

Problem-oriented research and the disciplinary dynamics of science: the case of atmospheric chemistry

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Abstract

The demand for "robust" knowledge in social problem solving appears to minimize the role of basic science in society, as Mode2-theorists claim. This article presents a case study of how a social problem – air pollution – and the ensuing research policy programs create a major research effort in the participating scientific communities. The outcome – the explanation of the causes of air pollution – required answers to basic questions of the dynamics and composition of the air which led to the creation of a new subdiscipline of atmospheric science – atmospheric chemistry. Rather than diluting the essence of scientific knowledge – to create an authoritative description of reality - in favor of its mere utility, problem-orientation of research has led in the case presented here to fundamental changes in the view of reality by the sciences involved.

1. Introduction

Scientific knowledge acquisition is problem-driven as Poppers claims with respect to the logic of scientific research: „Knowledge does not begin with perception or observation or the collecting of data or facts; it rather begins with a problem“ (Popper 1969: 104, translation by authors). The problem formulation as a stimulus for attaining new knowledge can stem from a variety of sources: unresolved questions of normal science (so-called anomalies in the sense of Kuhn's theory of scientific dynamics), inspirations and ideas of researchers or the need for remedies against social problems such as diseases, technical hazards or environmental risks. According to Popper's logic of research the social origins of problems, be they in science or the larger society (context of discovery), do not impinge on the quality of scientific proof which belongs to the context of justification of new knowledge and which is being dealt with exclusively by scientific rules. By introducing the distinction between the context of discovery and the context of justification, philosophers of science such as Popper meant to demarcate the realm of science (as a purely cognitive process) from that of the social world (as the realm of action). As cognition is no less a social activity than (political) decision-making it has to be asked how societal problems are translated into scientific problems. This insight has, however, been turned into an argument for dissolving the borders between social contexts, between the

contexts of problem raising and the contexts of problem solving. Proponents of the so-called Mode-2-theory argue that research driven by social problems is leading to new and very heterogeneous forms of knowledge production (Gibbons et al. 1994, Nowotny et al. 2001). This claim is based on the observations that basic research appears on the retreat compared to applied research, that research is increasingly becoming subject to demands for social accountability and utility and that political actors impose their interests on the choice and aim of research projects. As a consequence, these authors argue, academic research is becoming replaced by problem-oriented research whose knowledge acquisition is no longer fully controlled by scientific standards and procedures. Instead, actors who are subject to or users of scientific research results intervene into the definition of the validity and utility of new knowledge. Problem-orientation of research, thus, seems no longer connected to the dynamics of scientific development, but the resulting knowledge appears to be directly acquired by heterogeneous actors in society without prior certification by the science system.

In this article, one prominent case of problem-oriented research, atmospheric chemistry, will be studied in some detail to understand the dynamic relationship between social problems, research and the evolution of scientific fields. We will ask how problem-oriented research programs concerning various issues of atmospheric pollution initiated the rise of atmospheric chemistry as a sub-discipline of atmospheric science. In the case of ozone depletion, it will be shown how, in stark contrast to the Mode-2-hypothesis, the need for knowledge in tackling social problems such as smog or skin cancer generates fundamental problems which require basic research efforts and eventually reconfigure the disciplinary order of scientific knowledge.

Problems are the stimulus for any kind of research, to remind us again of Poppers formula. But the sources and types of problems impinge very differently on the research that follows from the posing of a problem. Research prompted by social problems (problem-oriented research) differs from that by demands for practical solutions (applied research) and from that by puzzles of scientific paradigms (basic research).

source of problem formulation	societal problems	problems of scientific knowledge - inconsistencies - lack of rules for knowledge recombination
a) basic research	no	yes
b) applied research	yes	no
c) problem-oriented research	yes	yes

Table 1: A rough typology of different forms of research

Table 1 shows a rough typology of different forms of research. *Basic research* is driven by problems resulting from the conduct of science itself. They attract attention as inconsistencies or as underdetermined recombinations of existing theories (lack of interfield theories in certain areas, Darden/Maul 1977). In contradiction, *applied research* results from problems of reconfiguring theories in contexts outside of the sciences. Scientific knowledge has to be fitted to local or tacit knowledge, used in organizational or technical contexts. By contrast *problem-oriented research* is dealing with both, the application of existing knowledge and, when relevant knowledge for problem-solving is not available, also with the inquiry into fundamental questions. In problem-oriented research literature societal and scientific problem formulations are not sufficiently distinguished. The case of zone research makes the difference very clear: The political problem addressed by publicly funded research programs was to find a way to regulate chlorofluorocarbons and other ozone-destroying substances to prevent harm to humans and the environment. Scientific knowledge had to gain authority within society against the interests of a whole branch of industry. The scientific problem was quite different. Here the goal was to find a complex chemical theory of the atmosphere which could be used to determine the potential effects of different forms of pollution and other environmental threats. Rather than claiming dedifferentiation of social contexts we will pursue the question of how societal (in our case: political) problems translate into scientific problems and how the finding of answers to social problems leads to fundamental questions in the scientific description of reality.

The outcome of this study will be that in the case of atmospheric chemistry problem-orientation has not only stimulated impressive research efforts, it also prompted evolutionary changes in the scientific understanding of the atmosphere of the earth. The following argument will be guided by the hypothesis that problem-oriented research into the chemistry of stratospheric ozone has lead to

establishing atmospheric chemistry as a new subdiscipline of atmospheric science.

2. Air pollution and the rise of atmospheric chemistry

Since the nineteenth century, chemists took a vivid interest in the surrounding air. Determining its contents and applying the law of conservation of mass to them became a strong challenge for theories and methods of chemistry which was on the verge of establishing itself as a discipline. Until the 1950s the then known fourteen constituents of the natural air were considered inert (except oxygen and ozone). Inertia of the air meant basically that these elements did not react with one another chemically. Trace gases including carbon dioxide and ozone were a curiosity that challenged analytic methods, their huge effects on the properties of the atmosphere were widely unknown by then. This holds true, even though Arrhenius claimed already in 1898 that a doubling of the carbon dioxide concentrations in the atmosphere would provoke a rise of temperatures (Crutzen and Ramanathan 2000). There were simply not enough interesting problems for a deeper exploration of chemical processes in the atmosphere, after determining its principle composition. This did not change until the appearance of large scale environmental problems resulting from air pollution, chemical warfare, and public health concerns. The evolution of modern atmospheric chemistry was certainly not prompted by problems arising within chemistry or meteorology but by problems stemming from the demand for solutions to environmental problems. Research efforts dealing with these societal problems became indeed the driving force behind the integration of atmospheric chemistry as a new subfield of atmospheric sciences (Warneck 1988).¹ This article is meant to outline the processes and to demonstrate the structural convergence of those fields, on

¹ ...It is only recently, however, roughly coinciding with Junge's book on Air Chemistry and Radioactivity, that atmospheric chemistry has matured to become a subdiscipline of the atmospheric sciences. About 20 years ago, the hitherto separate fields of precipitation and aerosol chemistry, of air composition, chemical kinetics, photochemistry, stratospheric ozone and aeronomy became more and more related. Ever since these and other subareas converged and crossfertilized, the field of atmospheric chemistry has experienced an enormous expansion in scope and ideas" (*Journal of Atmospheric Chemistry* 1, 1983, pp. i-ii)

the levels of problem perception, cognitive concepts employed in science to approach these problems, and the evolution of research and administrative organizations.²

In the wake of the growing industrialization and the concomitant increase in air pollution of the nineteenth century, the first social concerns and problem posing attempts emerged. One of the first social issues concerned acid rain. A famous example for this development is the book on *Air and Rain. The Beginning of a Chemical Climatology* by Robert Angus Smith (Smith 1972). Smith was a member of the *Royal Mines Commission* and later held a position as an inspector under the British *Alkali Act*. He started measuring air pollution by deploying scientific methods and correlated the chemical composition of the air to several human activities and places. These research efforts were conducted within a cognitive frame which one might call the air pollution paradigm. This paradigm addresses the questions of how particles with an immediate toxic effect to humans, animals, and plants are inserted into the atmosphere near the ground and of how they are washed out of the air through rain after a short time. Air pollution was treated as a local phenomenon near industrial towns and production facilities. Within this paradigm the air appeared to be simply a vessel or transport medium for detrimental particles, while the medium itself is not involved in the chemical processes. This paradigm predominated atmospheric chemistry until the beginning of the 1950s (see the review by Junge 1958). However, researchers started to study natural particles originating from sea salt or volcanic eruptions, when the far-ranging dimensions of transport processes were detected (Bolin 1959).

At the beginning of the twentieth century, another concern arose in relation to air pollution: poisonous gas. The poisoning of the air was viewed as a type of forced air pollution which incapacitates the enemy to continue fighting. The use of poisonous gas at Ypern by the German military became one of the most traumatic events of World War I. Poisonous gas, therefore, became a major subject of research in the US when preparing for World War II (Whittemore 1975). Much of the US poison gas research sponsored by the *Chemical Warfare Service* (CWS) took place on the West coast, at the California Institute of

² for the following see also Schützenmeister 2007, Chapter 5

Technology (Caltech), and at the Universities of California at Los Angeles, and at Berkeley - all three organizations becoming future centres of chemical research of the atmosphere. The US government enforced poison gas research not the least because of the fear that Japan might use it against civilians in an attack against US territory during World War II. Especially the Los Angeles basin was considered to be highly vulnerable (Johnston 2003). These research programs contributed to atmospheric chemistry predominantly by developing improved measurement methods of chemical constituents and micro-meteorological dynamics, which could be applied under real field conditions.

The air pollution paradigm was first challenged by the so-called "Los Angeles smog." In contrast to the European cities and the industrial Centers of the East Coast which were constantly afflicted by the fumes of burning coal, the haze over Los Angeles was an anomaly. The industrial infrastructure was comparably small and the warm weather in Southern California made coal heating unnecessary. The extent of pollution, which provoked heavy eye irritation, crop damage in the adjacent agriculture, and the fast aging of rubber products, could not be solely explained by the amount of gas and aerosols actually released in the environment. Even when the statistical connection to the enormous increase of car traffic in the 1940s was made, smog remained an unsolved societal as well as scientific problem (Doyle 2000; Dewey 2000). As a first step, the *Los Angeles Smoke and Fumes Committee* was established in 1943. Consisting of three scientists, its aim was to advice policy-makers in addressing the problem. Through its transformation into the *Bureau of Air Pollution Control* it was empowered to enforce particular measures. Referring to the theory of acid rain, this agency limited the emission of sulphur dioxide, albeit without improving the smog situation.

In order to explain the peculiarity of the LA smog, new theoretical directions had to be taken. Haagen-Smit claimed that the toxic gases, especially ozone close to the ground, were formed from elements of the natural atmosphere and that the emissions, or rather: their photolytic products functioned as catalysts which were not consumed during the catalytic process. According to Haagen-Smit, the LA smog consisted of an aerosol, which resulted from the oxidization of unsaturated hydrocarbons. These so called volatile organic compounds (VOCs) were found in

the remnants of incomplete burning processes of car gas and of vapours emitted by oil refineries. These substances were catalysts for the photochemical built-up of ozone (Doyle 2000). At the same time, the concepts of photolysis and catalysis became important concepts for atmospheric chemistry: not just the injection of poisonous substances, but the catalytic effect of these substances and their products can threaten the natural chemical balance of the atmosphere. Research on the smog dynamics refuted the belief in a mainly inert atmosphere. Obviously, a fundamental scientific finding emerged from a societal problem which challenged scientific research and eventually changed the perception of the atmosphere.

The problem of the “Los Angeles smog” shared with the aforementioned problems of toxic gases and acid rain several features: all three were *regional* phenomena of the *troposphere*, and the detrimental substances contained a *direct toxicity*. Completely unrelated to the problems of toxic gases, acid rain and LA smog, an important contribution to the emergence of atmospheric science resulted from research in radio chemistry.

The upper atmosphere became subject to intensified research in radio chemistry around the middle decades of the twentieth century. Radio chemistry is concerned with the chemical reactions of radioactive isotopes. The interest in the radio chemistry of the upper atmosphere arose because of two reasons. First, the radioactive carbon-14-isotope (^{14}C) had been discovered in 1940 by Martin Kamen and Sam Rubin at Berkeley. Cosmic rays release neutrons when entering the upper atmosphere, and these neutrons transform the ^{14}N isotope of nitrogen into a radioactive form of carbon (^{14}C). On their way through the atmosphere, the ^{14}C atoms react with oxygen to form $^{14}\text{CO}_2$. Only living organisms, first of all plants, can absorb CO_2 from the atmosphere. This process caused by cosmic rays is the source of all carbon in the earth system that built up over billions of years in earth history. So-called radiocarbon decays to other isotopes of carbon (^{12}C , ^{13}C) within a half-life of 5.600 years. From this finding Williard Libby developed a method to determine the age of organic materials – a technique which revolutionized archaeology. Later, this isotope ^{14}C would play an important role in the research of climate change. The changes in the ratio between “fresh” $^{14}\text{CO}_2$ and older CO_2 containing other isotopes of carbon allow to

determine which share of the CO₂ content of the atmosphere has its origins in human activities. Apart from the 11-year cycle of changing sun activity, the cosmic production rate of ¹⁴CO₂ is nearly constant.

Second, with the above surface tests of atomic bombs the control of the radioactive fall-out of substances such as strontium-90 became a pressing issue for military research. The aim of military research was both to find ways to protect the own population from radioactive fallout and to assess the activities and arsenals of the military opponents. While the fission products of bombs of the Hiroshima type reached only as far the troposphere from where they were washed out by rain within a relatively short time, the radioactive material from H-bombs was pushed way up into the stratosphere; the fall-out took much longer and as a result the radioactive substances were transported around the world. The above-surface atomic bomb tests were the biggest experiments with the atmosphere so far. In the context of these military experiments, the Atomic Energy Commission (AEC, the forerunner of the today's Department of Energy, DOE) put much money into radio chemistry research. In 1957, the US military installed the *High Altitude Sampling Program* which used six Lockheed U2 spy planes to collect particles in the stratosphere and to determine the radioactive content of the air (Feely 1960: 645). Later, this equipment formed the backbone of the NASA fleet during its research missions in the upper atmosphere. It was used again for the early ozone research campaigns, especially within the *Climate Impact Assessment Programs* (CIAP) before NASA acquired its own customized research variants of these air planes.

Ozone depletion became yet another source of the formation of atmospheric chemistry. It actually transformed the field which was focused on chemical processes *within* the atmosphere into a theory of the global atmosphere which is not only determined by physical processes of energy flow, but also by its chemical composition and dynamics. One might wonder why the explanation of the threat of anthropogenic ozone destruction and the controversy over the causes of the ozone hole had such a strong integrative effect on atmospheric sciences. It should be mentioned that already the discussion about acid rain as well as about the climate consequences of a nuclear war ('nuclear winter') required the integration of chemical and dynamical models of the atmosphere.

But the essential driving force behind the integration of atmospheric dynamics and chemistry within atmospheric science came out of large-scale research on ozone depletion.

The social perception of anthropogenic ozone depletion was characterized by a set of phenomena which are completely different from the problems outlined above. It was considered to be a *global* problem, based on reaction chains in the *stratosphere* which contain multiply feed back loops, and it was believed that the detrimental effects occur *indirectly* as a result of intensified solar ultraviolet radiation reaching the earth's surface. On the level of political and administrative decision making, the regulatory problems resulting from each of these dimensions of ozone depletion were treated as having very little in common. Convergence, however, appeared on the level of scientific concepts. Starting with the Haagen-Smit hypothesis which draws on photolytic and catalytic processes to explain the "Los Angeles smog" and continuing with the more sophisticated theory of the natural ozone balance in the stratosphere by Paul Crutzen, similarities between the chemistry of tropospheric smog and stratospheric ozone come to the forefront. These similarities consist of the role of photolysis, catalysis, and the role of nitrogen oxide (NO_x) in both processes.

Already in 1930, Sidney Chapman's theory of a dynamic equilibrium of stratospheric ozone had pointed at the importance of photolytic processes and thus challenged the established image of an inert atmosphere. Chapman claimed that the ultraviolet light of the sun dissects the O_2 molecules such that radicals consisting of single oxygen atoms (O) emerge which can unite with other O_2 molecules to form ozone (O_3). On the other hand, ozone itself is also split up by ultraviolet light. The ozone content of the stratosphere is determined by a balance between the build-up and the break-up of ozone, - a process, which is sometimes illustrated by way of the analogy with a leaky bucket. The level of water in such a broken bucket is determined by the amount of water which flows in and by the outflow which is dependent on the size of the hole and the level of water.

However, for chemists the Chapman mechanism was not complex enough to prompt any research interest. Chapman overrated the velocity of the depletion

process which he described as the only mechanism of ozone removal in stratosphere. In the 1930s, Chapman's theory seemed to meet the ozone observations pioneered by Gordon M. Dobson. It could explain the seasonal and geographical differences and also the low variability of the ozone layer between day and night time. Furthermore, the predictions of the vertical distribution of ozone derived from the theory were reflected in the measurements of optical remote sensing (reverse method) or ascending balloons. In the 1950s, improved measurement methods—missiles equipped with scientific instruments allowed measurements up to 70 kilometres altitude—challenged the claim that the Chapman mechanism could explain the vertical ozone profile. The improved measurement possibilities also established the finding that Chapman overestimated the intensity of ultraviolet light in the upper layers of atmosphere. It became clear that something else must break up the ozone in the stratosphere.

When searching for further ozone reducing mechanism, David Bates and Marcel Nicolet assumed the existence of catalytic processes which remove ozone from the stratosphere. A first catalytic theory of ozone balance was proposed by Norrish and McGrath (1958) who pointed out the close connection between photolysis and catalysis in atmospheric processes. In their theory water vapour was held to be the main catalyst. But this theory was also not able to explain the ozone balance since the stratosphere is very dry. A sophisticated theory of the natural ozone balance was developed by Paul Crutzen (1970), who identified NO_2 originating in biological processes in the troposphere as the main catalyst (Johnston 1992: 4). The growing complexity of the chemical processes in the atmosphere made the field eventually more and more interesting for chemists.

At the same time high-altitude airplanes and the "space shuttle" were discussed to be responsible for polluting the stratosphere. Airplanes travelling with supersonic speed fly in higher altitudes than conventional aircrafts in order to reduce friction. Since the exhaust of planes and also of missiles contain water and nitrogen, the injection of these substances might increase the amount of catalysts which then might remove ozone in stratosphere. From this inference the first hints of an environmental problem arose; initial research efforts to assess the possible effects were started. Another constituent of the shuttle

exhaust is chlorine, which NASA scientists considered to be a further possible threat for the ozone layer. Later, Mario Molina and Sherwood Rowland identified CFCs (chlorofluorocarbons) as a ozone destroying catalyst (Molina and Rowland 1974). The issue switched from a potential problem of a not yet existing technology to an actual problem since CFC has been in use since the 1930s. With these findings the problem became increasingly relevant. The argument of this article—that the diverse problem-oriented programs in atmospheric chemistry proposed and executed by particular research organizations converged eventually to a new subdiscipline because of mutually shared cognitive concepts and analytical methods—is illustrated by the following table:

a) localization	local	global	tropospher e	stratosphe re	toxicity to humans direct indirect	
(1) air pollution	x		x		x	
(2) chemical warfare	x		x		x	
(3) L.A. smog	x		x		x	
(4) <i>radioactive fall out</i>		x		x	x	
(5) ozone depletion		x		x		x
b) important groups of substances	ozone O/O ₂	HOx	NOx	ClOx	VOCs	SOx
(1) air pollution			x	x	x	x
(2) chemical warfare				x	x	
(3) L.A. smog	x	x	x		x	
(4) <i>radioactive fall out</i>						
(5) ozone depletion	x	x	x			
c) theoretical concepts in atmospheric chemistry	photolysi s	catalysi s	dynamic equilibrium		transport	Aerosole s
(1) air pollution					x	x
(2) chemical warfare					x	
(3) L.A. smog	x	x	x		x	x
(4) <i>radioactive fall out</i>	x				x	x
(5) ozone depletion	x	x	x		x	x
d) organizational embedding of problem definition	politics	leading agencies		research		
(1) air pollution	local, UK clean air act	local		diverse		
(2) chemical warfare	US Army	CWS		Caltech, UCB		
(3) L.A. Smog	L.A. County	Bureau Air Pollution Control		Caltech, SRI		
(4) <i>radioactive fall out</i>	military research	AEC		UCLA, UCB		
(5) ozone depletion	ozone regime	WMO, UNEP		NASA, diverse		

Table 1: Differences and convergence of different problem-oriented research areas leading to the appearance of modern atmospheric chemistry.

Section a) illustrates the preponderance of air chemistry with its air pollution paradigm in the early phase of the interest for the surrounding air. During this phase the air was interpreted as a vessel containing gases and pollutants. The toxic effects of the dynamics of air resulted from the washing out of pollutants which were emitted from either ground-based sources such as cars or power plants or from mobile sources such as air planes. With the nuclear bomb tests two new dimensions of air pollution arose. Radioactive substances were spread

around the globe and up into the stratosphere. Substances that reached the stratosphere were distributed all over the world due to its fast global mixture. Stratosphere ozone depletion turned into a problem of global dimensions. The effect of ozone depletion does not result from the actual toxicity of ozone, which is rather a problem in the lower atmosphere, but from the changed absorbing properties of the atmosphere. Reduced ozone levels allow ultraviolet radiation to pass. Resulting effects are a rise of skin cancer rates in the population and crop damage. With regard to the perception as a social problem, ozone depletion appeared not to have much in common with air pollution.

Section b) lists the groups of substances which became relevant within the diverse problem contexts. The substances stand not only for a single constituent but for the complex chemistry associated with these elements. The table indicates the relationship between the Los Angeles smog and ozone depletion involving many relevant groups of chemical substances and representing a complex challenge for the emerging atmospheric chemistry.

Section c) of the table shows the different concepts of atmospheric chemistry listed according to the temporal sequence of their introduction to the theory of stratospheric ozone and its depletion. The table clearly demonstrates that the same concepts were used to explain very divergent problems. The overlap of theoretical concepts increases also with respect to the relationship between ozone reduction and climate change, even though the problems were kept separate in terms of research programs and politics. Their explanatory power furthered the abstraction of these theoretical concepts from their original problem contexts and the emergence of a subdiscipline which is determined by these cognitive concepts and not by the problem definitions.

Section d) of the table refers to the organizational embedding of the problem perception and solution in different spheres of society. Because of the complexity of the problem context the table shows only a small selection of the contexts of the problem origins. This scheme gives a crude impression of the argument that the perception of the problems in politics and the translation into research problems through mediating organizations are not connected to one another. A convergence can be observed on the level of research organizations. The early

atmospheric chemistry has its origins in projects executed primarily at Californian universities and research institutes.

One might wonder why this development ended in atmospheric chemistry becoming a subdiscipline of atmospheric science rather than of chemistry. One might further ask why there is no atmospheric medicine; after all, the carcinogenic effects of ultraviolet light played an important role in constituting ozone depletion as a substantial environmental problem. The answers to these two questions have to be sought in two directions. First, classical laboratory chemistry was not prepared for the problems posed by atmospheric research. Classical laboratory chemistry did not offer a theory for measuring trace gases in the atmosphere, particularly for remote sensing. In addition, laboratory chemistry could contribute little to the conditions for chemical reactions in the atmosphere. In a nutshell, classical chemistry could not provide the necessary knowledge for atmospheric research. Medicine was a different case: from the beginning it was non-controversial that a high dose of ultraviolet radiation will increase the chances for skin cancer developing in the population. The question was only whether there will indeed be an exposure to that radiation. Second, atmospheric chemistry addresses very complex systems. And even though the basic reactions are rather simple, specific concepts such as reaction rates, heterogeneous reactions or aerosol surfaces require much of the research attention. As an outcome of this research problem drift, one can observe the emergence of a type of physical chemistry which was geared toward climate-specific reaction patterns rather than to the reaction patterns common in laboratory chemistry.

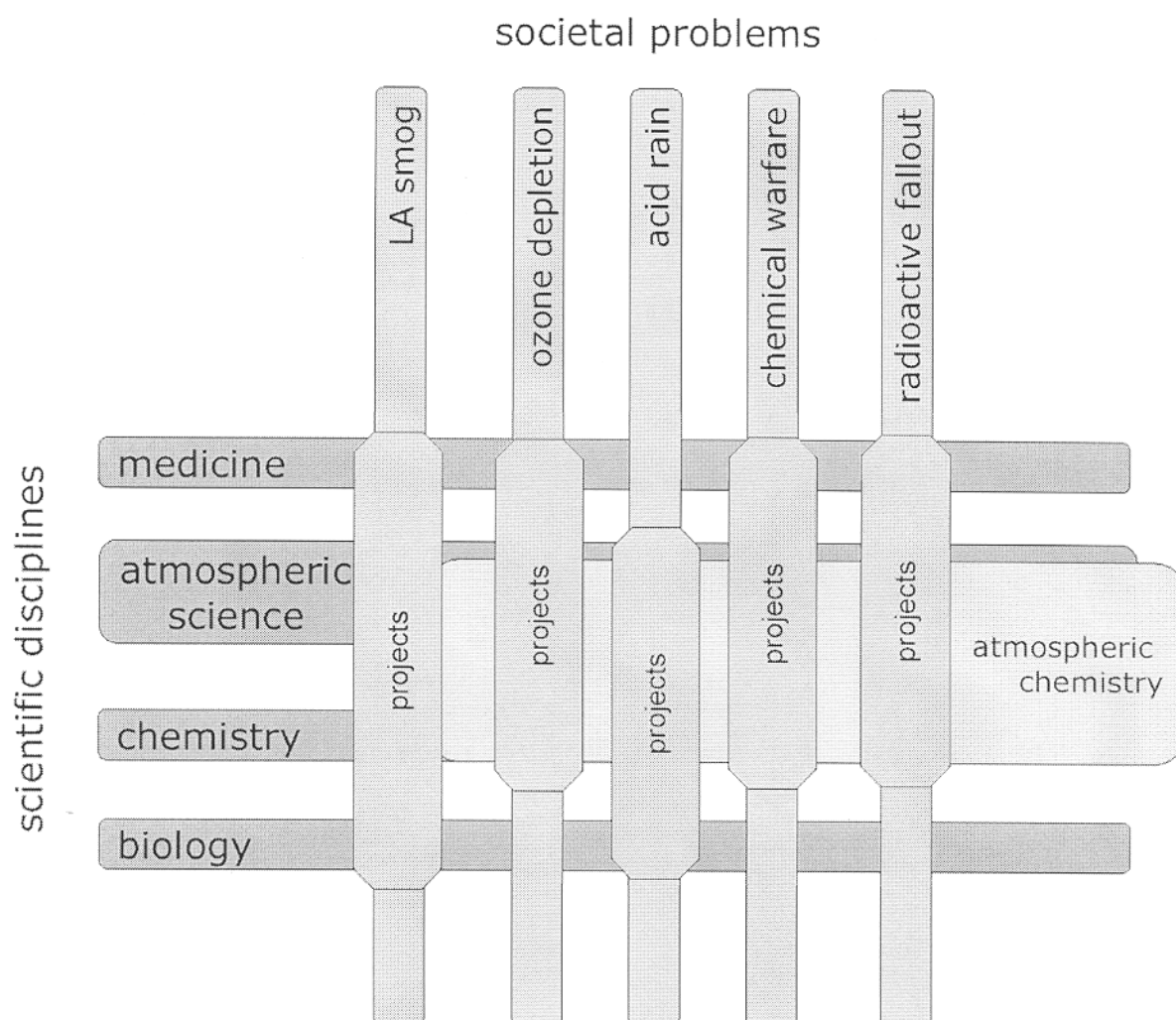


Figure 1: Relation between scientific disciplines and societal problems, which depend on interdisciplinary research

Figure 1 shows the four most important disciplines (medicine, atmospheric science or meteorology, chemistry, biology) from which the knowledge of atmospheric chemistry originates. The formation of atmospheric chemistry was due to the cognitive concepts which were used to address the social problems of LA smog, ozone depletion, and acid rain. These cognitive concepts originated in varying combinations of knowledge from the aforementioned "source" disciplines.

The research on ozone depletion played a particularly important role in the emergence of atmospheric chemistry as a subdiscipline of atmospheric science because it contributed most to the transgression of established disciplinary borders and to the reconfiguration of the disciplinary order in the realm of

describing the atmosphere. It seems appropriate, therefore, to devote a separate chapter to the integration of atmospheric chemistry into atmospheric science.

3. Chemistry of the global atmosphere - ozone hole and climate change

When the problem of ozone depletion arose, its global dimension was obvious. The ozone layer was considered a universal phenomenon and a permanent mixture of the stratosphere was assumed. Therefore, scientists worked with one-dimensional models taking only the vertical distribution of ozone into account. The physical dynamics of the atmosphere was not yet part of ozone depletion theory. The question of how the ozone-destroying substances being heavier than other gases of the natural air were transported into the stratosphere was subject to intensive controversy. Only in-situ measurements could convince the sceptics that the upward transport of these substances actually takes place. In the 1970s, the existing knowledge of chemical processes in the natural atmosphere had not yet arrived in the mainstream of atmospheric sciences. Despite the proclaimed unity of atmospheric science the integration of atmospheric chemistry still took a long way. The controversy over the causes of the ozone hole was an important milestone within this development because the problems of a one-dimensional chemical theory as well as of exclusively physical models of atmosphere became obvious. Today the atmospheric chemistry contributes increasingly to the explanation and the assessment of the global climate change.

The ozone hole is a phenomenon which appears seasonal, only in Antarctica, and it cannot be explained by processes in the gas phase of the atmosphere alone. The atmospheric chemists claimed that this anomaly has to be explained by the growing CFC content of the stratosphere. In contrast, the dynamists who in general had no reservations against the CFC-hypothesis of the ozone destruction, contested the claim that the CFC was also the cause of the ozone hole in the Antarctic spring. They considered this to be an anomaly caused by the break-up of the Antarctic vortex. Temperature differences bring about a worldwide air circulation. As a result, the air rises at the equator and sinks to the ground in the polar regions. The downward movement generates the Antarctic vortex. At the end of the Antarctic winter, the situation reverses. When the sun reaches the

polar regions again, it heats up the higher layers of air. The result is a temperature inversion, and the downward movement stops.

Between 1950 and 1970, improved techniques of ozone measurement (meteorological balloons, missiles, satellites) led to the insight, that Chapman's theory was marred by an important flaw. The actual measurements revealed that only half of the amount of ozone which Chapman had predicted could be detected in the atmosphere. Other factors than those implied in Chapman's equations appeared to contribute to ozone depletion. This finding led to the assumption that some catalyst increased the reactions rates of ozone molecules. In 1970, Paul Crutzen pointed at the role of nitrogen oxides (NO_x) for the increased rate of ozone depletion (Johnston 1992: 4). With this discovery in mind, ozone researchers started to suspect that man-made chemicals might contribute to the reduction of the ozone layer. After James Lovelock had demonstrated by way of gaschromography that the atmosphere indeed contains chlorofluorcarbons (CFCs), even at locations far from industrial production sites, Mario Molina and James Rowland tried to prove that CFCs are the main cause for increased reaction rates of ozone molecules (Molina/Rowland 1974). The knowledge generated from the equations of Molina and Rowland slowly became established knowledge in the seventies; it was, however, challenged by the discovery of the "ozone hole" which led to the insight that not only chemistry, but also climate dynamics and aerosol surfaces had to be taken into account to fully understand the ozone problem. The discovery of the "ozone hole" over the Antarctic shelf which indicated a much higher level of ozone depletion than expected seemed to disprove the Molina/Rowland hypothesis, or at least to demonstrate its explanatory limits. The search for other than anthropogenic causes of ozone depletion led to two Antarctic Ozone Expeditions in the eighties of the 20th century resulted in a basic confirmation of the Molina/Rowland theory which needed only slight modifications to cover the effects of atmospheric transport phenomena.

Ozone research has been particularly relevant for the emergence of atmospheric chemistry because it required the integration of various theoretical and methodical instruments which previously had been based in disciplines with few mutual contacts. Ozone research involved the need to understand the role of a

variety of substances involved in the chemistry of the atmosphere: ozone, HO_x , nitrogen oxide (NO_x), chlorine oxide (ClO_x) and SO_x . The relevant fields of scientific expertise for understanding ozone depletion belong to quite different scientific disciplines: Photochemistry to chemistry, gas kinetics to physics, and circulation dynamics of the atmosphere to meteorology. It was the recombination of the diverse theoretical and experimental concepts such as photolysis, catalysis, dynamic equilibrium, analysis of transport phenomena, and aerosoles stemming from different disciplines such as chemistry, meteorology, and physics which contributed to ozone research and were integrated into the new subdiscipline of atmospheric chemistry.

4. Conclusion

Some social problems for which there is no ready-made remedy available in terms of existing knowledge and technology may prompt fundamental scientific research. The origin of atmospheric chemistry from the mundane problems of acid rain, smog or radioactive fallout from above-surface nuclear bomb tests is a case in point. One of the prerequisites for major shifts in the structure of scientific knowledge is the existence of organizations which even if their primary purpose is not the pursuit of scientific knowledge provide the resources to pursue fundamental research with unknown outcomes. The other prerequisite is the organization of interest among scientists in such topics which deviate from normal science and exhibit features which cannot be clearly identified as belonging to one or another discipline.

This short study of the development of atmospheric chemistry into a subdiscipline of atmospheric science shows, however, that this process is marked by contingencies which result from the contribution of knowledge from a diverse range of disciplines involved in the research on issues such as the Los Angeles smog, acid rain or ozone depletion. Scientific contingencies indicate the need for closure in debates over controversial research results. Prior to the emergence of atmospheric chemistry a number of scientific controversies needed to be closed before the integration of research results from a variety of disciplines involved in the understanding of the dynamics of the atmosphere finally succeeded.

In this article, it has been shown, however, how research which started from an acute social awareness about critical changes of the environment lead to basic interdisciplinary research efforts which substantially changed the disciplinary matrix of atmospheric science. All the relevant research programs mentioned above were organized as interdisciplinary projects with specific missions. However, these projects produced knowledge in terms of methods and theory which allowed a certain level of integration along disciplinary lines. The new knowledge generated in these empirical projects led to the formation of a new scientific subdiscipline which eventually developed into a fully-fledged scientific field with a conceptual identity, text-books, research institutes and PhD-programs.

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