger mutual task dependence in systemic GEC fields. In contrast, the portion of co-authorships with developing, emerging and transition countries among all international publications is larger for Water Resources than for the three other fields, consistent with the most pressing needs for STI capacity development in these countries.

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Introduction

This paper investigates international collaboration in earth and environmental sciences (EES) by a combination of theoretical considerations and bibliometric methods. We start from three observations: a) Some EES disciplines are among the most internationalised fields of science, but this finding has not been explained so far. b) The geographical location and extension of research objects can influence decisions to collaborate. c) Since environmental problems and related innovation needs are ubiquitous, collaboration between scientifically advanced and less developed countries is an important issue.

According to Whitley (2000), the social organisation of scientific fields is strongly linked to their cognitive problem structures. A general distinction in this respect is between fundamental versus applied research. With regard to EES disciplines, another important distinction was introduced by Turner et al. (1990): systemic global environmental change (systemic GEC) and local or regional environmental changes that become global by worldwide accumulation (cumulative GEC). Our analysis shows that these spatial problem structures can explain different levels of internationalisation across environmental fields.

The paper gives for the first time a comprehensive overview of all EES fields based on relevant subject categories in the SCI (section 1). After a review of the bibliometric literature on internationalisation in EES (section 2), the main part investigates the relationship between spatial problem structure and internationalisation by comparing four SCI subfields in depth: Meteorology & Atmospheric Sciences, Oceanography, Ecology and Water Resources (section 3). This includes the theoretical discussion of spatial problem structures and their influence on collaboration decisions, the formulation of hypotheses, a description of the bibliometric methods used and a discussion of results. The main conclusions are presented in section 4.

1. Earth and Environmental Fields in the SCI

This section gives an overview on earth and environmental research as covered by the Science Citation Index (SCI). The SCI contains about 170 subject categories, from A-coustics to Zoology. Each SCI subject category is composed of a set of journals. 21 subject categories were selected that are directly related to knowledge of the environment.[1] SCI subject categories are a good starting point for bibliometric mapping, because such field delineations are easy to interpret and replicable. On average, a subject category contains ca. 35 journals (i.e. 5,900 journals divided by 170 categories), ranging from more than 50 journals for large and about a dozen for small categories. The total set of the 21 earth and environmental research fields accounts for 9.3 % of all SCI publications in 2002.

Table 1 gives an overview of all 21 earth and environmental subject categories (EES fields). The fields are grouped in three content domains: 36.7 % of all environmental publications cover the *geosphere*, the non-living environment on earth. Research on the *biosphere*, encompassing life and organic matter, accounts for 49.7 % of the total environmental output, whereas research related to the *management of environmental resources and environmental engineering* amounts to 22.5 % (some articles are assigned to more than one domain). For each domain, Table 1 lists the number of articles per field in descending order, as well as a comparison of output growth rates.

In the period from 1990-2002 publication output grew more strongly in the environmental management & engineering and in the geosphere fields than in the biosphere subset. The growth rate in the biosphere set (135) is slightly below that of the SCI total (147), whereas the growth in the set of all 21 EES fields (152) is similar to the database

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1 A few additional fields could be included in a still broader definition of environmental research (e.g. Agronomy, Energy & Fuels, or Toxicology).

average (the SCI contained 886,981 publications in 2002). Behind this broad comparison lie very different growth rates of individual fields. Six fields showed a doubling in volume or more since 1990: Meteorology & Atmospheric Sciences, Oceanography, Paleontology, Ecology, Environmental Engineering and Water Resources. Three fields were newly introduced to the database during this period: Remote Sensing, Geochemistry & Geophysics and Biodiversity Conservation.

Table1 about here

Figure 1 maps the 21 EES fields as a network. Circle size represents the number of articles in each field in the period 2001-2003. Linkages represent the degree of overlap among pairs of fields, based on the assignment of some journals to more than one subject category. Overlap is measured by the number of shared articles divided by the mean size of the two fields. For example, 8,000 articles belong to both Oceanography (field size 16,796 articles) and Meteorology & Atmospheric Sciences (23,193 articles) in 2001-2003. A linkage of 0.4 results, which is the strongest linkage observed among the environmental categories.

Figure 1 about here

The network graph underlines the relevance of the three domains geosphere, biosphere and environmental management & engineering for the cognitive organisation of environmental research. It shows two clusters and one pair of strongly overlapping fields. The first cluster is found in the geosphere domain, including the fields Meteorology & Atmospheric Sciences, Oceanography, Geochemistry & Geophysics, and Multidisciplinary Geosciences. The second cluster comprises all three fields of environmental management & engineering (Environmental Sciences, Environmental Engineering and Water Resources). The subject categories in the biosphere domain show weaker overlaps except for the pair of Biodiversity-Ecology. In fact, Biodiversity Conservation is a subfield of Ecology (93.6 % of biodiversity articles also belong to ecology, representing 17.5 % of the latter). Four EES fields are selected for comparison of internationalisation in section 3: Meteorology & Atmospheric Sciences, Oceanography, Ecology and Water Resources.

2. International Collaboration in EES Fields: Review of Statistical Data and Bibliometric Studies

Internationalisation in EES fields deserves the attention of STI research for several reasons. Firstly, some EES disciplines are among the most internationalised fields of science, but this finding has not been explained so far. Secondly, the geographical location and extension of research objects can influence decisions to collaborate. Thirdly, since environmental problems and related innovation needs are ubiquitous, collaboration between scientifically advanced and less developed countries is an important issue.

This section first presents data on internationalisation in the broad domain of Earth and Space Sciences as published by the USA National Science Board in its biennial report Science & Engineering Indicators. Then bibliometric studies on more narrow environmental fields are reviewed, including all published articles that we could identify (Wagner, 2005; Engels, Ruschenburg, and Weingart, 2005; Dastidar, 2004; Wishart & Davis, 1998; Resh & Yamamoto, 1994). There are some limitations with regard to the statistical sources, as the most recent data published by NSB on worldwide field-specific internationalisation cover the period 1995-97 (NSB, 2000: A6-60). The third edition of the European Report on S&T Indicators includes a definition of the EES domain, but no original data on international collaboration frequencies across fields (European Commission, 2003).

Intellectual exchange in trans-national communities is a central characteristic of scientific work organisation (Stichweh, 1999). The past decades witnessed a strong increase of international collaboration, as measured in internationally co-authored publications (briefly, international publications). International publications are defined as publications with author affiliations from at least two different countries. Between 1988 and 2001 the total number of international publications more than tripled, while their share of all articles increased from 7.8% to 18% (NSB, 2004; 2000). In 1976 only 4% of all articles were internationally co-authored. The share of international publications among all publications is commonly called the INI-index.

While growing collaboration is a general trend, the portion of international publications is highly field-specific. In Science & Engineering Indicators, the SCI+SSCI database is subdivided into eleven broad scientific domains, among which Earth and Space Sciences (*ESS*) includes the largest subset of the 21 earth and environmental fields (*EES*) discussed in section 1. In the mid-nineties, 24.1 % of publications in ESS worldwide had institutional affiliations from at least two different countries, followed by Physics with 22.4 %. In comparison, Clinical Medicine, the largest field in the database, had only 11.5 % of international publications (14.8 % for database total). ESS covers the subfields of Astronomy and Astrophysics, Earth and Planetary Science, Environmental Science, Geology, Meteorology and Atmospheric Sciences, Oceanography and Limnology but excludes biological research on the environment.

Figure 2 shows the dynamic increase of internationalisation from the mid-eighties to 2001, comparing ESS with the database average. Ten countries with the largest scientific output are listed in descending order. In 1996, ESS INI is more than 20 % higher than the database average for publications from Japan and Germany, and 18 % higher for the United Kingdom, France, China and Australia. If INI growth in ESS continues at the rate of the total database, in 2001 more than 65 % of ESS publications from Germany and France are international and around 60% from the United Kingdom, Italy, Russia and Australia. Among the group of countries with the largest scientific output, France and Germany have the highest INI (ESS and total database), considerably higher than the INI of the smaller scientific producers Canada and Australia (although the use of English as a national language favours collaboration by the latter). China is the only country where the INI in 2001 had not increased compared to 1996.

Figure 2 about here

In spite of the remarkable degree of internationalisation, few studies investigated more narrow EES fields to arrive at an explanation of these internationalisation patterns. The findings of four studies are summarised in Table 2. While these studies present interesting data, they use different criteria for journal selection and cover different time periods, which limits cross-field comparability.

Table 2 about here

Wagner (2005) compares INI across six fields, three of which are of interest in the present paper: Astrophysics, Geophysics, and Soil Science. Dastidar (2004) investigates the SCI subject category of Oceanography in the year 2000. Wishart & Davis (1998) sample articles from ten leading journals in Limnology over a decade. Resh & Yamamoto (1994) select 33 journals specialising in Freshwater Ecology and sample the 100 most recent articles from each journal.

Table 2 clearly indicates that levels of internationalisation vary significantly across environmental fields. Since Astrophysics, Geophysics, Oceanography and Limnology are all part of the broader ESS (Figure 2), it is apparent that ESS is itself very heterogeneous, with Astrophysics at the top and Limnology at the lower end in terms of internationalisation.[2] According to Wagner's findings, INI in Geophysics and Soil Science are even higher than INI in ESS which is estimated at 29.3% for 2001. Much lower INI in

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2 Astrophysics is not among the earth and environmental fields in Table 1 but is part of NSB's category of ESS.

Limnology and Freshwater Ecology are partly due to earlier time periods investigated, and are consistent with the finding that biology on the whole is less internationalised. The broad category of Biology (as defined by NSB, excluding biomedical research) had 7.4 % of international publications in the mid-1980s and 13.9 % in the mid-1990s, values slightly below database average (7.8 % and 14.8 % respectively; NSB, 2000: A6-60). Findings from Glänzel & Schubert (2005: 335) point in a similar direction, with INI ratios of 48 % in the broad field of Geosciences & Space Sciences in 2000 as compared to 29 % in Agriculture & Environment, as defined by the authors.

The bibliometric studies take different perspectives on the topic of international collaboration in environmental research. Dastidar (2004) presents collaboration networks on the level of countries, institutes and scientists. The study demonstrates a strong concentration of oceanographic publications in the USA, but offers little qualitative interpretation of collaboration patterns. Wagner (2005) aims to elucidate field-specific INI growth. She distinguishes four types of motivations for international collaboration ("resource-driven, equipment-driven, data-driven and theory-driven") and postulates different growth rates of internationalisation. Country networks are presented for six fields in 1990 and 2000. Yet the findings do not support this hypothesis. Nevertheless, Wagner's attempt underlines the need for a better qualitative understanding of EES fields to explain internationalisation patterns. Resh & Yamamoto (1994) carefully select specialised journals and report collaboration frequencies per journal. Their conclusion that internationalisation in Freshwater Ecology approximates that of Physics does not seem well-founded because it disregards a time lag of almost a decade between investigated periods. Engels et al. (2005) focus on collaborations between scientific centre and periphery. They analyse INI ratios of a sample of US American and German institutes in "GEC research" with different world regions (1993-2002). The study does not investigate field differences in internationalisation in the sub-samples of climate and biodiversity institutes.

Wishart & Davis (1998) is the only investigation that is motivated by a scientific concern about the limited knowledge of phenomena in developing countries. Apart from INI ratios, they analyse the regional origin of senior authors, the regional distribution of membership in professional societies, and the frequency of certain thematic areas in papers with Third World authorship. The authors conclude that "(…) given the widening gulf in terms of personnel and resources, the future of essential research on inland waters in the Third World does not bode well unless in situ capacity building within Third World countries becomes a target of First World research and funding agencies" (p. 558).

In sum, we conclude from the literature review that (1) some EES fields are among the most strongly internationalised areas of science, (2) only few EES fields have been studied with regard to internationalisation, and (3) cross-field comparability among these studies is limited by varying approaches to field definition and by different time periods.

3. Systemic versus Cumulative Global Change: A Comparison of Four Scientific Fields

We now compare four environmental fields in terms of internationalisation and scientific output concentration. According to Whitley (2000), the social organisation of scientific fields is strongly linked to their cognitive problem structures. This perspective is applied here to EES research. We follow Turner et al. (1990) who distinguish systemic and cumulative global change. Another relevant distinction is fundamental versus applied research. We explore how both cognitive dimensions as independent variables explain international collaboration and output concentration as dependent variables of social structure in EES. The central hypothesis is that systemic GEC fields show higher ratios of international collaboration than cumulative GEC fields. The relationship is explained by the influence of higher mutual task dependence in systemic fields. The basic-applied distinction influences distributions of scientific activity and collaboration patterns between countries.

Four fields were chosen to represent two different problem structures of GEC research: Meteorology & Atmospheric Sciences (MAS) and Oceanography as examples of systemic GEC research, Ecology and Water Resources as examples of cumulative GEC fields. Together, these four fields account for ca. 30 % of all environmental research in the SCI. The selection also represents different environment-related domains, as MAS and Oceanography belong to the category of geosphere research, ecology is part of biosphere research and Water Resources part of the environmental management & engineering category. All four fields are highly dynamic, with above-average long-term growth rates (1990-2002) ranging from 1.95 in Ecology to 2.26 in MAS, compared to 1.47 database average (Table 1).

3.1 Spatial Problem Structures of GEC

Turner et al. (1990) distinguish between two types of GEC. Applied to research problems, their distinction characterises two different spatial problem structures:

"In the first or systemic meaning, *'global' refers to the spatial scale of operation or functioning of a system*. A physical system is global in this sense if its attributes at any locale can potentially affect its attributes anywhere else, or even alter the global state of the system. (…) Globally systemic changes need not be caused by global scale activity, only the physical impacts of the activity need to be global in scale, manifested through the systemic adjustments that follow. (…) In the second – the cumulative – sense, *'global' refers to the areal or substantive accumulation of localized change*. A change is global in this sense if it occurs on a worldwide scale, or represents a significant fraction of the total environmental phenomenon or global resource. (…) If cumulative changes reach a global scale, it is typically as the consequence of worldwide or wide-spread human activity that may not be directly registered on the major geosphere-biosphere systems" (Turner et al., 1990: 15f.).

Only a subset among the EES fields described in section 1 investigates environmental change from a systemically global perspective. Most systemic GEC research is located in the cluster of four geosphere fields in Figure 1: MAS, Geochemistry & Geophysics, Oceanography, and Multidisciplinary Geosciences. The expression "systemic GEC fields" signifies that these fields include large portions of research on the systemic understanding of GEC. Of course, this neither implies that all publications in the respective categories treat global systemic topics, nor that no other subject category contains any global systems research. For example, there is some global systems research in Ecology, while the bulk of ecological research is cumulatively global and the SCI subject category of ecology shows little overlap with the systemic fields.

The systemic fields show substantive mutual overlap because they are cognitively connected by scientific concepts, such as the global "climate system", the "earth system" or global "life support systems". The Intergovernmental Panel on Climate Change gives the following definition of the climate system:

"The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms, the most important of which is the sun. Also the direct effect of human activities on the climate system is considered an external forcing. (…) Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behaviour, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated" (IPCC 2001, Vol.I, Ch. 1.1.2).

Over the past 20 years, the importance of biological processes in the regulation of the climate system gained increasing recognition among climate scientists. Consequently, the global systems perspective has been extended in the direction of a total earth system that emphasises the coupling of physical, chemical and biological aspects. "In the context of global change, the Earth System has come to mean the suite of interacting physical, chemical and biological global-scale cycles (often called biogeochemical cycles) and energy fluxes that provide the conditions necessary for life on the planet." (Steffen et al., 2004: 10; see also Schellnhuber et al., 2004).

The components of the physical climate system are long-standing objects of MAS and Oceanography (Weart, 2004). Research in Geochemistry & Geophysics is essential for the study of global biogeochemical cycles, along with the establishment of a subdiscipline of global ecology (Mooney, 1996). Along the same lines, the category "Multidisciplinary Geosciences" is described by the databank provider as covering "resources having a general or interdisciplinary approach to the study of the Earth and other planets."

In contrast to the systemic perspective, much environment-related knowledge production is focused on smaller spatial scales and is to a greater or lesser extent place-specific. Due to this combination of smaller spatial scales and interest in place-specific conditions this research could also be called "place-based". While systemic GEC research usually implies long-term fundamental research, cumulative GEC research can be either basic or applied. Ecology exemplifies the importance of place-specific knowledge, due to the heterogeneity and complexity of ecosystems on local to regional scales, in combination with a strong basic research orientation (Bocking, 1997; Golley, 1993). Water Resources has been chosen because it represents a cumulative field that contains both fundamental and applied knowledge (Reuss, 2003).

The systemic versus cumulative distinction marks the cognitive perspective and the spatial scale of research, but no physical separation in nature. This is well illustrated by the case of water. While the global hydrological cycle is central for the movement of energy and chemicals in the earth system, little of this systemic research is categorised under the SCI subject category Water Resources. The topics in this field rather refer to the management of freshwater for human needs, such as "desalination, ground water monitoring and remediation, hydrology, irrigation and drainage science and technology, water quality, hydraulic engineering, ocean and coastal management, river research and management, waterways and ports" (database description). The field Water Resources thus covers mostly regional hydrological knowledge and technological knowledge for water resource management.

Technological knowledge usually has no geospatial reference and thus is neither systemic nor cumulative. Yet the effectiveness and sustainability of technological applications for the management of natural resources and ecosystems often depends on site-specific adaptations (e.g. water quality or soil degradation). Thus, environmental research with a strong practical orientation is often partly universal and partly place-specific. This holds not only for the case of Water Resources, but also for Soil Science, Forestry, Marine and Freshwater Biology (fisheries research). Given that anthropogenic interference with the environment and the need for improved management approaches are spread worldwide, these fields are also considered cumulatively global in the sense of Turner et al. (1990).

3.2 Influence of Problem Structures on International Collaboration

Three different motivations for international collaboration in EES fields are linked with the spatial problem structure: (1) high mutual task dependence in systemic GEC fields, (2) scientific interest in particular places, (3) capacity building and technology transfer.

(1) The main difference with regard to internationalisation is that systemic fields depend on a global perspective, whereas research in cumulative global problems can be conducted independently in many places. The inherently global perspective leads to stronger mutual task dependence among scientists in systemic fields. High levels of mutual task dependence are due to (a) large investments in global scale observation, including investments in international coordination of data collection, and (b) closer cognitive integration of research efforts through shared global frameworks, i.e. theories and numerical models.

Mutual task dependence is a concept introduced by Whitley (2000) for the analysis of scientific work organisation. According to Whitley,

"modern sciences essentially are systems of jointly controlled novelty production in which researchers have to make new contributions to knowledge in order to acquire reputations from particular groups of colleagues. (…) The degree of mutual dependence has two analytically distinct aspects. The first is the extent to which researchers have to use the specific results, ideas, and procedures of fellow specialists in order to construct knowledge claims which are regarded as competent and useful contributions. This can be called *the degree of functional* *dependence* between members of a field and refers to the need to co-ordinate task outcomes and demonstrate adherence to common competence standards. (…) The second aspect of mutual dependence refers to the extent to which researchers have to persuade colleagues of the significance and importance of their problem and approach to obtain a high reputation from them. This can be called the *degree of strategic dependence* for it covers the necessity of co-ordinating research strategies and convincing colleagues of the centrality of particular concerns to collective goals." (2000: 85; 88; italics in original).

Two steps connect the systemic problem structure with internationalisation patterns. The first hypothesis for systemic GEC is that global observation systems and cognitive integration through theories and numerical models give rise to high levels of task dependence among scientists and working groups in scientifically advanced nations.[3] The second hypothesis is that stronger task dependence results in more frequent collaboration within a research field, and in particular more frequent international collaboration.[4] High international task dependence is manifested in bottom-up collaborations among individual scientists, as measured by international co-authorships, as well as a strong tradition of international scientific collaboration programmes (cf. Greenaway, 1996; Weart, 2005b; Jappe, 2005).[5]

International cooperation is central to establishing and enhancing the global observation systems that systemic GEC research depends on. As Edwards notes, "behind the emerging consensus on climate change lie more than 150 years of slow, painful negotiations over global standards for measuring, recording, and communicating about the weather" (2004: 827). The oldest worldwide operational system for meteorology is the World Weather Watch/ GOS, established in 1963 under the auspices of WMO. Similarly comprehensive systems are still being developed for the oceanic and the terres-

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3 For the purpose of this paper, we do not distinguish functional and strategic aspects of task dependence.

4 On the aggregated level of entire disciplines, high collaboration frequencies are probably due to the combined effect of a number of subfields with high mutual task dependence. In cases of non-public research such as industrial big science projects or classified military research, the second hypothesis may not apply (cf. Hamblin, 2005: 192f.) This hypothesis has not yet been investigated bibliometrically.

5 Stronger task dependence is also likely to result in more pronounced stratification among scientists and among research institutions (elite-periphery structures).

trial domain.[6] International programmes such as GARP (1967-1980) and WCRP (since 1980) complement operational data networks through in-depth investigations and experiments. International data centres serve the collection, storing and processing of data, ensuring open access to scientific information (Greenaway, 1996: 160ff., 175).[7]

Mutual task dependence does not result merely from the cooperation required to enhance operational observation systems, but also from the fact that global expert communities operate with highly standardised data products. Due to the complex operations involved in the generation of global data sets, it has been argued that global data and global models are "no longer distinct entities, but parts of a single system for representing the world" (Weart, 2005a: 12).

Atmospheric general circulation modelling (AGCM) is a prime example for strong mutual task dependence through cognitive integration.[8] GCMs are at the centre of research on climate change and are used to integrate observations and analytical contributions from diverse specialities (cf. history of AGCM in Weart 2005a). Although observation and experiments are undertaken on a broad range of spatial scales and may include the sun and other planets, their ultimate purpose is to inform understanding of global system functioning. In turn, enhanced simulation of system behaviour is seen as the prerequisite for the prediction of regional impacts.

Model complexity and the requirements of computing power restrict the number of approaches that are used in parallel within the AGCM field, so that researchers follow the

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6 For example on-going planning for a Global Earth Observation System of Systems, http://www.epa.gov/geoss/index.html; last accessed 22nd March 2006.

7 GOS stands for Global Observation System, GARP for Global Atmospheric Research Programme, WCRP for World Climate Research Programme, WMO is World Meteorological Organisation.

8 "Communities of collaboration among experts had been rapidly expanding throughout geophysics and the other sciences, but perhaps nowhere so obviously as in climate modelling." (Weart, 2005a: 27).

development of a limited number of shared global frameworks (Edwards, 2001: 58). Even today, only a limited number of research centres worldwide are capable of developing and running the most advanced earth system models that couple processes of the atmosphere, land surface, ocean and sea ice, aerosols and the carbon cycle.[9] Experiments that systematically compare the performance of different models are part of the research strategy and an additional element of cognitive field integration.

Ecology and Water Resources exemplify fields that typically combine finer spatial resolutions with a stronger adaptation of research approaches to specific local conditions. Certainly, theories and methods contain generalisations which make them applicable in different contexts and allow the accumulation and progress of knowledge across sites. Still, the dependence of scientists at different places on each other's achievements remains weaker relative to systemic fields. Comparatively low mutual task dependence leads to a greater diversity of approaches and reduces the pressure for a standardisation of data, methods and concepts.

(2) In earth and environmental research, the scientific motivation for international collaboration is often connected to particular qualities of a geographic locality. This holds independent of the degree of task dependence in the entire scientific field. For example, ecologists investigate the island Hawaii as a model for the role of nutrient cycles and nutrient limitations in ecosystems (Vitousek, 2004). International collaboration also serves to compare objects and to exchange experiences across sites, as in river basin management (e.g. Bressers, Kuks 2004) or to investigate connections between distant places. Synoptic assessments of environmental conditions for large regions or the entire planet are especially demanding in cumulative fields since they require in-depth investigations at a large number of carefully selected places. Models and satellite re-

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9 Cf. AGCM family tree on http://www.aip.org/history/sloan/gcm/famtree.html; on development stages of coupled modelling see Carson (2005).

mote-sensing can substitute for in situ data to a lesser extent than in systemic GEC research. For this reason, global assessments are often compilations of existing knowledge and include only some original research (e.g. the Millennium Ecosystem Assessment).

(3) Apart from the purely scientific motivations, international collaboration relates to different levels of STI capacity among developed and less developed countries. This is more relevant in research on natural resource management and related technological applications than in fundamental natural sciences. Two approaches to collaboration can be distinguished: to solve a specific problem in a developing country by applying and adapting externally developed S&T solutions, or to support STI capacity building within the developing country itself.

"At one extreme, it is possible to use the S&T capabilities of developed countries (…) to generate knowledge, technologies and products that address the problem under consideration. (…) At the other extreme, it is possible to support the creation of domestic STI capabilities, which may involve institutional support programs, long-term scientific and technical assistance, information sharing, and graduate fellowships to train S&T researchers, as well as policy-makers and technology managers"; (Sagasti, 2004: 106).

Pressing environmental problems related to water use, health and food production are likely to receive more attention in emerging and developing countries than long-term environmental risks that are characterised by high scientific uncertainties. As a consequence, scientific production is likely to be more concentrated in the scientifically most advanced countries if fields require high investments in basic research. This holds both for systemic and cumulative long-term risks, such as climate change and biodiversity loss.

Apparently, scientific interest in distant localities is not always well documented by co-authorships. Dahdouh-Guebas et al. (2003) analysed research on least developed countries (operationalised as publications which mention at least one of the 48 least developed countries in the title) and found that 69 % of this research is published by authors from industrialised countries without including local research institutes. The authors attribute this to a "spirit of neo-colonial science" (pp. 334, 340). It is noteworthy that the LDC sub-sample amounts to less than 0.2 % of the basic set of publications in the database Current Content (1999-2000).

3.3 Hypotheses

Hypothesis (1): summarising the argument in section 3.2 with regard to the effect of spatial problem structures, we hypothesise that systemic GEC generates a higher degree of mutual task dependence among scientists than cumulative GEC, resulting in higher international collaboration frequencies (**INI**). This hypothesis can be specified further by assuming that the portion of systemic GEC research is higher in MAS than in Oceanography, leading to the following hypothesis:

1) **INI** MAS > **INI** Oceanography > { **INI** Ecology
INI Water Resources }

Hypothesis (2): the fields MAS, Oceanography and Ecology contain a higher share of fundamental research than Water Resources, leading to the expectation that the former show higher concentrations of publication output among the scientifically most advanced countries. Furthermore, the initial investments in technology that are required to establish competitive research are typically larger in the two systemic fields compared to Ecology and Water Resources, constituting a higher entry threshold to the former fields.

If output concentration (**OC**) is defined as the output share of the 20 largest scientific producing countries (as a group), the following hypothesis can be formulated:

(2) { **OC** MAS
OC Oceanography } > **OC** Ecology > **OC** Water Resources

Hypothesis (3): although levels of scientific capacity are heterogeneous, developing, emerging and transition countries (DET countries) generally face important tasks of

R&D capacity development (cf. Sagasti, 2004: 123ff.) Applied problems related to water resources are likely to receive more attention in DET countries than systemic or other long-term environmental risks associated with high scientific uncertainties. Participation of DET countries in international collaboration is measured as the ratio of international publications with authors from DET countries in relation to all international publications in a field (**DET ratio**). The hypothesis is:

(3) **DET ratio** Water Resources > **DET ratio** { MAS / Oceanography / Ecology

3.4 Methods

The hypotheses are investigated in three steps, measuring (a) share of international publications, (b) output concentration, and (c) ratio of international publications with DET countries for two fields of systemic GEC (MAS, Oceanography) and two fields of cumulative GEC (Ecology, Water Resources).

Publication output was searched in SCI expanded for the period of 2002-2003. The software VantagePoint is used to construct field and country databases. Output concentration is measured for the group of the top twenty countries in terms of output size. In order to ensure that scientific size is accounted for independently of that country's propensity for international collaboration, fractional assignments of articles to countries are used to determine output ranks (NSB, 2004: A5-35).[10] All other computations in this paper assign publications to countries on a whole count basis.

Internationalisation is compared on the level of entire fields and for individual countries, as it is well-known fact that countries' propensity for international collaboration differs

10 20 countries with largest output in 2001 in descending order: USA, Japan, United Kingdom, Germany, France, Canada, Italy, China, Russia, Spain, Australia, Netherlands, India, South Korea, Sweden, Switzerland, Taiwan, Brazil, Israel, Belgium.

significantly (Glänzel & Schubert, 2004). The relative internationalisation index (**RI**) measures how much a country collaborates internationally in an EES field relative to that same country's internationalisation across the total database. **RI** is defined as:

RI = 100 tanh ln [(INI kj) / (INI k sci)],

where INI kj is country k's share of international publications in field j, and INI k sci is that same country's share of international publications in the database SCI+SSCI. The hyperbolic index is symmetrical and bounded to ± 100 (cf. Grupp, 1998: 158).

In order to assess the relative importance of collaborations with countries that are still more peripheral to the global science system, we define the umbrella category of "developing, emerging and transition countries" (DET). This group includes all countries except USA, Canada, Japan, EU-15, Iceland, Switzerland, Norway, Israel, Australia, New Zealand and Russia. The importance of collaborations with DET countries is measured by international publications that include author affiliations from at least one of these countries. The participation of DET countries in scientific collaboration is measured by the ratio of international publications that include author affiliations from DET countries by all international publications in that field (DET ratio).

3.5 Results

International collaboration. Consistent with hypothesis (1), we find that internationalisation is significantly more developed in systemic GEC fields than in cumulative GEC fields. As expected, INI MAS is higher than INI Oceanography (25.8 % and 24.3 %, respectively). INI Ecology (21.3 %) is still considerably above, and INI Water Resources (18.7 %) close to database average (18.0 %). On the country level, the systemic fields are characterised by high degrees of relative internationalisation. RI indicates how much a country collaborates internationally in a given field relative to the country's internationalisation in all fields of the database (Figure 3).

Figure 3 about here

In MAS, all 15 countries have very high RI values, with the exception of Spain (RI = -12.4). By far the highest RI are attained by Japan (67.8) and South Korea (50.2), followed by China, Italy, United Kingdom, Germany and France, (between 37.9-33.6). A similar pattern is observed in Oceanography, although on a slightly lower level, again led by South Korea (55.7) and Japan (47.4). In Oceanography, three countries show interesting deviations from the average pattern of high RI: India (-71.8), Russia (-32.2) and Australia (-11.9). In all three cases, this is due to strong domestic journals (see below).

By comparison with the systemic fields, RI is on average lower in the fields of Ecology and Water Resources and more variable across countries. Although Ecology is more internationalised than Water Resources, similar RI levels of both fields are observed for Japan, China and the Netherlands. In a number of other countries, RI is more elevated in Ecology than in Water Resources, including the UK, Germany, France, Canada, Italy, Spain and India. The opposite pattern (higher RI for Water Resources than Ecology) is observed only for Russia and to some extent for the USA. Again, the highest RIs are attained by East-Asian nations, with South Korea leading in Ecology (RI = 54.6), Japan and China in Ecology and Water Resources (Japan 35.8 and 37.7; China 43.0 and 36.3 respectively). However, the three East-Asian countries have negative specialisations in Ecology, and the contribution of South Korea to this field remains small in absolute terms. China is the only country in our sample that combines a strong internationalisation in Water Resources with a comparatively strong orientation towards this field.

The influence of domestic journals was checked for all four fields. Domestic journals in English language are an important vehicle for oceanographers from India, Russia and

China to communicate results to an international audience.[11] In the cases of Russia and Australia, this international communication strategy is also linked with strong national specialisations, pointing to the existence of important oceanographic communities in these countries. In MAS, national journals play a similar role for China and, to a lesser extent, for Australia and Japan. In the two cumulative fields, domestic journals generally have less influence, with the exception of a Russian journal in Ecology. A limited role of domestic journals is also observed in the cases of Canada and Australia in Ecology, and for France and Canada in Water Resources.

Output concentration. Consistent with hypothesis (2), scientific output is more concentrated in systemic GEC fields than in cumulative GEC fields (Table 3). In the two systemic fields, more than 91 % of all publications carry author affiliations from the 20 largest producing countries. Output concentration in Ecology is close to and Water Resources considerably below the database average. Although output concentration is still high in the field of Water Resources, these aggregate values indicate more participation by countries that are smaller in terms of scientific output.

Table 3 about here

Collaboration with developing, emerging and transition countries. The differences in the degree of internationalisation between systemic and cumulative fields are not reproduced in collaboration with DET countries (Table 4). INI DET is highest in Water Resources (9.7 %) and lowest in Oceanography (7.6 %). However, the difference is much more striking if we consider the fraction of DET collaborations in all international collaborations. Consistent with hypothesis (3), it is evident that DET countries play a more

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11 Domestic journals contain large portions of national output in a field but low shares of international publications, e.g. "Indian Journal of Marine Sciences" (49% of Indian publications); "Oceanology" and "Izvestiya Atmospheric and Oceanic Physics" (74 % of Russion publications); "Marine and Freshwater Research" (24 % of the Australian publications); "Acta Oceanologica Sinica" (30 % of Chinese publications).

important role in the internationalisation of Water Resources than in the three other GEC fields: 49.8 % of all international publications in Water Resources include authorships from at least one DET country, as compared to 33.6 % in MAS, 38.6 % in Ecology and only 31.1 % in Oceanography. This finding supports the conclusion that motives related to technology transfer and capacity building are an important factor for international collaborations in Water Resources.

Table 4 about here

Figure 4 about here

On the country level, the strongest differences between DET ratios in Water Resources and other GEC fields are found in Japan, France, Netherlands, Canada, Spain, and Sweden. 63.7 % of Japan's international publications in this field also include authors from DET countries. Still, in absolute terms, the USA remains the largest collaborator of DET countries in Water Resources, with South Korea, China and Taiwan as its most frequent partners, followed by Brazil, Mexico, Turkey and India.

Apart from a country's attained level of scientific capacity, cultural and geographic ties shape the channels of DET collaboration: Japan's most prominent collaboration partner in Water Resources is China, followed by South Korea and Taiwan. France collaborates most frequently on water issues with authors from Mexico and Morocco, followed by Algeria, Brazil and Tunisia. Canada's most frequent partners are China, India and Mexico. Spain collaborates with Mexico, Brazil and Cuba; the Netherlands with China, followed by Egypt and India. Sweden's most frequent DET partners in Water Resources are China, the Czech Republic, India and Poland.

Large regions are barely included in global change science. Taking Africa as an example[12], we observe a striking difference between systemic and cumulative fields: MAS and Oceanography include authors from African countries in 6.6 % and 6.7 % of international publications, as against 17.5 % and 18.4 % in Ecology and Water Resources, respectively. However, these small numbers of African collaborations are very concentrated, with authors from South Africa in more than half of international publications across fields.

4. Conclusion

Nature-society interaction is becoming increasingly knowledge-intensive. As yet, bibliometric indicators are rarely used to monitor environment-related knowledge production and knowledge transfer, although this is common practice in other high-tech fields, such as nanotechnology (Heinze 2006, 2004). Our results confirm that linking bibliometric data, sociological theory and insights in cognitive field structures advances our understanding of internationalisation patterns in earth and environmental research.

International collaboration is a central feature of scientific work organisation in the scientifically most advanced countries, but it also contributes to capacity building for DET countries. Few studies have investigated internationalisation in environmental fields and their comparability is limited. Our findings demonstrate that different spatial problem structures of GEC can explain different levels of internationalisation across EES fields. In particular, the high mutual task dependence generated by problems of systemic GEC leads to levels of internationalisation that are matched by few other SCI fields. On the other hand, knowledge transfer and capacity building are important motives for international collaboration in application oriented fields, as shown by very high

12 This definition of African countries excludes Arab states as a separate regional category.

DET ratios in Water Resources. Output concentrations suggest that pressing environmental problems, e.g. water management issues, attract more scientific attention in DET countries than long-term environmental risks characterised by high scientific uncertainties. The present study of international co-authorships is complemented by an institutional analysis that compares the role and design of important international scientific collaboration programmes in systemic and cumulative GEC (Jappe, 2005).

Science is at the core of our society's capabilities to anticipate environmental risks, to manage natural resources, to improve eco-efficiency and to adapt to long-term global change in climate and ecosystems. Therefore, we suggest that STI research should examine environment-related knowledge production in a more comprehensive manner (cf. Cash et al., 2003). The study of international collaboration patterns is a small but important part of a larger endeavour to conceptualise and observe environment-related STI capacity development in scientifically advanced, emerging and developing countries.

References

BOCKING, S. (1997), *Ecologists and Environmental Politics: A History of Contemporary Ecology*, Yale University Press, New Haven, CT.

BRESSERS, H., KUKS, S. (2004), *Integrated Governance and Water Basin Management. Conditions for Regime Change Towards Sustainability*, Kluwer Academic Publishers, Dordrecht.

CARSON, D. J. (2005), Introduction to the International GEC Programmes & their Earth System Science Partnership, *Presentation at IGFA - ICSU Workshop on the Interface Between Global Change and Development-Oriented Research*. 17-19 May 2005. Uppsala, Sweden.

CASH, D. W., CLARK, W. C., ALCOCK, F., DICKSON, N. M., ECKLEY, N., GUSTON, D. H., JÄGER, J., MITCHELL, R. B. (2003), Knowledge systems for sustainable development, *Proc. Natl. Acad. Sci USA*, 100 : 8086-8091.

DAHDOU-GUEBAS, F., AHIMBISIBWE, J., VAN MOLL, R., KOEDAM, N. (2003), Neo-Colonial Science by the Most Industrialised upon the Least Developed Countries in Peer-Reviewed Publishing, *Scientometrics*, 56 : 329-343.

DASTIDAR, P. B. (2004), Ocean Science & Technology Research across the Countries: A Global Scenario, *Scientometrics*, 59 : 15-27.

EDWARDS, P. N. (2001), Representing the Global Atmosphere: Computer Models, Data and Knowledge about Climate Change. In: C. A. Miller, P. N. Edwards (Eds), *Changing the Atmosphere: Expert Knowledge and Environmental Governance*. MIT Press, Cambridge, MA.

EDWARDS, P. N. (2004), "A Vast Machine": Standards as Social Technology, *Science*, 304 : 827-828.

ENGELS, A., RUSCHENBURG, T., WEINGART, P. (2005), Recent Internationalization of Global Environmental Change Research in Germany and the U.S., *Scientometrics*, 62 : 67-85.

EUROPEAN COMMISSION (2003), *Third European Report on Science & Technology Indicators*, Office for Official Publications of the European Communities, Luxembourg.

GLÄNZEL, W., SCHUBERT, A. (2004), Analysing Scientific Networks through Co-Authorship. In: H. F. MOED, W. GLÄNZEL, U. SCHMOCH (Eds), *Handbook of Quantitative Science and Technology Research*. Kluwer Academic Publishers, Dordrecht, pp. 257-276.

GLÄNZEL, W., SCHUBERT, A. (2005), Domesticity and Internationality in Co-Authorship, References and Citations, *Scientometrics*, 65 : 323-342.

GOLLEY, F. B. (1993), *A History of the Ecosystem Concept in Ecology: More than the Sum of the Parts*, Yale University Press, New Haven, CT.

GREENAWAY, F. (1996), *Science International - A History of ICSU*, Cambridge University Press, Cambridge.

GRUPP, H. (1998), *Foundations of the Economics of Innovation: Theory, Measurement and Practice*, Edward Elgar, Cheltenham, UK.

HAMBLIN, J. D. (2005), *Oceanographers and the Cold War. Disciples of Marine Science*, Washington University Press, Seattle, WA.

HEINZE, T. (2004), Nanoscience and Nanotechnology in Europe: Analysis of Publications and Patent Applications including Comparisons with the United States, *Nanotechnology Law & Business*, 1 : 427-447.

HEINZE, T. (2006), *Kopplung von Wissenschaft und Wirtschaft. Das Beispiel der Nanotechnologie*, Campus, Frankfurt, New York.

JAPPE, A. (2005), International Collaboration Schemes in Earth and Environmental Sciences: IGEC Programmes and Unesco IHP, *Fraunhofer ISI Discussion Papers Innovation System and Policy Analysis*, No 5/2005.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE IPCC (2001), *Climate Change 2001. The Scientific Basis. Third Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, New York.

MOONEY, H. A. (1998), *The Globalization of Ecological Thought*, Ecology Institute, Oldendorf/Luhe.

NATIONAL SCIENCE BOARD NSB, *Science and Engineering Indicators*, National Science Foundation, Arlington. Reports 2004 and 2000.

RESH, V. H.,YAMAMOTO, D. (1994), International Collaboration in Freshwater Ecology, *Freshwater Biology*, 32 : 613-624.

REUSS, M. A. (2003), Geomorphology and the Rise of Modern Hydrology, Paper presented at the *Third Annual Meeting of the International Water History Association (IWHA)*, 11-14 Dec. 2003.

SAGASTI, F. (2004), *Knowledge and Innovation for Development: The Sisyphus Challenge for the 21st Century*, Edward Elgar, Cheltenham, UK.

SCHELLNHUBER, J., CRUTZEN, P. J., CLARK, M., CLAUSSEN, M., HELD, H. (eds) (2004), *Earth System Analysis for Sustainability* , MIT Press, Cambridge, MA.

STEFFEN, W., TYSON, P., JÄGER, J., MATSON, P. A., MOORE, B., OLDFIELD, F., RICHARDSON, K., SCHELLNHUBER, J., TURNER, B., WASSON, R. (2001), Earth Systems Science. An Integrated Approach, *Environment*, 46 (3): 8-20.

STICHWEH, R. (1999), Globalisierung von Wirtschaft und Wissenschaft. Produktion und Transfer wissenschaftlichen Wissens in zwei Funktionssystemen der modernen Gesellschaft, *Soziale Systeme*, 5: 27-40.

TURNER , B. L., KASPERSON, R. E., MEYER, W. B., DOW, K. M., GOLDING, D., KASPERSON, J. X., MITCHELL, R. C., RATICK, S. J. (1990), Two Types of Global Environmental Change: Definitional and Spatial-Scale Issues in their Human Dimension, *Global Environmental Change*, 1: 14-22.

VITOUSEK, P. M. (2004), *Nutrient Cycling and Limitation: Hawai´i as a Model System*, Princeton University Press, Princeton, NJ.

WAGNER, C. S. (2005), Six Case Studies of International Collaboration in Science, *Scientometrics*, 62: 3-26.

WEART, S. R. (2004), *The Discovery of Global Warming*, Harvard University Press, Cambridge, MA.

WEART, S. R. (2005a), General Circulation Models of the Atmosphere. Essay in the Web Site *"The Discovery of Global Warming"*: Spencer Weart & American Institute of Physics.

WEART, S. R. (2005b), International Cooperation. Essay in the Web Site *"The Discovery of Global Warming"*: Spencer Weart & American Institute of Physics.

WHITLEY, R. (1984), *The Intellectual and Social Organization of the Sciences*, Clarendon, Oxford, UK.

WISHART, M. J., DAVIES, B. R. (1998), The Increasing Divide between First and Third Worlds: Science, Collaboration and Conservation of Third World Aquatic Ecosystems, *Freshwater Biology*, 39: 557-567.

Table 1 Earth and Environmental Research Fields in the SCI

SCI Subject Categories	Publ. 2002	% 21 fields	Growth (1990=100)
1. Geosphere	30,135	36.7	164
Multidisciplinary Geosciences	12,382	15.1	141
Geochemistry and Geophysics*	9,358	11.4	n.a.[1]
Meteorology & Atmospheric Sciences	7,439	9.1	*226*
Oceanography	5,608	6.8	*223*
Geology	1,750	2.1	48
Mineralogy	1,675	2.0	141
Paleontology	1,643	2.0	*213*
Physical Geography	1,277	1.6	157
Remote Sensing	1,171	1.4	n.a.[2]
2. Biosphere	40,805	49.7	135
Plant Sciences	14,311	17.4	122
Ecology	9,189	11.2	*195*
Zoology	7,631	9.3	118
Marine & Freshwater Biology	6,728	8.2	143
Agriculture, Soil Science**	2,813	3.4	101
Forestry	2,406	2.9	145
Biodiversity Conservation	1,714	2.1	n.a.[3]
Limnology	1,177	1.4	127
Ornithology	951	1.2	127
3. Env. Management & Engineering	18,458	22.5	201
Environmental Sciences	14,446	17.6	188
Environmental Engineering	4,664	5.7	*429*
Water Resources	5,709	7.0	*203*
All 21 fields	82,139	100	152

Source: SCI via host STN.

* Before 1996, this research was partly included in the category "Geology".

** Field contains only agricultural research in connection with soils.

[1] Field introduced in 1996; [2] in 1992; [3] in 2000.

The 21 EES fields do not include all technological knowledge pertinent to sustainability. The more eco-efficiency criteria are integrated in the development of technologies, the more difficult the separation between environmental engineering and other engineering tasks. As a consequence, relevant engineering literature is often found in other subject categories. The same holds for agricultural technologies (e.g. biotechnology).

Table 2 Earlier Bibliometrical Studies of Earth and Environmental Fields

Study	Field examined	Years analysed	Journals covered	Number of articles	INI %
Wagner	Astrophysics	2000	14	6547	47.3
	Geophysics	2000	13	2789	34.0
	Soil Science	2000	10	1382	32.8
Dastidar	Oceanography	2000	35	4008	n.a.*
Wishart/ Davis	Limnology	1987-1996	10	8960	9.2
Resh/ Yama-moto	Freshwater Ecology	100 most recent articles (before 1994)	33	3300	9.0

* Dastidar presents networks of countries and institutes in oceanography but no field INI.

Table 3 Output Concentration across GEC Fields (% of Articles)

2002-03	SCI	Meteo & Atmos	Oceano-graphy	Ecology	Water Resources
Top 20 countries*	86.8	92.7	91.3	86.2	81.8
USA	33.0	47.7	45.8	41.2	27.6
Japan	9.3	8.0	7.7	3.1	4.3
UK	8.1	9.5	10.3	11.1	8.0
Germany	8.3	11.0	9.6	5.7	5.8
France	5.8	7.5	8.5	5.6	6.7

Source: SCI via host STN. Country assignment on the basis of whole article counts.

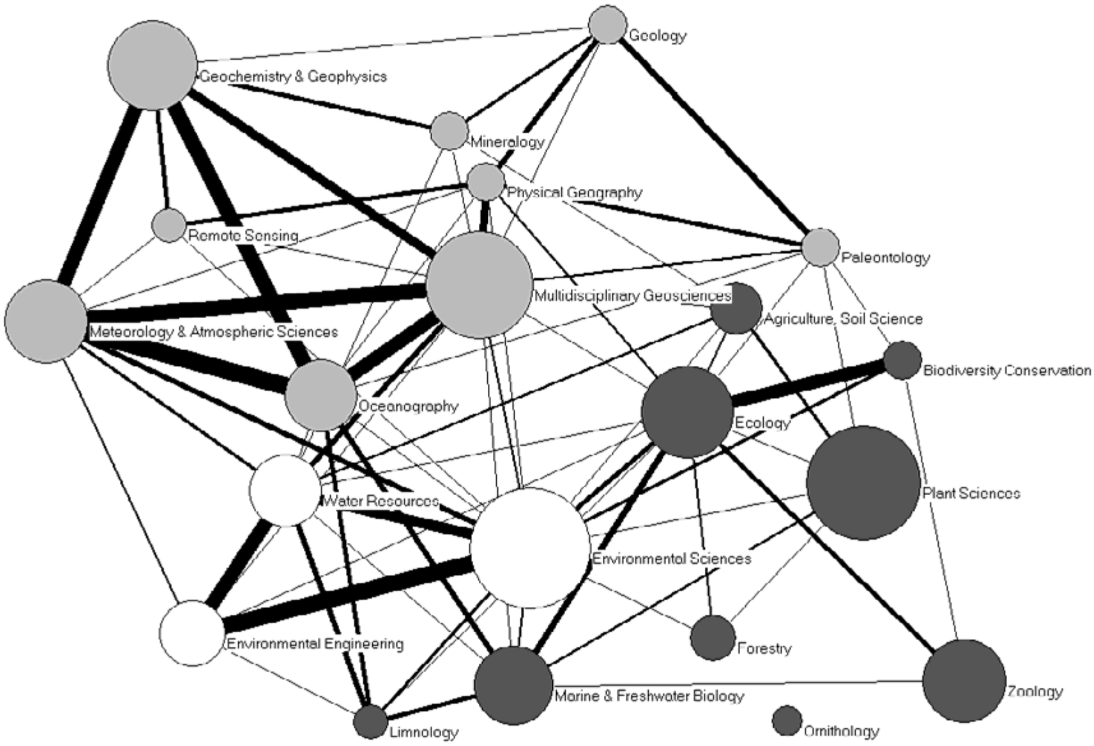
* The 20 countries with the largest scientific output are searched as a group to avoid double counts of intra-group international publications.

Table 4 International Collaboration across GEC Fields (%)

2002-03	Meteo & Atmos	Oceanography	Ecology	Water Resources
INI total (A)	25.8	24.3	21.3	18.7
INI DET (B)	8.7	7.6	8.2	9.3
DET ratio (B/A)	33.6	31.1	38.6	49.8

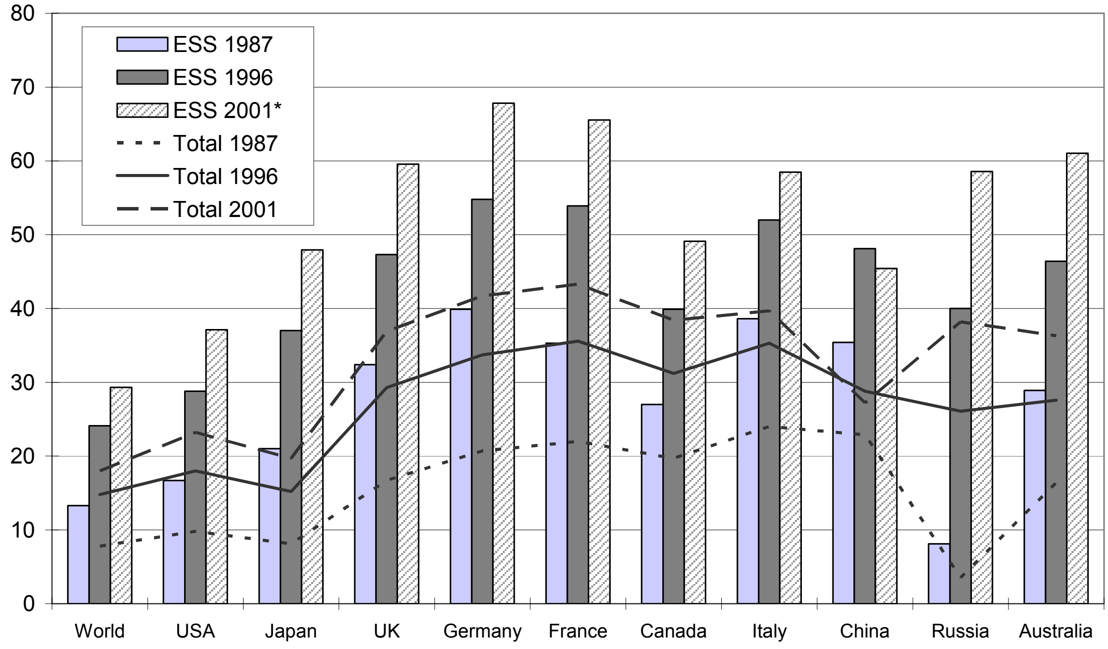
Source: SCI via web of science.

Figure 1: Relative Size and Overlap among 21 EES Fields



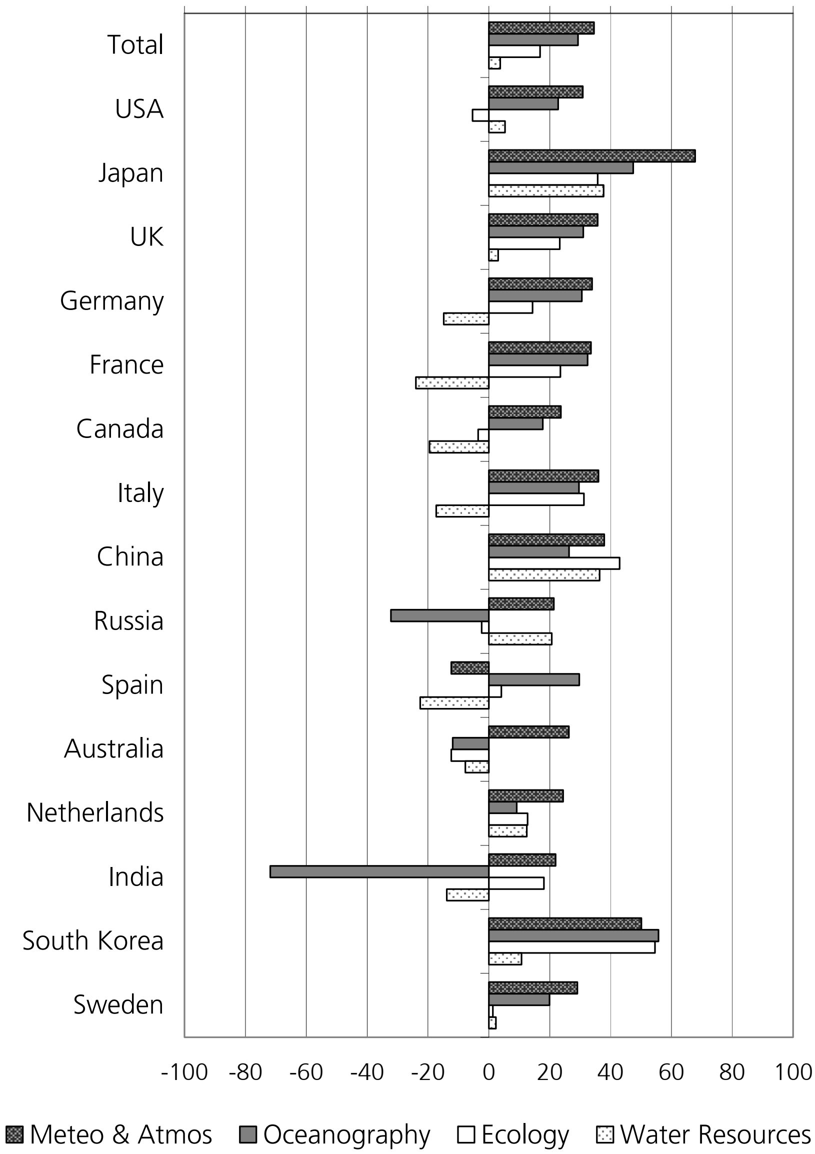
Source: SCI via host STN, subject categories 2001-2003. Circle areas represent the number of publications in each field. Linkages represent overlap between pairs of fields relative to field size.

Figure 2 Internationalisation of Earth and Space Sciences (ESS) in Ten Major Scientific Producing Countries (INI %)



* ESS 2001 data are estimates.
Data: NSB (2000, 2004). Earlier data refer to three year averages: 1986-88 and 1995-97, 2001 refers to only that year. For 1986-88, the respective values of East and West Germany have been added. Australia (11th in output size) is included instead of Spain (10th).

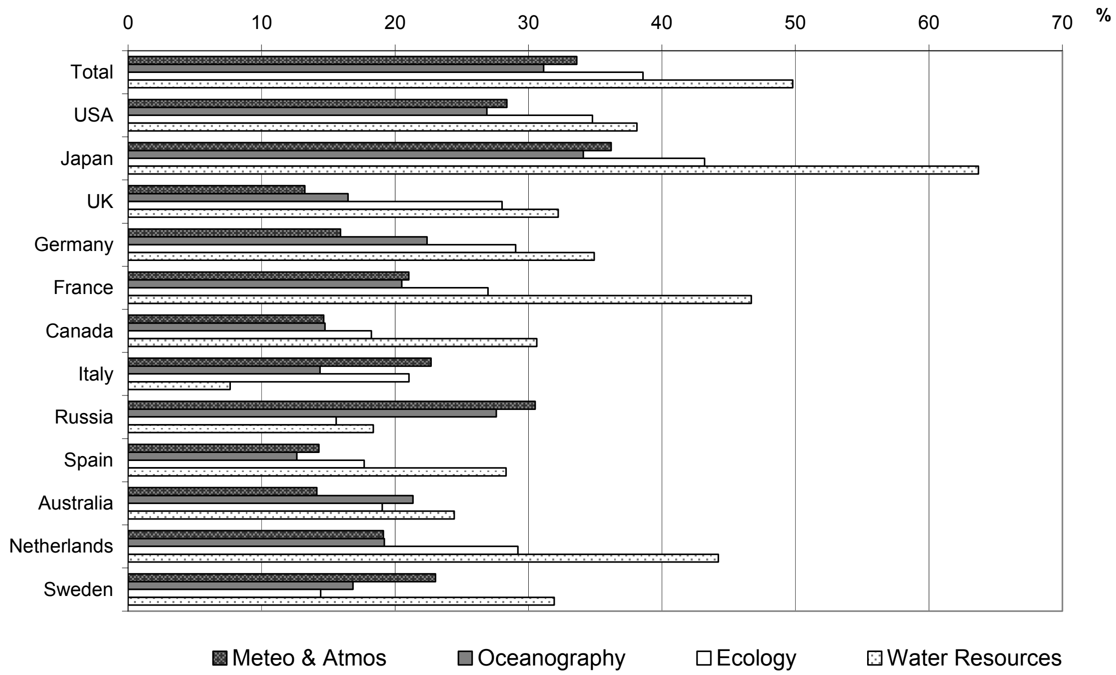
Figure 3 Relative Internationalisation (RI) in Four GEC Fields



Source: SCI web of science, 2002-03.

If a country holds a large share of the reference database, as in the case of the USA, its RI tends to deviate less from the database average compared to countries with smaller publication output.

Figure 4 DET Ratio in Four GEC Fields (% of International Publications)



Source: SCI web of science, 2002-03.