Revisiting the "Ozone Hole" Metaphor: From Observational Window to Global Environmental Threat

Sebastian Grevsmühl

Published in *Environmental Communication*, doi : 10.1080/17524032.2017.1371052

Revisiting the "Ozone Hole" Metaphor: From Observational Window to Global Environmental Threat

Sebastian Vincent Grevsmühl
Centre de Recherches Historiques (CNRS-EHESS)

Postal address:
CRH (CNRS-EHESS)
54 boulevard Raspail
75006 Paris
France

E-mail: sebastian.grevsmuhl@ehess.

Abstract

In 1985, just over 30 years ago, the "ozone hole" made its appearance in the press as a truly global environmental threat. As one of the most important global environmental issues of the late twentieth century, the "ozone hole" is also and maybe most importantly a remarkable metaphorical, visual and imaginary construction. This essay examines the historical trajectory of one of the most influential environmental metaphors of the twentieth century, the famous "ozone hole," from its birth within the astronomical community at the beginning of the twentieth century to its contemporary framing as a global environmental threat. The article provides evidence why metaphors constitute a valuable object of historically informed studies of scientific practice, and shows in particular how metaphorical landscapes shift over time, mapping at the same time larger social and political developments. The essay ends by showing how scientific images and metaphorical framings interact and how they shape scientific and popular discourse on nature, as well as our understanding of the global environment.

Keywords

metaphor; ozone hole; global environmental change; scientific images; geoengineering; environmental history

Towards a framework for a history of the "ozone-hole" metaphor

On January 17, 1934, eminent geophysicist Sydney Chapman delivered a somewhat fameless but nonetheless remarkable presidential address before the *Royal Meteorological Society* in London. In a section pragmatically entitled "Can a hole be made in the ozone layer?," Chapman speculated on the possibilities of artificially intervening in the chemical composition of the Earth's atmosphere in order to allow astronomers better ultra-violet observations of the sun and other celestial objects (Chapman, 1934; cf. Fleming, 2010; Wells, 1997).

Rather optimistic in regard to proposed geoengineering solutions, Chapman made several practical suggestions on how to introduce a hypothetical chemical agent into the atmosphere in order to create what he called an "ozone hole." Aircraft, he

argued, could disperse large quantities of a catalytic agent in the lower stratosphere, and balloons and rockets deployed in higher altitudes to ascertain full-scale atmospheric distribution of the ozone-destroying agent. Although partly conscious of possible health dangers that such an experiment with a yet untested "deozoniser" might invoke, Chapman nevertheless believed that "small isolated islands with few inhabitants" represented a suitable test ground and that "proper clothes and headgear" would be sufficient protection during the artificial opening of the sky (Chapman, 1934, quotations on p. 133 & 134).

Yet when we use the metaphor of the "ozone hole" today, we obviously refer to a very different scientific and environmental phenomenon, with very different political or ethical ramifications. Quite evidently, the famous "ozone hole" metaphor has a rich history, a history that has remained largely neglected by what one may call the "classic" philosophical, political or socio-historical ozone literature (cf. Benedick, 1991; Christie, 2001; Grundmann, 2001; Litfin, 1994; Parson, 2003; Roan, 1989). In the following, I propose a rather unorthodox account of the history of ozone depletion by following the historical trajectory of the "ozone hole" metaphor throughout the twentieth century. Close analysis of the different scientific contexts in which the "hole" metaphor emerged allows to gain new insights into how to engage in historical analysis of metaphors, revealing how scientific theories and conceptual frameworks shift over time, and tracing at the same time larger social, economic and political dynamics. As I will argue below, atmospheric "hole-making" or "hole-provoking" techniques dramatically shifted from "welcomed," "hypothetical," and "impartial" overtones to "threatening," "geopolitical," and finally "environmental" connotations. As an alternative account of the history of ozone depletion mainly based on close analysis of public speeches, scientific publications, reports, newspaper articles and interviews with scientists, the following narrative will also draw on findings in theoretical metaphor literature as well as on metaphorical case studies explored in history of science, science and technology studies and communication studies.

A profusely growing field of literature in environmental communication and science studies claims that metaphors (often together with visual renditions) shape scientific and environmental knowledge in many important ways (on environmental metaphors, see: Cozen, 2013; Milstein, 2016; Nerlich & Jaspal, 2012; Nerlich & Koteyko, 2010; Nerlich, Koteyko & Brown, 2010; Wiman, 1995; on metaphor theory, see: Maasen & Weingart, 2000; Ortony, 1993). A useful starting point for a theoretical discussion of the uses of metaphors and their meaning is Max Black's so-called "interactionist" theory (Black, 1955). Its main claim is that there are no stable metaphorical meanings but only context related meanings that are created within specifically constructed systems of ideas. Each specific metaphorical framing produces an expansion or shift of the metaphors literal meaning. Yet, the new context and meaning influence also the common-sense associations invoked in the first place when mobilizing a specific metaphor. Metaphors may therefore be seen as "filters" of reality: they show certain aspects of our world while blocking out others, allowing one field of thought (the subject) to organize another by selection and filtering. According to Black, it is not the literal meaning but the common-sense associations that play the most important role in the creation of metaphorical meaning. Moreover, these common-sense associations – and hence the meaning of a metaphor – cannot be paraphrased without destroying its cognitive content (Black, 1955, p. 293).

To be sure, some scholars have challenged Black's interactionist theory. Donald Davidson, for instance, argues that metaphors may only be read in a literal way. He believes that the conventional denotation of a word which is employed in a metaphorical way is the only meaning that counts, arguing that its meaning is not a question of semantics, but of pragmatics. His main claim reads: "[…] metaphors mean what the words, in their most literal interpretation, mean, and nothing more" (Davidson, 1978, p. 32).

As the "ozone hole" case shows below, both positions hold some important truths about metaphors and their meanings. Max Black is right to insist on the fact that two words coming from two different semantic fields produce new meanings. However, Davidson also has a point when he insists on the literal interpretation of metaphors: metaphors often work well when we can interpret and understand them in a literal way. In what follows, I will argue that it is necessary to adopt a historical perspective on metaphors, and to analyze metaphors and their framings within their specific historical context. Indeed, as already mentioned in the introduction, the same metaphor can produce very different meanings within different historical and social contexts.

In history of science and science and technology studies, many case studies have shown that analyzing metaphors in their historical context can be highly productive. Stepan, for instance, has described the very concrete political effects racial metaphors had on scientific research programs in biology, medicine and anthropology. She has argued that the context decides if, for example, the analogy between women and Negros as "inferior race" is perceived as a metaphor – or rather as a robust scientific relationship based on statistics (Stepan, 1986). Other scholars have shown the important effects the "information" metaphor had, from the 1950s onwards, on very different fields of research such as cybernetics, psychology, ecology or molecular biology (Edwards, 1996; Kay, 2000; Fox Keller, 1995 & 2002; Kwa, 1987; Galison, 1994). Finally, historian Philipp Sarasin has shown how in the Nineteenth century war metaphors successfully "invaded" the field of bacteriology, and how "external" factors such as migration movements closely linked to certain diseases influenced the research frameworks (Sarasin, 2007). All of these studies show that metaphors, often transferred from very different contexts, can actively shape scientific practice and that the choice of vocabulary rarely is innocent, implying that one needs to pay close attention to the specific historical context in which metaphors evolve.

Adopting a historical perspective therefore allows also to move beyond the mere scientific context and to question tacit assumptions and connotations that are built into metaphors, revealing larger socio-political settings and agendas. The "ozone hole" case presented here provides new critical insights into scientific practice and scientific communication strategies, in particular into how the environmental sciences create their objects of knowledge, especially when phenomena of an important scale are involved. It also illustrates how scientific material culture informs discursive and visual framings in various manners and how environmental communication is shaped by scientific practice.

Early theories on "ozone holes" within the astronomical community

Any standard account in the history of ozone depletion begins in the 1970s with the Supersonic Transportation (SST) debate and follows with the first serious concerns about anthropogenic pollution of the stratosphere with CFC's until their gradual global

phase-out under the Montreal Protocol and its successive amendments (see for example Litfin, 1994; Parson, 2003). However, Sydney Chapman's 1934 presidential address serves as an ideal entry point into a rather unusual history of atmospheric "hole-making" which focuses on neglected episodes of ozone research, namely the years preceding the well studied ozone controversy or, as science writer Lydia Dotto and chemist Harold Schiff bluntly have called it, the "ozone war" (Dotto and Schiff, 1978).

The first important strand that Chapman evokes in his presidential address is the apparent usefulness of so-called "ozone holes" to astronomers for observations. In Chapman's opinion, this could "extend [research] some hundred Angstroms further into the ultra-violet." (Chapman 1934, p. 133). Erich Regener, contemporary of Chapman and important pioneer of balloon-borne and rocket-borne ozone measurements, mobilized in his articles the same metaphor, stating in 1946 that an "ozone hole" might be welcomed by astronomers to conduct observations in the range of normally blocked ultra-violet wavelengths (Regener, 1946, p. 165).

The astronomical community closely defined in other words the discursive use of these early "ozone hole" theories. In addition, they also centered on the pioneering history of ozone research influenced by the work of the French physicist Alfred Cornu and eminent chemist Walter Hartley. Cornu argued in 1879 that the rather sharp limitation of the ultra-violet end of the solar spectrum was due to some kind of absorption in the atmosphere (Cornu, 1879). One year later, in 1880, Walter Hartley suggested that this could only be due to the presence of ozone. In tribute to Hartley's pioneering work, scientists named the absorption band in the ultra-violet region the "Hartley band" (Hartley, 1880).

Early ozone research within the astronomical community was moreover greatly influenced throughout the 1880s, by the introduction of photographical spectroscopic methods as standard instrumentation of scientific inquiry. Spectroscopy shaped not only scientific understanding of the upper atmosphere – such as the UV-absorbing effects of ozone – but it also played a fundamental role in early metaphorical framings of the atmosphere and the global environment. Indeed, the metaphor of the "ozone hole" was already in this early historical stage closely linked to the conception of the stratosphere containing an "ozone shield," another influential environmental metaphor which stands for the scientific idea that atmospheric ozone forms a protective layer against harmful UV-radiation. Ozone research pioneers such as Gordon Dobson and Paul Götz helped developed this idea especially in the 1920's and 1930's through their continuous efforts to effectively quantify atmospheric ozone, by establishing spectrophotometer observation networks first in Europe and little later on a global scale (Dobson, 1968).

The "ozone hole" Chapman is referring to has to be analyzed within this specific historical context and it can be read in a very literal sense, just as Davidson suggested: as the ozone shield is interfering in astronomical observations, one may purposefully modify its chemical composition in order to create an "observational window" for astronomers, a "hole" through which they could look out at the sky. This early framing of the "ozone hole" as an "observational window" closely relates to observational practices well established within astronomy at the time, especially the idea that the atmosphere is a strong filter with very limited transparency. Moreover, the use of the ocular and therefore rather neutral "window" metaphor shows that scientists placed the observational, scientific benefits clearly above possible negative side-effects such experiments might provoke.

While Chapman and Regener reflected on creating an "ozone hole," they referred at the same time to a highly speculative phenomenon that might prove to have some useful effects on scientific observations but, in this early period, the "hole" or "window" in the sky remained nevertheless a fully hypothetical suggestion. For instance, Chapman did not know which substance to use to destroy atmospheric ozone and he believed that the "ozone hole," if created, could only be very short-lived, stating that "[a]ny long persistence of such a hole, even if once created, could scarcely be hoped for" (Chapman, 1934, p. 133). Moreover, possible environmental and health dangers played in this early stage of hole theories (if at all) only an inferior role. In consequence, Chapman attributed very little importance to the potential environmental or health risks, especially when considered in contrast to the possible gain of scientific knowledge he hoped to obtain from the suggested experiments.

This early framing of the "ozone hole" ties in well with many historical studies identifying a general optimism in science and technology which can be observed in the Western world throughout the first half of the twentieth century, as well as parts of the Cold War, and which was rarely met by public criticism (cf. Hughes, 1989). Indeed, during this period scientific optimism clearly outplayed any environmental or health concerns which, as we will see below, only started to gain ground from the 1970s onwards.

Geoengineering and geophysical warfare

Chapman's hypothetical "deozonizer" (Chapman, 1934, p. 134) and the proposal to cut a "hole" in the ozone layer gained during the Cold War increasingly in substance, yet for completely different reasons. The 1934 speech points to a rapidly growing field of interest in the late twentieth century, namely the suggestion of purposefully interfering in the composition of the atmosphere (Fleming, 2006 & 2010). Science historians have shown that a direct link exists between geoengineering, meaning purposeful environmental modification, and warfare, and that even during the 1930s, scientists would have found nothing profoundly new about this idea (Fleming, 1998; Hamblin, 2013).

German philosopher Peter Sloterdijk suggested that environmental warfare, as we understand it today, traces back to the First World War when society witnessed the rise of what he calls "atmoterrorism" (Sloterdijk, 2009) with the introduction of highly poisonous chlorine gas, released for the first time in 1915 by German troops in the trenches of Ypres. This new form of "atmospheric terrorism" allows one side to turn the enemy's environment into a weapon against them. While, during the 1930s, cutting an observational "hole" in the ozone layer for the convenience of astronomers did not seem completely out of reach, during the Cold War this very same question became a potentially relevant research topic of important geostrategic and military interest. During the era of geophysical warfare and purposeful interference in the chemical composition of the atmosphere, Chapman's hypothetical "deozonizer" could become in other words a weapon of significant potential threat.

One of the first serious inquiries into this issue was conducted in the late 1950s, a time when public concern about global radioactive fallout and unintended consequences of U.S. and Soviet nuclear weapon testing programs grew considerably. At a meeting in 1958 in Washington D.C., members of the RAND Corporation, Los Alamos Scientific Laboratory, the Naval Research Laboratory and other institutions discussed the

possibility of atmospheric nuclear bomb explosions being able to "burn a hole" into the ozone layer (Hoerlin, 1976, p. 43, fn 98). Some of the important scientific studies that followed focused on the crucial role that nitric oxides might play in ozone chemistry. Scientists assessed many new aspects of complex chemical reactions at extreme temperatures and different atmospheric pressures throughout the testing period. During the 1950s and 1960s, nuclear bomb testing provided unique opportunities to study the creation of large amounts of ozone during sea-level explosions (DeWitt, 1955) as well as positive and negative feed-back cycles due to transport of ozone and other trace substances between the troposphere and the stratosphere (Danielsen 1968a, 1968b). Although critics later minimized ozone depletion effects of atmospheric nuclear bomb explosions (claimed for instance by Johnston, Whitten, & Birks, 1973) as lying within the margin of error of the measuring techniques (Bauer & Gilmore, 1975; Office of Technology Assessment, 1979), researchers discovered new important characteristics of the atmosphere as a direct spin-off of atmospheric nuclear bomb testing. They developed new knowledge on global circulation patterns and large-scale transportation effects which could be easily followed due to the impulse-like injection of large quantities of unique transient radioactive tracers into the troposphere and the stratosphere (Machta, List, & Hubert 1956; Goldsmith & Brown, 1961).

The theme of purposefully cutting a "hole" in the ozone layer was also investigated in other scientific fields throughout the 1960s. Historian of meteorology James Fleming (2011) has shown that Harry Wexler of the U.S. Weather Bureau discussed the "ozone hole" issue as early as 1962 in a working paper entitled "On the possibilities of Climate Control." Following Chapman's practical suggestion to seek "the advice of chemists" (Chapman, 1934, 134) in order to find possible candidates for catalytic ozone destruction, Wexler turned to Caltech chemist Oliver Wulf who suggested chlorine and bromine as possible "ozone hole" creators. Wexler assumed in his paper that a relatively small amount of bromine could severely interfere in the radiation budget of the stratosphere (cf. Fleming, 2010, p. 221).

This type of concrete scientific proposition would certainly have been of great interest to the Department of Defense whose direct involvement in the ozone case stays until today unexplored. However, the most cited war-related suggestion was made by one of the advisors of President Lyndon Johnson's Scientific Advisory Committee, Harvard-trained geophysicist Gordon MacDonald of the University of California. MacDonald warned in 1968 that the creation of an "ozone hole" might indeed be used in the near future as a geophysical weapon and concluded: "The ozone is replenished daily, but a temporary 'hole' in the ozone layer over a target area might be created by physical or chemical action" (MacDonald, 1968). Contrary to Sydney Chapman, MacDonald had a clear idea about the "disastrous effects" such geophysical weapons could produce, very much in the way Sloterdijk characterizes "atmoterrorism," by pointing out that removing the ozone shield could even be fatal to all life.

During the Cold War environmental issues stood in other words at the very center of American national security considerations (cf. Hamblin, 2013), an observation which can also be extended to most European countries for this period (Roberts & Turchetti, 2014). The metaphor of the "ozone hole" refers here again in a very literal sense to a "hole" in the sky. Yet its military framing during the early Cold War changed its meaning radically: the "hole" could no longer be read as an observational "window" potentially beneficial to the astronomical community but stood now for the deliberate exploitation of the vulnerability of the ozone shield for military purposes. Knowing the

global environment was from now on closely entangled with potentially disastrous consequences of a new kind of alliance between the geophysical sciences and the military (cf. Doel, 2003).

From the "bromine bomb" to the rise of environmentalism

Those different voices emanating from quite disparate fields in the sciences and the science policy community claiming that one could purposefully interfere in the atmosphere in order to cut a "hole" in the ozone layer continued during the so-called classic era of the ozone controversy in the 1970s. For example, Harvard-based atmospheric physicist Michael McElroy picked up MacDonald's suggestion in order to point to the potential threat some chemical compounds may represent to national security if used as atmospheric weapons – a warning which provoked some catastrophism-infused articles in the national press, with for instance a *National Enquirer* headline reading "Harvard Professor …Warns of … the Doomsday Weapon … It's Worse Than the Most Devastating Nuclear Explosion – and Available to All" (cf. Dotto & Schiff, 1978, p. 188). According to the press coverage, McElroy suggested in 1975 at a meeting of the recently established Federal Interagency Task Force on Inadvertent Modification of the Stratosphere (IMOS), that bromine "appears so effective at ozone depletion that it could be used as a weapon. If injected into the stratosphere over enemy territory in sufficient quantity […] it would purge the ozone, permitting ultraviolet radiation from the sun to reach the ground with such intensity to destroy crops and incapacitate the inhabitants" (Sullivan, 1975, p. 20; cf. Dixon, 1975).

McElroy claimed that he feared the hostile use of bromine and called therefore for an immediate worldwide ban of the use of chemicals as atmospheric weapons. More by coincidence than as a direct consequence, the ban came only two years later, in 1977, in form of the United Nations "Convention on the Prohibition of Military or any other Hostile Use of Environmental Modification Techniques" (ENMOD), a fruit of serious U.S. and U.N. investigations into the Vietnam Conflict (cf. Westing, 1984).

However, colleagues lacked McElroy's fear of geophysical warfare. They considered his comments as extremely counterproductive given the fact that science framed ozone research since the early 1970s within serious inquiries into environmental consequences of anthropogenic pollutants (cf. Gribbin, 1988, p. 80). With the identification of unintended anthropogenic effects on the ozone layer and the environment in general, intentional ozone destruction as a war scenario was since the 1970s clearly no viable research topic anymore and the question was dropped with the introduction of ENMOD. Other themes took over research priorities, including the planned Supersonic Transportation fleet and thereafter, the fundamental role of CFCs in ozone depletion chemistry as first revealed by chemists Sherry Rowland and his PhD-student Mario Molina in 1974 (Molina & Rowland, 1974). The *unintended* causes and certainly not the *purposeful* ozone modification plans proved to be significantly more important in the end, with anthropogenic pollutants (such as nitric oxides and CFCs) posing a real threat to the global ozone layer.

What followed is what I call above the "classic" ozone story, a period that has already received wide attention by scholars coming from various domains, including sociology, history, science studies, the political sciences and law studies. Most of these studies reconstructed in detail how this shift towards an environmental framing took

place, a large body of work that can only be referenced here (cf. Benedick, 1991; Christie, 2001; Grundmann, 2001; Litfin, 1994; Parson, 2003; Roan, 1989).

The historical analysis of the "ozone hole" metaphor as proposed here allows also mapping a more general shift identified by a growing body of literature as the rise of environmentalism from the late-1960s onwards (see for an introduction Rome, 2003). As we have seen, between Chapman's presidential address in the 1930s and McElroy's "bromine bomb" (term adapted from Gribbin, 1988, p. 79) in the 1970s, the "ozone hole" metaphor evolved from a hypothetical observational window within the astronomical context to a potentially threatening weapon of considerable geopolitical reach. The geophysical war scenario lost however substantially in credibility with the new framing of ozone research within fears of environmental degradation and health hazards in the 1970s. Even though new important knowledge on ozone chemistry and global circulation patterns emanated from those different research contexts, the "hole" in the sky stayed nevertheless a largely hypothetical entity.

In 1985, however, this changed dramatically with the announcement of Joseph Farman, Jonathan Shanklin, and Brian Gardiner (1985) from the British Antarctic Survey that stratospheric ozone was severely depleted every year above Halley station during austral spring. Less than one year later, NASA scientists officially confirmed this observation on a significantly larger scale Stolarski, 1986).

The use of the actual "ozone hole" metaphor by NASA officials was certainly nothing new in the 1980s, its meaning however had gradually changed throughout the twentieth century. The atmospheric sciences adopted the metaphor only within the context of powerful visualizations that NASA scientists presented to both, the scientific community and the larger public in 1986, one year after the groundbreaking publication of the British research team. In other words, in 1986, the "ozone hole" had finally become a both, a global and threatening reality. This reality, however, had to be visually constructed first.

The Antarctic "ozone hole" and the making of an icon of the precautionary principle

Just over thirty years ago, in 1985, Joseph Farman, Jonathan Shanklin, and Brian Gardiner of the British Antarctic Survey (BAS) published the alarming article in *Nature*, showing that stratospheric ozone was rapidly declining over Halley station in Antarctica. Interestingly, their groundbreaking paper never mentioned a "hole" in the sky and a closer look at the published version of the original "ozone depletion" graph (figure 1) helps explain why this was the case. Indeed, evidence from material and visual history documents an explanation as to why British scientists referred in their early papers to the phenomenon of "ozone depletion" while American scientists spoke of a veritable "hole" in the sky.

The British graph shows mean total ozone values measured at Halley station between 1957 and 1984, with a deliberately short ordinate in order to reinforce the visual impression of rapid ozone decline.[1] To put it in other words, the visualization technology employed, a simple graph, was very efficient in depicting a tendency (in this

[1] Jonathan Shanklin has in his personal archive the original ozone plot which he submitted to *Nature*. The ordinate he initially chose is considerably longer than in the published version.

case rapid ozone decline), but it clearly could not make the case for a "hole" in the ozone layer.

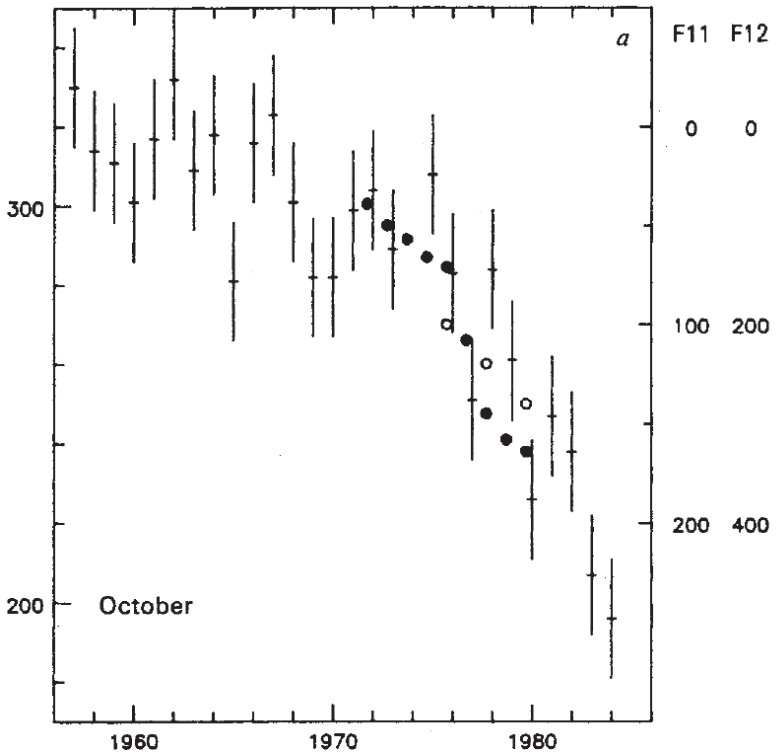

Figure 1: Ozone depletion graph showing mean total ozone values. The short ordinate reinforces the impression of rapid decline (Farman et al., 1985).

The "ozone hole" metaphor as we know it today was only introduced with the help of a complementary set of environmental observations. NASA was at the time the only space agency with a global view on the stratosphere and its ozone content, and it was therefore the American space agency's global imagery, based on measurements of the Total Ozone Mapping Spectrometer (TOMS) flown on the Nimbus-7 satellite, that inspired the introduction of the powerful environmental metaphor of the "ozone hole." According to NASA scientist Pawan Bhartia (personal communication September 10, 2010), New York Times science writer Walter Sullivan (1985) published the first story on the "hole" in the ozone layer on November 7, 1985, adopting the metaphorical suggestion of atmospheric chemist Sherwood Rowland who was familiar with NASA's early ozone images. To illustrate the "hole" in the sky, Sullivan used a simplified black-and-white total ozone contour visualization, following the iconographical tradition of NASA's early ozone contour maps (see fig. 2 & 3). It is therefore fair to say that only the synoptic view on the Antarctic continent, combined with a powerful visual tool – the contour line –, helped introduce this highly influential global environmental metaphor (see Grevsmühl, 2014 for more detail on the visual strategies employed). Indeed, mobilizing the contour line allowed for both, creating an "inside" and an "outside" of the "hole" in the ozone layer, as well as effectively homogenizing a substantial number of satellite measurements by correlating a certain data interval with a specific color.

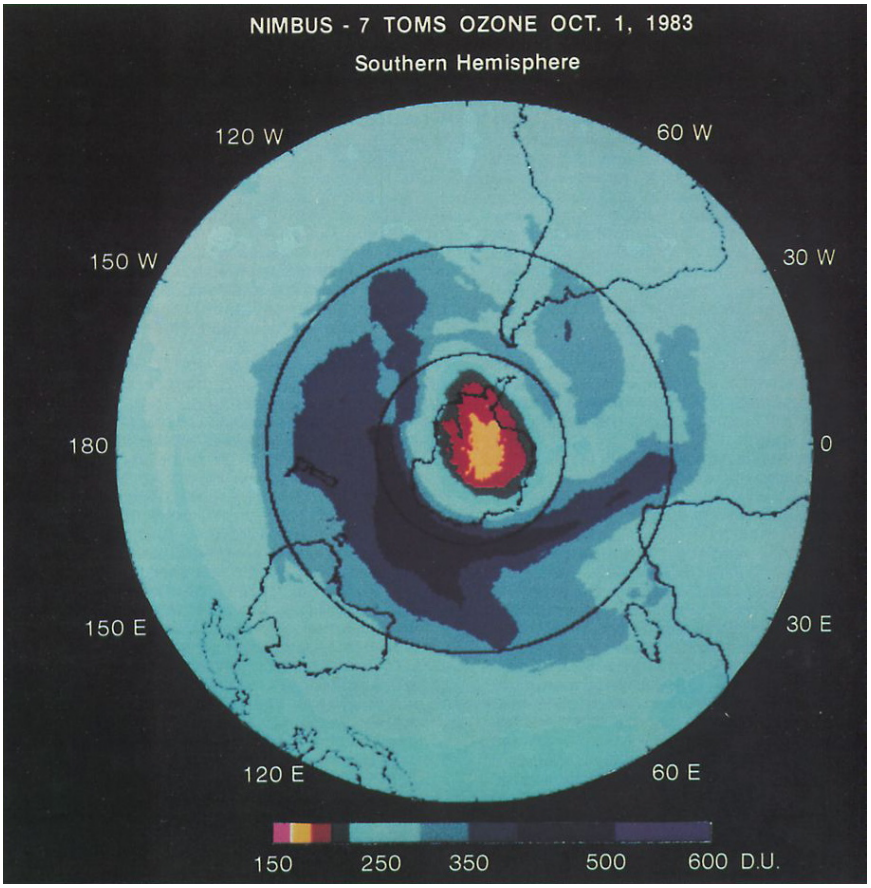

Figure 2: First published total ozone map using contour lines to map TOMS data for the Southern hemisphere on October 1, 1983 (NASA).

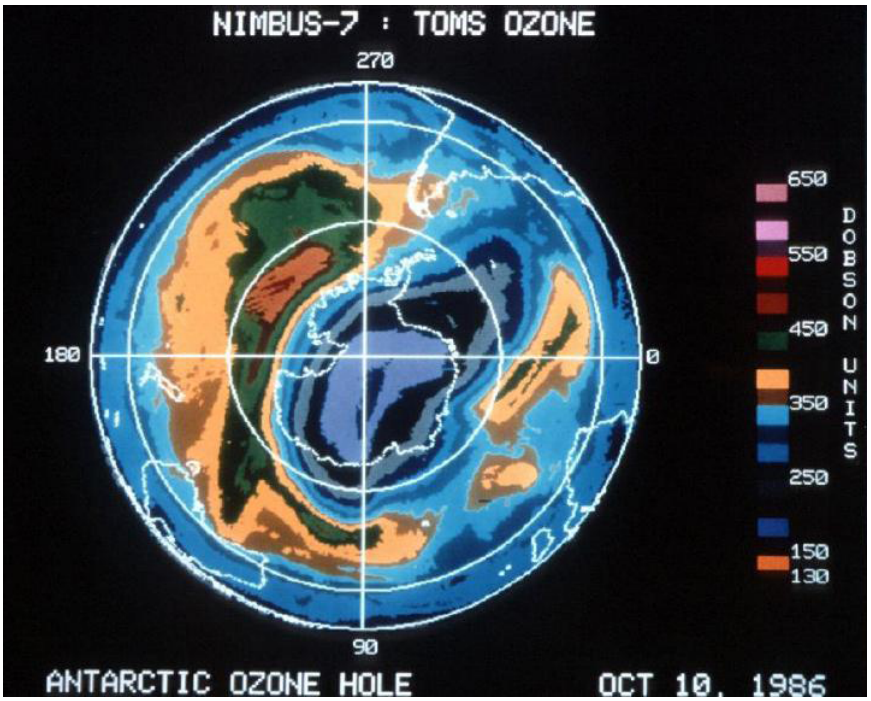

Figure 3: Typical early Antarctic "ozone hole" map, showing the "hole" in the center of the image as seen by TOMS on Nimbus-7, October 10, 1986 (NASA).

The scientific community adopted the powerful metaphor rather quickly. Scientists of NASA's image processing team referred to the "hole" in the sky in a paper published as early as 1986, and Paul Crutzen and his colleague Frank Arnold were able to introduce the "ozone hole" metaphor in the title of a paper (that was published in the same journal) just a few months later (Stolarski et al., 1986; Crutzen & Arnold, 1986). Within three years of its first apparition in press, the "ozone hole" had become an almost entirely "naturalized" phenomenon with its widespread use allowing for an application in scientific and public discourse without implying reflections on its metaphorical status anymore.

Most importantly however, the metaphor and its associated imagery showed important ramifications in environmental policy making. To be sure, the Vienna Convention for the Protection of the Ozone Layer was in 1985 already well under way (it was agreed upon in 1985 and entered into force in 1988) but it did not include any legally binding restrictions for ozone depleting substances (cf. Litfin, 1994, p. 73-77). Within this context, the highly persuasive visual and metaphorical framing of the "hole" in the ozone layer helped raise awareness for an otherwise invisible global environmental threat, well before a general scientific agreement on the specific causes of Antarctic ozone depletion could be achieved. It is true that the negotiators of the Montreal Protocol chose to deliberately "ignore" the "ozone hole" findings precisely because there was no scientific theory at hand explaining its mechanisms, as chief United States negotiator to the Montreal Protocol Richard Benedick (1991) has explained. However, the "ozone hole" had nonetheless an overriding impact, also because it was presented in a very persuasive way, both visually and metaphorically.

As Karen Litfin has argued in a detailed discourse analysis of the ozone case, the ozone hole "provided dramatic evidence in favor of precautionary action, evidence that participants could not ignore, despite their conscious decision to ignore it" (Litfin, 1994, p. 80). Indeed, it eventually helped pave the way to the signing of the Montreal Protocol in 1987, introducing a worldwide ban on ozone depleting substances. The successful environmental reframing of the "hole" in the sky as a broken shield, letting hazardous ultraviolet rays pass through Earth's broken protective layer, proved therefore a highly influential and efficient image for both, the legislators and the environmental movement. NASA's satellite images which were widely shared in the media as well as the agencies' "ozone hole" animation movies, that showed the temporal evolution of the hole that could become as large as the entire Antarctic continent, rapidly became icons of the precautionary principle as they were shown on national television and at congressional hearings (cf. Litfin, 1994, p. 101). Indeed, the powerful metaphor and the associated imagery gave support to those groups who believed that the consequences of taking no actions would be far worse than the consequences of over-restrictive regulations.

Considered in retrospect, the "ozone hole" also made the case for the necessity and usefulness of fundamental science and its long-term environmental monitoring programs (a program that would hardly find any funding today) as well as big science and global Earth observation programs (Grevsmühl, 2014). Together, these environmental observation programs were able to demonstrate the unforeseen, yet disastrous long-lasting environmental effects of CFCs on a truly global scale.

From 1988 onwards, a large scientific consensus formed on the physical and chemical causes of the annual destruction of stratospheric ozone above the Antarctic continent. And the "ozone hole" metaphor would be finally find acceptance as a global environmental risk in both spheres, scientific discourse as well as public and political

discourse. The metaphor and the associated imagery could hence communicate a strong message of environmental urgency, a message that was picked up by many media outlets worldwide, often mobilizing a catastrophic framing (see for instance the various catastrophic framings in the German newsweekly *Der Spiegel* throughout 1986, with the "ozone hole" making it on the front cover in August 1987).

The historical canvas described up to here explains however only partially the outcome of the negotiations and the political responses that led to the signature of the Montreal Protocol and its successive amendments. It would in other words be wrong to overestimate the power of environmental metaphors and images because they do not automatically lead to widespread political or social action. Other elements were clearly also important for this successful political outcome. Litfin (1994, p. 81) for instance has shown that the specific institutional setting played a very important role. Only an international organization with no formal national ties – in this case UNEP – could provide a sufficiently neutral ground for the fruitful political discussions. Other elements included the rise of strong pressure groups such as NGOs and the implication of knowledge brokers and individual scientists, such as Nobel laureate Sherwood Rowland, who publicly spoke out from the very beginning, advocating strong regulatory measures and thereby actively reshaping the boarders between science and policy (Litfin, 1994, p. 99).

Conclusion

The various frameworks for the creation of a "hole" in the sky evolved considerably throughout the 20th century. Early "ozone hole" theories were tightly bound to the metaphorical shaping of holes in the sky as windows to the universe, a tribute to the astronomical community that made important contributions to early ozone research. The new geopolitical context after World War II shifted "ozone hole" debates to inquiries into their geostrategic military potential. The rather innocent astronomical question of artificially opening the sky could become therefore in the fifties and sixties a research topic of significant geopolitical potential. From the early seventies onwards, the geophysical war scenarios of holes in the sky lost however their credibility and environmental questions moved rapidly to the forefront of scientific investigation. Yet only during the middle eighties one could observe how a hypothetical "hole" in the sky became a threatening geophysical reality. NASA researchers succeeded efficiently in creating a powerful global environmental imaginary, the Antarctic "ozone hole," with the help of the TOMS satellite instrument that provided a truly synoptic view on Antarctica. As argued above, material and visual culture largely shaped not only the actual creation of this important environmental phenomenon, but also its very perception as a "hole" in the sky.

The field of environmental communication has a lot to learn from the ozone hole case. It shows that metaphors are valuable historical objects of study in their own right, allowing to study how metaphorical landscapes shift over time, how scientific images and metaphorical framings interact, and how they shape scientific and popular discourse on nature, as well as our understanding of the global environment. A historically informed metaphorical analysis can therefore also contribute to mapping larger social and political developments – even though this was not the main objective of this article.

Acknowledgements

I would like to thank the anonymous reviewers for their helpful critics, comments and suggestions, as well as the Editors of this special issue for their support and guidance.

References

Bauer, E., & Gilmore, F. (1975). Effect of Atmospheric Nuclear Explosions on Total Ozone. *Reviews of Geophysics and Space Physics*, *13*, 451-458.

Benedick, R. (1991). *Ozone Diplomacy. New Directions in Safeguarding the Planet.* Cambridge, Massachusetts: Harvard University Press.

Black, M. (1955). Metaphor. *Proceedings of the Aristotelian Society*, *55*, 273-294.

Chapman, S. (1934). The Gases of the Atmosphere. *Quarterly Journal of the Royal Meteorological Society*, *60*, 127-142.

Christie, M. (2001). *The Ozone Layer. A Philosophy of Science Perspective*. Cambridge: Cambridge University Press.

Cornu, A. (1879). Sur la limite ultraviolette du spectre solaire. *Proceedings of the Royal Society of London*, *29*, 47-55.

Cozen, B. (2013). Mobilizing Artists: Green Patriot Posters, Visual Metaphors, and Climate Change Activism. *Environmental Communication*, *7*(2), 297-314.

Crutzen, P., & Arnold, F; (1986). Nitric acid cloud formation in the cold Antarctic stratosphere: a major cause for the springtime 'ozone hole.' *Nature*, *324*, 651-655.

Danielsen, E.F. (1968). *1964: Report on project Springfield*, Washington D.C.: Defense Atomic Support Agency.

Danielsen, E.F. (1968). Stratospheric-tropospheric exchange based upon radioactivity, ozone and potential vorticity. *Journal of Atmospheric Scientists*, *25*, 502-518.

Davidson, D. (1978). What Metaphors Mean. *Critical Inquiry*, *5*(1), 31-47.

DeWitt, H.E. (1955). *A Compilation of Spectroscopic Observations of Air Around Atomic Bomb Explosions*. Los Alamos, New Mexico: Los Alamos Scientific Laboratory.

Dixon, B. (1975, March 27). Comment: Weather Warfare. *New Scientist*, 762.

Dobson, G.M.B. (1968). Forty Years' Research on Atmospheric Ozone at Oxford: A History. *Applied Optics, 7*(3), 387-405.

Doel, R. (2003). Constituting the Postwar Earth Sciences: The Military's Influence on the Environmental Sciences in the USA After 1945. *Social Studies of Science*, *33*(5), 635-666.

Dotto, L., & Schiff, H. (1978). *The Ozone War*. New York: Doubleday.

Edwards, P. (1996). *The Closed World*. *Computers and the Politics of Discourse in Cold War America*. Cambridge: MIT Press.

Farman, J., Gardiner, B., & Shanklin, J. (1985). Large losses of total ozone in Antarctica reveal seasonal ClOx/NOx interactions. *Nature*, *315*, 207-210.

Fleming, J. (2010). *Fixing the Sky: The Checkered History of Weather and Climate Control,* New York: Columbia University Press.

Fleming, J. (2006). The Pathological History of Weather and Climate Modification: Three cycles of promise and hype. *Historical Studies in the Physical Sciences*, *37*, 3-25.

Fleming, J. (2011). Planetary-Scale Fieldwork: Harry Wexler on the Possibilities of Ozone Depletion and Climate Control. In J. Vetter (Ed.), *Knowing Global Environments: New Historical Perspectives on the Field Sciences* (pp. 190-211). New Brunswick: Rutgers University Press.

Fleming, J. (1998). Weather modification. In G. Good (Ed.), *Sciences of the Earth: An Encyclopedia of Events, People, and Phenomena*, *2* (pp. 843-844). New York: Garland.

Fox Keller, E. (1995). *Refiguring Life: Metaphors of Twentieth-Century Biology*. New York: Columbia University Press.

Fox Keller, E. (2002). *Making Sense of Life: Explaining Biological Development with Models, Metaphors and Machines*, Cambridge, Massachusetts: Harvard University Press.

Galison, P. (1994). The Ontology of the Enemy: Norbert Wiener and the Cybernetic Vision. *Critical Enquiry*, *21*(1), 228-266.

Goldsmith, P., & Brown, F. (1961). World-wide Circulation of Air within the Stratosphere. *Nature*, *191*, 1033-1037.

Grevsmühl, S. (2014). The Creation of Global Imaginaries: The Antarctic Ozone Hole and the Isoline Tradition in the Atmospheric Sciences. In B. Schneider & T. Nocke (Eds.) *Image Politics of Climate Change* (pp. 29-53). Berlin: Transcript.

Gribbin, J. (1988). *The Hole in the Sky. Man's Threat to the Ozone Layer*, New York: Bantam Books.

Grundmann, R. (2001). *Transnational Environmental Policy: Reconstructing Ozone*. London: Routledge.

Hamblin, J. (2013). *Arming Mother Nature: The Birth of Catastrophic Environmentalism.* Oxford: Oxford University Press.

Hartley, W.N. (1880). On the probable absorption of the solar ray by atmospheric ozone. *Chemical News*, *42*, 268.

Hoerlin, H. (1976). *United States High-Altitude Test Experiences. A Review Emphasizing the Impact on the Environment*. Los Alamos, New Mexico: Los Alamos Scientific Laboratory.

Hughes, T.P. (1989). *American Genesis. A Century of Invention and Technological Enthusiasm, 1870-1970*. Chicago: University of Chicago Press.

Johnston, H., Whitten, G., & Birks, J. (1973). The Effect of Nuclear Explosion on Stratospheric Nitric Oxide and Ozone. *Journal of Geophysical Research*, *78*, 6107-6135.

Kay, L.E. (2000). *Who Wrote the Book of Life ? A History of the Genetic Code*. Stanford: Stanford University Press.

Kwa, C. (1987). Representations of Nature Mediating Between Ecology and Science Policy: The Case of the International Biological Programme. *Social Studies of Science*, *17*(3), 413-442.

Litfin, K. (1994). *Ozone Discourse: Science and Politics in Global Environmental Cooperation*. New York: Columbia University Press.

Maasen, S., & Weingart, P. (Eds.). (2000). *Metaphors and the dynamics of knowledge*. London: Routledge.

Machta, L., List, R.J., & Hubert, L.F. (1956). World-wide Travel of Atomic Debris. *Science*, *124*, 474-477.

MacDonald, G.J.F. (1968). How to wreck the environment. In N. Calder (Ed.), *Unless Peace Comes, A Scientific Forecast of New Weapons* (pp. 165-183). London: Allen Lane The Penguin Press.

Milstein, T. (2016). The Performer Metaphor: 'Mother Nature Never Gives Us the Same Show Twice'. *Environmental Communication*, *10*(2), 227-248.

Molina, M.J., & Rowland, S. (1974). Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone. *Nature*, *249*, 810-812.

Nerlich, B., & Jaspal, R. (2012). Metaphors we die by? Geoengineering, metaphors, and the argument from catastrophe. *Metaphor and Symbol*, *27*, 131-147.

Nerlich, B., & Koteyko, N. (2010). Carbon Gold Rush and Carbon Cowboys: A New Chapter in Green Mythology?. *Environmental Communication*, *4*(1), 37-53.

Nerlich, B., Koteyko N., & Brown, B. (2010). Theory and language of climate change communication. *Wiley Interdisciplinary Reviews: Climate Change*, *1*, 97-110.

Office of Technology Assessment. (1979). *The effects of nuclear war*. Washington D.C.: Government Printing Office.

Ortony, A. (Ed.). (1993). *Metaphor and Thought*. Cambridge: Cambridge University Press.

Parson, E. (2003). *Protecting the Ozone Layer*. New York: Oxford University Press.

Regener, E. (1946, June). Über das 'photochemische' Klima der Erde. *Die Naturwissenschaften*, *33*, 163-166.

Roan, S. (1989). *Ozone Crisis. The 15-Year Evolution of a Sudden Global Emergency*. New York: Wiley.

Rome, A. (2003). 'Give Earth a Chance': The Environmental Movement and the Sixties. *Journal of American History*, *90*(2), 525-554.

Sarasin, P., Berger, S., Hänseler, M., & Spörri, M. (Eds.). (2007). *Bakteriologie und Moderne. Studien zur Biopolitik des Unsichtbaren 1870–1920*. Frankfurt am Main: Suhrkamp.

Sloterdijk, P. (2009). *Terror from the Air.* Los Angeles: Semiotext(e).

Stepan, N.L. (1986). Race and Gender: The Role of Analogy in Science. *Isis*, *77*(2), 261-277.

Stolarski, R., et al. (1986). Nimbus 7 satellite measurements of the springtime Antarctic ozone decrease. *Nature*, *322*, 808-811.

Sullivan, W. (1975, February 1975). Ozone depletion seen as a war tool. *New York Times*, 20.

Sullivan, W. (1985, November 7). Low Ozone Level Found Above Antarctica, *New York Times*, B-21.

Wells, B. (1997). The hole truth. *Nature*, *390*, 438.

Westing, A. (1984). Environmental Warfare. *Environmental Law*, *15*, 645-666.

Wiman, B.L.B. (1995). Metaphors, analogies, and models in communicating climate change uncertainties and economics to policy: A note on a pre-UNCED U.S. case. *Ecological Economics*, *15*, 21-28.