Getting to the (Tipping) Point

Incorporating Discourse and Narratives into a Social Tipping Points Framework

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Thesis submitted in partial fulfillment of the requirements for the degree of *Master of Science in Industrial Ecology* at Leiden University and TU Delft

To be defended publicly on:

October 17th, 2024

Acknowledgements

I began the process of this thesis by asking myself how I could combine my passion for music with the knowledge I had gained while studying Industrial Ecology. After some (both personal and academic) realizations and compromises, I arrived at the topic which is developed here. While it is not particularly related to music, it still relates to a deeply personal search for multi-disciplinarity. I have always been drawn to complex and broad issues which require me to dive into different topics and put them together. The thesis at hand synthesises a wide range of fields and topics -such as linguistics- which I had no previous familiarity with. Being an Industrial Engineer, I often wondered how smart of a choice this was. Nevertheless, I am proud of the work I have done and present here. I believe this thesis is a true embodiment of interdisciplinarity, which is one of the core values of Industrial Ecology. I strongly believe in the need for more interdisciplinarity within science, but I now know that it does not come without its challenges. This thesis process gave me a new appreciation for any scientist who chooses to undertake interdisciplinary research. Nevertheless, I urge more of them to do so, as the process is still deeply rewarding.

The thesis process was quite long and presented a range of challenges (apart from the ones related to interdisciplinarity) which I could have never anticipated. That is why I first want to thank my primary supervisor, Rutger. Thank you for sticking through all the different issues that came up, through all the iterations of the thesis, and for your enthusiasm, support, and guidance. I always enjoyed our conversations and felt free to explore crazy ideas with you.

To my second supervisor, Jaco. Thank you for offering to help and jumping on the team on such short notice. I enjoyed working with you both on the thesis and on the Integrated Project course.

To Carole, thank you for your enthusiasm and eagerness to help me from the very beginning. Also thank you for sticking around until the very end. I always felt like I could reach out to you for help.

To all my friends from IE. I love this community we built, I am so happy to be a part of it and to be surrounded by such beautiful people.

[Acknowledgments continue in Spanish for my family and friends from back home]

Gracias mamá por tu apoyo y amor incondicional, y por ser un gran ejemplo de resiliencia.

Gracias papá por tu apoyo y por ser una eterna inspiración, por tu cerebro científico que indudablemente ayudó de alguna manera a que pudiera completar esta tesis.

Gracias Yahan por siempre ser un modelo a seguir, por tu humor y por estar ahí para discutir cualquier tema durante horas, sin importar que tan mundano o complejo sea.

Gracias Luis Fa y Fofo por ser mis hermanos desde siempre y para siempre.

Abstract

Human activities have increasingly affected Earth's natural systems, threatening ecological balance and sustainability. Social-Ecological Systems (SESs) are complex structures where human and environmental processes interact. Within these systems exists the concept of "tipping points" thresholds where small changes can trigger non-linear, irreversible shifts towards a new state. This concept has been widely studied in the natural sciences and has recently become popular within the social sciences, as research on Social Tipping Points (STPs) looks to uncover the tipping mechanisms at play within societal systems.

Discourse and narratives, as key linguistic practices, play a crucial role in how humans perceive, understand, and disseminate information across all levels of society. This makes them particularly interesting for the study of STPs, as they may act as key tools for triggering feedback mechanisms within SESs. Such feedback mechanisms are identified as complex contagion and cascading effects. Social actors within SESs create and share discourses and narratives between them, which in turn influence these feedback mechanisms and shape social behaviours towards positive change.

The study introduces the Discourse and Narratives-Social Tipping Points (DN-STP) framework, integrating six societal spheres (Politics, Industry, Society, Media, Science and Culture) which house actors at institutional and individual levels. These actors, through discourse and narratives, interact within and across spheres to trigger feedback mechanisms and shape behaviours towards the management of an ecological system. The ozone layer issue, where damages to the stratosphere were reversed through global coordinated action, serves as an ideal case study for the DN-STP framework and highlights the role of discourse and narratives in guiding positive change.

The study finds that discourses and narratives are indeed powerful avenues for understanding societal change within an SES. Integrating them within the study of STPs showcases the vital role of actor spheres within a socio-ecological issue and aids in explaining its developments and dynamics. While the study establishes the relevance of including discourse and narratives within STP research, further studies are needed to credibly establish the specific role of narratives in influencing social behaviours at the system level. Further expansions of the DN-STP framework can look to integrate other relevant societal mechanisms that may be central to triggering positive feedback effects towards STPs.

Keywords: *social tipping points, discourse, narratives, social-ecological systems, tipping dynamics, behavioural change, ozone layer*

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1. Introduction

Humanity faces several environmental challenges largely due to the unsustainable growth of its activities on Earth (Folke et al., 2021; Lenton et al., 2008; Rockström et al., 2009). The relationship between human activities and the natural resources required to sustain them is embedded in what are known as Social-Ecological Systems (SESs) (Ostrom, 2009). SESs are complex structures composed of multiple sub-systems, actors and variables related to both social and natural elements, which interact to produce outcomes at the SES level (Lenton et al., 2022; Ostrom, 2009). As human activities pose a growing threat to the stability of Earth's systems (Lenton et al., 2008), locating "tipping" elements within SES -both in the social and ecological contexts- can provide valuable tools to guide solutions to the different ecological crises that humanity faces.

The term "Tipping Point" has recently gained popularity in research within both social and natural sciences. The initial use of the term is mainly attributed to Malcolm Gladwell (2000), where the author uses it to explain how behaviours and ideas, however small, catch on and make a big difference. Tipping points are defined as thresholds where a small perturbation can trigger an alteration in the future state of the system, leading to a -usually- irreversible qualitative change (Centola, 2021; Lenton et al., 2008; McKay et al., 2022; Walker, 2006). In the study of Earth's natural systems, several tipping points have been identified with quantifiable control parameters[1] which, if surpassed, might cause irreversible damage to the Earth's stability (Lenton et al., 2008, 2019). The study of these natural tipping points is crucial in the context of SESs, as human activities -or "anthropogenic forcing"- directly affect them (Lenton et al., 2008). An example of a tipping element which has already been significantly impacted by human activity is the Antartic ozone hole, as identified by Lenton et al. (2008). The Montreal Protocol is widely regarded as a global success in policymaking and showcases how humanity can revert its effects on an ecological system to stop it from reaching an irreversible tipping point (Grevsmühl, 2018; Lenton et al., 2008; Sterner et al., 2019). As such, the ozone layer issue is an ideal case to exemplify how societal actors can collaborate to manage their impacts on environmental systems and keep them from surpassing critical thresholds.

The term Social Tipping Point (STP) has been increasingly used by scholars to explore positive tipping points in socio-technical and socio-ecological systems (Geels & Ayoub, 2023; Milkoreit et al., 2018; Stadelmann-Steffen et al., 2021; Winkelmann et al., 2022). The existence of social tipping points has important implications for modifying our societal structures and behaviours to solve ecological issues. Additionally, improving our understanding of STPs can enable successful and rapid socio-economic transitions towards economic systems seeking to foster more sustainable human activities. For example, proponents of alternative economic systems such as Doughnut Economics (Raworth, 2017) and degrowth (D. W. O'Neill, 2012) use terms such as "safe and just operating space" and "steady state economy" to describe new states that the current economic system must transition into. These terms highlight the potential for positive tipping points to facilitate those changes and achieve the rapid structural modifications they require to avoid further damage to the environment.

Often, strategies for addressing ecological and societal crises revolve around increasing awareness and informing the public. In the case of climate change, for example, the role of the media in shaping public discourse is mentioned in the IPCC's Sixth Assessment Report as an important driver for both positive and negative effects on climate action (IPCC, 2023). Meanwhile, a growing body of scientific literature has focused on the concept of narratives to understand their

[1] Here, I refer to the study of Tipping Points presented by Lenton et al. (2008), not to be conflated with the Planetary Boundaries framework by Rockström et al. (2009) which does not have define such control parameters.

role in effective climate change communication (Bushell et al., 2017; Fløttum & Gjerstad, 2017; Moezzi et al., 2017). These two concepts -discourse and narratives- lie at the centre of this study, as important factors shaping societal responses to ecological and social issues within SES.

Discourse can be defined as the linguistic practices that are embedded in societal networks and are tied to human conceptions of knowledge and power, and therefore to the construction of the world (Litfin, 1995; Souto-Manning, 2014). More specifically, discourse is a broader term, encompassing diverse instances of linguistic social interactions (Blommaert & Bulcaen, 2024; R. Wodak, 2002). Hence, discourse is a powerful linguistic tool that can serve to study social exchanges and their complex relationships within societal systems (Souto-Manning, 2014).

Another important linguistic concept is that of narratives, which are stories we use to perceive and explain the world around us (Nyman et al., 2021). Narratives influence both individual and collective responses to issues, affecting decision-making processes and societal systems, such as financial markets (Nyman et al., 2021). In economics, Roos & Reccius (2024) define narratives as sense-making stories about a topic, which are shared among members of a group and suggest an action. Shiller (2019) proposes the term "narrative economics" to link stories to important economic events such as the Great Depression. Like epidemic modelling, where contagion rates are used to study the spread of diseases through the population, the diffusion of simplified and easily transmitted narratives can drive fluctuations in economic systems (Shiller, 2019). These stories are often presented in a sentence which serves as the "bottom line" and offers an interpretative summary of the causal relationship between facts and mechanisms surrounding an issue (Fløttum & Gjerstad, 2017; Roos & Reccius, 2024). Therefore, narratives present an explanation of an issue which is shared among members of a group, following a structure which describes a cause-and-effect relationship and suggests an action (Dahlstrom, 2014; Roos & Reccius, 2024).

As such, both discourse and narratives play a crucial role in how humans perceive, understand, and disseminate information across all sectors of society. For this study, discourse is understood as being composed of several competing narratives surrounding the same topic (Roos & Reccius, 2024). To exemplify this, Roos & Reccius (2024) state that the discourse about the Great Depression at the time of the 2008 economic crisis was comprised of at least three narratives:

1. *"Fiscal stimulus is needed to prevent another Great Depression.*
2. *Monetary policy-makers have learned the lessons from the Great Depression.*
3. *The elites have forgotten the lessons from the Great Depression."* (Roos & Reccius, 2024)

In this example, the topic is the Great Depression, the narratives are the three sentences which relate the topic to the situation at hand, and the discourse is the combination of these narratives within the broader social conversation about the Great Depression in the context of the 2008 economic crisis. It is therefore important to mention that both discourse and narratives cannot be separated from the societal context and specific actors that create them (Souto-Manning, 2014).

While several studies make use of discourse and narratives within STP research, their role in influencing social network mechanisms within SESs has not been described. Additionally, these studies often identify agents and stakeholders in an unstructured and at times incomplete manner, highlighting the need for a clear and comprehensive framework to guide further studies on the topic. So far, no research has taken on the task of integrating discourse and narratives within the STP field as powerful drivers of social behavioural change, which are produced and exchanged between the different actors of an SES. Hence, in this study, I propose a novel framework which synthesises the concepts of STPs and linguistic practices of discourse and narratives to answer the research question:

What role do discourses and narratives play in shaping behavioural change towards social tipping points?

To further aid in answering this question, I formulate the following sub-research questions:

- *SRQ1: What are the major spheres of a socio-ecological system, and how do discourses and narratives influence actor behaviours within and across these spheres? How can these elements be integrated into a Discourse and Narratives-Social Tipping Points (DN-STP) framework?*
- *SRQ2: How does the proposed DN-STP framework help explain the developments and dynamics in the ozone layer issue?*

I aim to answer these questions by first describing the theoretical base for the DN-STP framework. I draw on previous STP research and studies on social network dynamics to identify the most relevant actors at play within an SES. Then, I establish the link between discourses and narratives within the context of each sphere, to describe the potential for them to influence social behaviours. These elements are all synthesised into a comprehensive framework, setting the groundwork for researchers looking to study instances of social tipping and the role of discourse and narratives in achieving widespread societal change. Subsequently, I use the ozone layer issue to test the DN-STP framework. This is a useful case study due to it being an example of a socio-ecological crisis which was widely solved by the societal actors involved. I argue that analysing this case can provide valuable insights to shape our use of narratives, understanding their interaction with broader societal discourses and the relationships between them to enable positive change.

2. Literature Review

2.1. Social Tipping Points - definitions and frameworks

Interest in STPs has been growing in recent years, but one of the main challenges for the field is properly defining what constitutes a tipping point in the social context. Establishing comprehensive definitions and empirical thresholds is harder within social systems, as they are generally less understood than natural ones (Milkoreit, 2023; Milkoreit et al., 2018). Kopp et al. (2016) state that the same definition as Lenton et al. (2008) can apply to tipping elements in social or engineered systems. However, other authors argue that different factors must be considered when dealing with SES. Social systems are defined by Winkelmann et al. (2022) as a network of agents within a social-ecological environment. The concept of agency is therefore an important distinguishing factor within social systems. Additionally, these systems can be considered to have social tipping elements if a small change within them or in their environment can lead to qualitative changes through network effects such as complex contagion or positive feedback (Winkelmann et al., 2022).

Milkoreit et al. (2018) extensively analysed the field and propose four main conditions that identify tipping, these being: 1) having multiple stable states, 2) abruptness (also understood as non-linearity), 3) the existence of positive feedback, and 4) irreversibility. This last characteristic, however, is often debated and is not necessarily present in social tipping or characterised as "limited" reversibility (Winkelmann et al., 2022). In the later study, Milkoreit (2023) adds the dimensions of desirability and intentionality in line with Moser & Dilling's (2009) assumption that tipping points can be intentionally activated.

The complexity of social systems requires similarly complex frameworks and definitions to study them. Stadelmann-Steffen et al. (2021) propose tipping dynamics as a more useful notion due to the role of agency, the different spatial and temporal scales, and the social, institutional, and

cultural networks at play in an SES. The authors then propose a framework incorporating technological, political, and behavioural sub-dynamics, serving as a starting point to research the STP concept more holistically. While the framework integrates a necessary perspective of tipping in different societal spheres, it leaves out important aspects related to communication between actors and the existence of other spheres within society. I aim to integrate these aspects into a new framework focusing on discourse and narratives, therefore expanding Stadelmann-Steffen et al's work (2021).

2.2. Discourse and narratives as drivers of social change

Due to societal actors being central to SES, information exchanges are part of the fundamental differences between tipping processes in social and environmental contexts (Winkelmann et al., 2022). As discourse and narratives are key mechanisms for spreading, processing and interpreting information by societal actors, they are highly relevant to the study of social networks and behavioural change (Blommaert & Bulcaen, 2024; Souto-Manning, 2014). Specifically, a large quantity of literature links narratives to social change (Chabay et al., 2019; Christiansen, 2014; Fløttum & Gjerstad, 2017; Morris et al., 2019; Shiller, 2019; Squire, 2012), though they remain largely disconnected from studies on tipping points. In the field of economics, Shiller (2019) presents several instances where narratives trigger changes in economic systems but does not mention the concept of tipping points, even though the types of events he describes closely resemble those presented in previous tipping points literature. Meanwhile, in the book that popularised the term, Gladwell (2002) groups together ideas, trends, and behaviours as tipping elements that can quickly spread across the population. Here, the concept of "ideas" can be linked to narratives, as narratives are a way to share and formulate ideas within a social group (Roos & Reccius, 2024). These examples highlight the potential for the concepts of discourse, narratives and tipping points to be combined to strengthen our understanding of tipping dynamics within social systems.

Financial markets and political systems are examples of systems that can present tipping processes which can be explained through social network dynamics (Kopp et al., 2016; Winkelmann et al., 2022), and therefore partly through discourse and narratives. In the study of social networks, Centola (2021) identifies information and ideas as central points to understanding the spread of behaviours across the population. The author states that the spread of information is not enough to trigger changes in a social system, rather, it is the beliefs and behaviours that must be modified before achieving widespread change. However, information spread is still a central part of the dynamics of social change, and narratives have been used in the past to study social movements such as the Arab Spring (Centola, 2021; Comunello & Anzera, 2012; Smidi & Shahin, 2017) and the civil rights movement (Christiansen, 2014; Polletta, 1998).

2.3. Narratives and related concepts within STP literature

The concept of narratives is not entirely disconnected from the field of STPs. Studies such as Hansen and Tàbara, (2024), Ismail et al. (2024), van der Leeuw (2024) and Veland et al. (2024) integrate the concept of narratives but identify these in differing levels of detail and focus specifically on coal and carbon-intensive regions (CCIRs). Veland et al. (2024) combine the frameworks by David Tàbara et al. (2018) and Lieu et al. (2020) to identify transition and transformation narratives, but do not show a clear empirical analysis of narratives and STPs. The study that more closely relates the concept of narratives to STPs is that of Biddau et al. (2023), where the authors identify tipping dynamics and lock-in mechanisms through a lexicometric analysis of newspaper articles. However, they ground their study in transitions theory and do not

differentiate societal spheres or the interactions between actors when identifying discourse and narratives.

Moser & Dilling (2009) aimed to understand the role that communication plays in social change in one of the first studies linking the idea of tipping points to the climate change movement. The authors state that modifying climate change communication and framing can help the movement reach a tipping point and achieve widespread behavioural change. However, its aim centres around dispelling common myths regarding the interactions between social change and communication and calls for further interdisciplinary research on the topic. Stadelmann-Steffen et al. (2021) identify the notion of "Ideas" as an external factor which, along with external shocks and material conditions, influences the tipping dynamics of a system. The paper does not further develop these factors but focuses directly on the dynamics they trigger. This notion of "Ideas" or indeed, narratives, could be useful when taken as a central aspect of social tipping dynamics, existing both within the analysed system and in its surrounding environment. In the framework proposed by O'Brien & Sygna (2013), the authors identify three spheres: practical, political and personal. They include discourses and worldviews within the personal sphere, and transformations within this sphere are described as having "more powerful consequences" than the others. The authors also mention that transformations in this space cannot be forced but fail to describe the dynamics that arise from this sphere and how they relate to narratives. Winkelmann et al. (2022) use survey data to visualize shifts in public opinion regarding the environment and the German Green Party in the context of events such as the FridaysForFuture protests. While the authors find that increases in climate awareness and intent to vote for the Green Party align with the protests organized by FridaysForFuture, they do not attempt to explain how the information was spread throughout the population, for example, through news stories covering the protests.

Though related linguistic concepts and narratives themselves are often mentioned within the field of STPs, there has not been a study that directly links discourse and narratives as intrinsic mechanisms within SES that contribute to driving societal systems towards a tipping point. Additionally, the definitions and level of detail used to analyse the concept of narratives differ greatly between studies. The present study therefore aids in proposing a clear definition for discourse and narratives to be used by STP scholars. Furthermore, I aim to make a first approach to integrate discourse and narratives as important mechanisms of social network dynamics influencing behavioural change, setting the groundwork for future studies seeking to integrate discourse, narratives and related concepts within the STP field.

3. Methodology

To develop this study and answer the research questions presented previously, I first present a novel theoretical framework which integrates the concepts of discourse and narratives within STPs. Therefore, the Discourse and Narratives – Social Tipping Points framework (hereafter referred to as DN-STP framework) is introduced here and further developed in Section 4. Thereafter, I use the framework to analyse the ozone layer issue in the United States between 1966 and 2010, adding a quantitative layer to further observe the development of the issue throughout time. The case study integrates both quantitative and qualitative methods to contextualise the issue and empirically test the framework. The methodology followed for both the theoretical framework and the empirical case study is described in this section.

The first objective of the study is to identify the main actor spheres within SESs, establishing the base for the analysis of discourse, narratives and STPs within them. Previous studies within STP research have identified social spheres and integrated them within a variety of frameworks. Particularly, the social tipping dynamics framework presented by Stadelmann-Steffen et al. (2021) represents a starting point for the DN-STP framework. I subscribe to the author's notion of

emphasizing agency as a critical aspect to be integrated into the study of tipping points. However, differing from their approach of identifying actors at the citizen and political elite levels, I propose a categorisation of actors at Institutional and Individual levels. Therefore, the role of agency is maintained as a central aspect of the DN-STP framework. Stadelmann-Steffen et al. (2021) additionally identify three spheres of tipping dynamics: the technological, political and behavioural spheres. While these elements indeed cover important actors within SESs, some important actors related to disseminating information across society are left out. This is evidenced by the fact that the authors mention "atmospheric scientists" as key actors within the case study of the ozone layer, but it is not clear where these would fall within their proposed framework. Considering this, I draw on the work of Stadelmann-Steffen et al. (2021) as a base for the present DN-STP framework but expand upon it by integrating three additional spheres related to the dissemination of information and knowledge through science, media and culture. Therefore, six total spheres are integrated within the DN-STP framework: Politics, Industry, Society, Media, Science and Culture. Finally, discourse and narratives are integrated within all spheres as important elements shaping social change through reinforcing feedback mechanisms. These mechanisms and their interactions with discourse and narratives are further described in the next section, based on research on social network dynamics and STPs.

Once the DN-STP framework has been established, I develop a case study to empirically test it. As previously mentioned, the ozone layer serves as an appropriate example to analyse through the lens of STPs, due to being an issue that has been identified in both natural and social tipping points literature (see Lenton et al., 2008 and Stadelmann-Steffen et al., 2021, respectively). Milkoreit (2018) mentions the lack of time-series data in social systems as a limitation for the study of STPs. I argue that the methodology proposed here can aid in this issue, and the DN-STP framework can provide valuable insights into the dynamics of an STP issue over time. A lexicometric analysis of keywords (similar to topic modelling) can identify public discourses and show their development over time (Roos & Reccius, 2024). For this, I broadly follow the methodology of Shiller (2019) in his study of narrative economics. In this study, Shiller presents what he refers to as "narratives" by searching for topics within newspaper texts. Roos & Reccius (2024) make an important distinction in that Shiller identifies public discourses instead of narratives, and often conflates the term "topic" with narratives. I therefore aim to follow Shiller's methodology while accounting for and correcting these conflations.

The spheres added to the framework for their role in disseminating information, namely: the Media, Science and Culture spheres, adapt well to the Shiller methodology. For these spheres, I identify corpus data and apply a lexicometric analysis by searching for the keywords "ozone layer" and quantifying the number of appearances within the databases throughout time. This quantification of keywords can be described as a way to identify "discourse intensity". Following Roos & Reccius' (2024) previously mentioned rectification of the Shiller (2019) methodology, quantifying keywords can only serve as a first step in narrative analysis and generally identifies public discourse. Hence, this lexicographic methodology is mainly used for visualisation purposes, and further context on discourse and narratives is added qualitatively. Specifically, a historical database of newspaper and magazine articles is extracted from ProQuest for the Media sphere; scientific journal articles are collected from the Web of Science Core Collection for the Science sphere; and TV show and Movie transcripts from the English corpora website are used for the Culture sphere.

For the Politics, Industry and Society spheres, the same methodology cannot be directly applied. This is because corpus data incorporating sufficient text is not often found for actors within these spheres. Therefore, quantitative data which could directly or indirectly point to actor behaviours within them is used instead. For the Politics sphere, data related to press releases on the ozone layer is found in the Environmental Protection Agency (EPA) and United Nations Environment

Programme (UNEP) websites dedicated to the ozone layer case. This information is presented as a timeline, as this serves as a clearer visualisation for the purpose of this study. For the Industry and Society spheres, data on production and consumption is used as proxies for their behaviours, respectively. For the Industry sphere, data on the production of CFCs is taken from a previous study by Cook et al. (1996) on the historical developments of the ozone layer case. For the Society sphere, data on consumption of CFCs is taken from the UNEP Data Centre website. This data has some important limitations for the study, mainly because it does not directly relate to the behaviour of the actors within the social sphere. A discussion of these limitations is included in Section 6. Nevertheless, this data is still considered useful for the contextualisation of the issue at hand and is presented as an approximate indicator within the Society sphere.

Once the visualisation data is obtained, each sphere is presented combining the quantitative data with a discourse and narrative analysis. This is again based on Shiller's methodology, where the author adds historical accounts to contextualise the lexicometric analysis of newspaper articles. Therefore, I apply desk research on discursive and narrative texts and describe the relevant historical developments of the ozone layer case, looking to pinpoint changes in actor behaviours which can be explained through discourse and narratives.

As an additional analysis, I seek to investigate the development of the "ozone hole" as a narrative that was particularly strong and influenced the development of the ozone layer issue. The large corpus data available for the Media and Science spheres makes it possible to develop this analysis and look for links between the underlying "ozone hole" narrative and actor behaviours in the spheres. Therefore, I search for the keywords "ozone hole" and "hole in the ozone layer" in the Media and Science databases and combine the results with the previously identified ozone layer data, while accounting for duplicates[2]. While this approach cannot be considered fully a narrative analysis, as per the definitions and clarifications stated earlier, it is valuable as a first approach to uncovering competing narratives that took place within the ozone hole discourse. I argue that texts mentioning the ozone hole are still related to the "ozone layer" topic and can therefore be considered part of the same discourse.

Finally, all the data described above is combined in Section 4 to provide a complete visualisation of the DN-STP framework. Both the theoretical framework and the empirical case study are further developed in the following sections. For further explanation on data sources and data processing, see Appendix A1, while the databases used can be consulted in Appendix B.

4. Discourse and Narratives – Social Tipping Points Framework

In this section, the main considerations for the DN-STP Framework are outlined. The first aspect considered central to the framework is that of agency. As stated earlier, agency is one of the main differentiators between natural and societal systems and can be considered the main driver for social tipping processes (Stadelmann-Steffen et al., 2021; Winkelmann et al., 2022). Language is the primary form of interaction between humans (Litfin, 1995), making agency a critical consideration when analysing discourse and narratives. Both discourse and narratives are related to the use of language in society, and as such can also be used to understand agency (Souto-Manning, 2014). For example, Souto-Manning (2014) uses narrative analysis to unveil how linguistic processes can convey a change in agency or moral stances over time. As such, discourse and narratives are critical ways in which agency is both constructed and understood within social systems. The six spheres which compose the DN-STP framework, namely: Politics, Industry, Society, Media, Science and Culture, house societal actors which create and exchange discourses

[2] Duplicates are identified through a search of repeated titles between databases for each keyword. If an occurrence is found in the "ozone layer" database and on either the "ozone hole" or "hole in the ozone layer" database, they are marked as "both".

and narratives through diverse communication pathways. Examples of actors within each sphere, as well as their communication pathways are presented in Table 1.

Table 1 – Spheres within the STP Narrative framework, including examples of institutional and individual actors and their means of communicating with other actors within a system

Sphere	**Actor type**	**Actor(s)**	**Communication pathway(s)**
Politics	Institutional	Federal governments, municipalities	Press releases, policy reports, social media, official website posts
	Individual	Politicians, policymakers	Speeches, articles, social media, books
Industry	Institutional	Companies, for-profit organisations	Advertisements, press releases, social media, official website posts
	Individual	Company workers	Word of mouth, social media, interviews, public lectures
Society	Institutional	Civil society organisations,	Press releases, social media, official website posts
	Individual	Citizens	Word of mouth, social media
Media	Institutional	Newspapers, magazines, social media platforms	Newspaper articles, magazine articles, television and radio broadcasts, official website posts, press releases
	Individual	Journalists	Newspaper articles, magazine articles, interviews, social media, public speeches, word of mouth
Science	Institutional	Journals, universities, research institutes	Journal articles, reports, publications, press releases, official website posts
	Individual	Researchers	Publications, public lectures, books, articles, interviews, social media
Culture	Institutional	Cinemas, theatres, museums, concert venues, film and entertainment broadcasting companies	Movies, plays, displayed artworks, TV shows, official website posts, press releases, social media
	Individual	Actors, musicians, artists, writers	Live performances, songs, poems, paintings, social media, interviews

Social network dynamics represent the mechanisms through which discourse and narratives shape social behaviours. Agents within social networks share meanings and identities, which in turn influence their norms and behaviours (Winkelmann et al., 2022). To trigger a tipping process, these norms and behaviours must spread throughout the population to surpass the threshold where a new state is reached. In other words, the social system embedded in an SES must go through a qualitative change through what are known as network effects (Winkelmann et al., 2022). For the study of STPs, positive or reinforcing feedback mechanisms are a crucial instance of these network effects (Lenton et al., 2022; Milkoreit et al., 2018; Stadelmann-Steffen et al., 2021; Winkelmann et al., 2022). Drawing on literature on complex social network systems and STPs, I identify two main feedback mechanisms that are most likely to be influenced by discourse and

narratives and are therefore integrated within the DN-STP framework. These are complex contagion and cascading effects.

Contagion is often understood by its association with the spread of diseases. Shiller (2019) uses this metaphor to explain how narratives go “viral”, meaning that they spread rapidly throughout the population and in turn influence financial systems. Centola (2021) states that the viral metaphor only applies when related to simple ideas or information, which spread through simple contagion. According to the author, beliefs and behaviours spread through deeper processes called complex contagion, which are related to the concept of strong ties. Referring to the links connecting actors within a network, strong ties relate to those actors that interact frequently and carry emotional intensity, such as close friends or family (Centola & Macy, 2007; Granovetter, 1973). These strong local ties between actors can promote complex contagion of behaviours (Lenton et al., 2022). Discourse and narratives can therefore facilitate the creation of strong ties between actors by their sense-making mechanisms and the creation of group identities thus leading to complex contagion of behaviours.

Meanwhile, cascading effects refer to the process whereby events or tipping elements in different sub-systems interact and trigger tipping in other (sub)systems (Klose et al., 2021; Lenton et al., 2022). As discourse and narratives are spread by different actors through an SES, they have the potential to reach wide audiences and amplify behaviours across spheres. Cascading effects are therefore related to the dissemination of information and ideas. For example, information put forward by researchers and broadcasters (Science and Media spheres) can initiate or stop tipping cascades in a societal system (Lenton et al., 2022).

These feedback mechanisms are interrelated and can work in conjunction to trigger tipping dynamics, sometimes making it difficult to tell them apart. The main difference between them is that complex contagion relates to the creation of strong ties, which often occurs within a particular social sphere (Centola, 2021; Centola & Macy, 2007). Complex contagion is therefore a slower process, requiring reaffirmation or reinforcement within the specific social network where it takes place. On the other hand, cascading effects are understood as faster and more far-reaching mechanisms (Lenton et al., 2022), which can quickly trigger tipping dynamics across actors that might not be strongly connected. As such, both mechanisms exist both within and outside the DN-STP spheres, being influenced by the spread of discourses and narratives across the system. Figure 1 shows a graphic representation of the DN-STP framework, where the six societal spheres create and distribute discourses and narratives, which in turn influence mechanisms of complex contagion and cascading effects leading to widespread behavioural change which affects an ecological system.

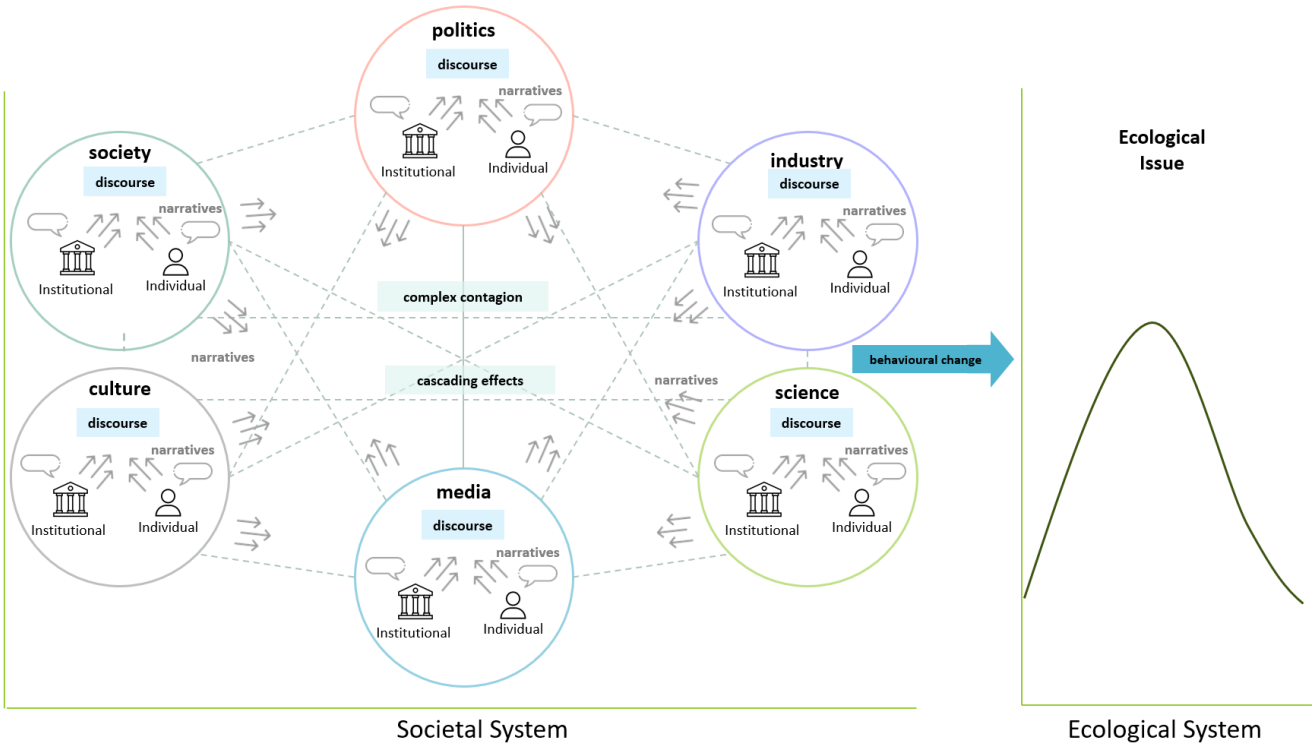

Figure 1 – Graphic representation of the DN-STP Framework, showcasing the six societal spheres, housing actors at institutional and individual levels. Actors share narratives, making up broader discourses about topics and sharing them within and across the spheres. These discourses and narratives shape the overall behaviours of the system towards the management of an ecological system.

4.1. The Spheres

It has already been established that discourse and narratives spread by the actors identified by the DN-STP framework spheres have the potential to trigger STPs through social network mechanisms. In this section, the links between discourse, narratives and social behavioural change are described within the context of each sphere.

4.1.1. Politics

The Politics sphere integrates the political structures of society. The main political actors relevant to the spread of discourse and narratives are federal and local governments at the institutional level and policymakers and politicians at the individual level.

The act of governing is related to the exchange of information about policies, ideas and decisions between political actors and society (Canel & Sanders, 2012). Politicians frequently use narratives strategically within their speeches and campaign ads, as they are rhetorically powerful and harder to challenge by others (Souto-Manning, 2014). Therefore, narratives are central to the political space, as actors within the sphere must carefully shape their discourse to attract voters and support from the public. In political-economic terms, Eliaz & Spiegler (2018) frame the public's acceptance of a policy based on the combination of narrative and policy that maximises their anticipatory payoff. Therefore, the narrative framing of a policy is deeply relevant to its success, and it is usually embedded within the broader ideological narrative of a political party or actor. For example, research has shown that political ideologies affect people's compliance with

government mandates such as stay-at-home orders during the COVID-19 pandemic (Painter & Qiu, 2021). Furthermore, shared political beliefs can be an important factor in creating strong ties between groups of individuals, as actors with certain political affiliations seek to interact with individuals who reaffirm their views (Boutyline & Willer, 2017). This highlights the relevance of incorporating discourse and narratives when observing issues of policymaking.

4.1.2. Industry

As STP issues often deal with socio-technical systems, it is important to integrate actors related to the production of technical innovations. As such, the Industry sphere considers for-profit corporations at the institutional level and the workers affiliated with these companies at the individual level.

In today's economic system, widely permeated by neoliberal ideas, corporate power has increased, and companies have used discursive tools to position themselves and promote their interests as those of the general population (Hathaway, 2020). Through activities such as lobbying and marketing, Industry actors seek to influence other spheres in alignment with their interests, mainly to increase profits and drive sales. Within the sphere, millions of dollars are spent between corporations and agencies, shaping effective discourse -in the shape of slogans, for example-, which can have a strong effect on brand awareness and consumer behaviour (Aslan & Çağatay, 2021). Therefore, companies must closely manage the narratives that they put forward through their communication strategies. Hossain et al. (2017) reviewed studies on discourse analysis in corporate communication which show that companies use narratives to position themselves as reasonable and trustworthy, to convince stakeholders of their sustainable practices and to attract investors by highlighting their profitability. Marketing is perhaps the most direct way to measure narrative effects on social behaviours, as studies on advertising show their potential for influencing consumers (Chang, 2019; Kang et al., 2020).

4.1.3. Society

The Society sphere considers civil society organisations, such as non-governmental organisations (NGOs) at the institutional level, and citizens at the individual level. For the study of discourse and narratives, citizens are highly relevant. While citizens also make up the individual level of other spheres, for example: politicians from the Political sphere or artists from the Cultural sphere are at the same time citizens, this sphere is primarily concerned with their role as independent members of the community they inhabit. The interaction between citizens and the Industry sphere for example, mainly relates to the economic activity of consuming goods and services. Consumers can therefore be defined as citizens from the Society sphere interacting with the Industry sphere. As STP research usually focuses on socio-technical solutions, the role of citizens as consumers of new products and technologies is highly relevant.

As mentioned in the previous section, companies aim to influence consumer behaviour through advertising campaigns and by creating attractive corporate images. On the other side of this relationship, research shows that consumers often recognise the embedded interests of industry or environmental actors, and therefore perceive independent third parties and government as more reliable (Yang & Hobbs, 2020). This shows the main difficulty with the diffusion of narratives within the social sphere: actors from other spheres (mainly at the Institutional level) must curtail their interests and carefully craft their narratives to ensure they achieve the desired behavioural change.

Mass media and social media platforms have given citizens access to an enormous amount of information, which can at times contradict information from more "trustworthy" actors such as

scientists (Yang & Hobbs, 2020). The concept of complex contagion is particularly relevant here, as social actors rely on their close networks to spread information and beliefs (Centola, 2021). Recently, social media platforms have given researchers additional tools to understand these mechanisms. For example, during the Arab Spring, social media enabled the rapid spread of revolutionary narratives and played a pivotal role in mobilising actors to challenge the established regimes (Centola, 2021; Comunello & Anzera, 2012; Smidi & Shahin, 2017).

4.1.4. Media

The Media sphere integrates mainly news organisations and magazines at the institutional level. For more recent issues, social media companies are also relevant at this level. These outlets serve as a primary source of knowledge, shaping public perception and attitudes towards various issues. At the individual level, journalists acting independently are also considered.

Dimopoulos & Koulaidis (2001) find that media coverage significantly affects public understanding of scientific issues, such as the greenhouse effect, thereby influencing environmental behaviours and support for policies. The publications within newspapers are commonly referred to as "news stories", highlighting their narrative aspect. As such, the author's framing of the reported issues is important to how it is perceived by the general public. S. J. O'Neill et al. (2013) find that fear-inducing tones within climate change news can have an adverse effect on people's engagement with the topic. Moreover, mass media acts as a "translator" between science, policy and the public, and citizens often rely on media outlets to get informed on scientific issues, but the media's reliability is curtailed by power structures and economic pressures (Boykoff, 2007; Boykoff & Yulsman, 2013; Dahlstrom, 2014). Building on Shiller's (2019) premise that economic narratives in the media contribute to collective market behaviours, Nyman et al. (2021) find that the sentiment of news stories correlates well with certain financial and economic variables and can therefore be used as a potential approach to detect systemic risk. As a primary source for the diffusion of information and knowledge, and through its role as an amplifier of other spheres' discourses and narratives, the Media sphere can play a central role in triggering cascading effects (Lenton et al., 2022).

4.1.5. Science

This sphere is composed mainly of scientific research institutes, journals and universities at the institutional level, as the main disseminators and facilitators for scientific knowledge. Researchers correspond to the individual level of the sphere, though it can often be difficult to truly separate discourses and narratives of researchers acting at the individual vs institutional level.

Storytelling often has a negative connotation within science, as narratives are seen as a contrasted way of presenting information to the logical-scientific communication commonly used by the Science sphere (Dahlstrom, 2014). However, research shows that a narrative approach to science communication often increases comprehension and information retention (Dahlstrom, 2014; Yang & Hobbs, 2020). Yang & Hobbs (2020) find that scientific narratives positively influence consumer responses to food biotechnology when compared to the same information framed in a logical-scientific manner. Therefore, as also stated in the previous section, the Science sphere relies on mass media to translate their findings into narratives which are digestible by the public. This comes with several risks, however, as actors in other spheres can interpret scientific findings differently or misconstrue them to fit their interests. In entertainment media such as TV shows (see Culture sphere), for example, science is often used as a tool for storytelling, which influences audiences through often inaccurate portrayals of scientific issues (Dahlstrom, 2014). Another example is highlighted by Boykoff (2007), who finds that the US media have portrayed climate

change science through a contentious lens, rather than highlighting the scientific consensus that exists around the issue. Taking ownership of the discourse can greatly influence how the Science sphere contributes to social behavioural change. For instance, the Open Access movement, driven by scientists supporting the widespread diffusion of science, has benefits for actors within the scientific sphere and society in general by making knowledge more accessible and impactful (Tennant et al., 2016). This movement can potentially influence cascading effects by enabling scientific knowledge to reach wider audiences, as opposed to maintaining it enclosed within the network of the sphere. This, however, must be accompanied by an effective use of narratives to enhance the understanding of scientific knowledge by actors outside the Science sphere.

4.1.6. Culture

Cultural actors relate to the entertainment that is widely consumed within our societal system. As such, examples of actors at the institutional level correspond to film and entertainment broadcasting companies -such as movie production companies or TV channels-, as well as cinemas, theatres, museums or other actors related to the spread of entertainment media. At the individual level, musicians, actors, writers and artists are highly influential in spreading discourse and narratives across the population.

“Culture” refers to how human societies express themselves (Davies et al., 2019). It is deeply related to how individuals interact with the world on both the individual and collective levels. It encompasses forms of entertainment and artistic expression such as music, movies, television shows, and novels. Culture and art are directly linked to the values that people hold in society, and can evoke powerful emotions, which in turn can spark dialogue and encourage innovative thinking (Eernstman & Wals, 2013; Publicover et al., 2018).

Specifically, music is an art form that is closely related to emotion and can affect personal aspects such as subjective well-being through the emotional response that it generates (Västfjäll et al., 2012). As such, music is an important element of the Cultural sphere, which can have a significant impact on social behaviours towards positive change. Rabinowitch (2020), for example, mentions several ways in which music can encourage prosocial behaviour, such as collaborative music-making, educational music, composition and art and technology.

Other cultural mediums such as movies and TV have also been shown to influence societal responses to certain issues. Neff (2015) examines the ways that narratives from movies are used to influence policy discourse and implement policies in response to certain issues. This highlights the role of Culture within the wider societal system and its importance for the study of social behaviours towards STPs.

4.2. Interactions between spheres

In the previous sections, it has already become evident that the spheres are highly interconnected. It has often been unavoidable to mention actors from other societal sectors when explaining how discourse and narratives influence behaviours within each sphere. This is due to the complex nature of SESs, highlighting the potential for feedback mechanisms to be triggered across spheres. The fact that mass media acts as the main venue for nonexpert audiences to obtain scientific knowledge (Dahlstrom, 2014), for example, is essential to understanding the relationship between scientific actors and the rest of society. There are many examples of these links, ranging from the potential for music to effectively communicate science (Publicover et al., 2018; J. Wodak, 2018) to how citizens engage with political narratives depending on the media platform used to deliver

the message (McLaughlin & Velez, 2019). This underscores the importance of including every sphere when analysing STP issues to not miss potentially relevant links.

5. Case Study: The Ozone Layer

As stated earlier, the ozone layer issue is widely acknowledged as a success story of policymaking due to the global ratification of the Montreal Protocol and the successful near-total ban on ODS in the face of an imminent environmental threat (Cook & Forte, 1996; Whitesides, 2020). Having been previously used by Stadelmann-Steffen et al. (2021) as a case study within STP research, the ozone layer issue is useful to test the DN-STP framework. Apart from the study developed in this section, an additional analysis looking into the role of Media in spreading discourse about other spheres can be found in Appendix A2.

5.1.1. Politics

The main institutional actor mediating the development of the ozone layer issue in the United States was the Environmental Protection Agency (EPA). Additional governmental agencies included the Food and Drug Administration (FDA), the Consumer Product Safety Commission (CPSC) and the National Aeronautics and Space Administration (referred to as WMO/NASA). At the individual level, agency representatives, spokespersons and politicians gave out speeches and put out statements showcasing their opinions on the issue. Examples of such actors are Richard Benedick, chief US negotiator for the Montreal Protocol, and William Graham, the Science Advisor to President Reagan (Litfin, 1995).

In 1976, the EPA held the first public meeting to tackle chlorofluorocarbons. The agency's administrator at the time, Russel E. Train stated that "The National Academy of Sciences released a report in September confirming hypothetical predictions that the introduction of fluorocarbons into the upper atmosphere does deplete the ozone layer around the earth" (Train, 1976). The meeting presented a panel composed of members of the FDA and the CPSC. The administrator further stated the immediate start of examination of alternatives, "using the expertise and advice of industry, the public and other affected federal agencies" (Train, 1976). This statement marks the start of the political discourse surrounding the issue in the United States. It also shows the collaborative effort of different governmental agencies within the political sphere and with other actors from the Social and Industry spheres. Importantly, it highlights the role of the Science sphere -in this case, the National Academy of Sciences- as the main actor informing the agency's decisions.

Figure 2 shows the press releases, speeches, and treaties (mainly by the EPA) throughout the case study period. The main role of the discourse within the Politics sphere can be described as a mediating one. Political actors at the time, such as WMO/NASA, communicated confidence in the ozone layer as an issue to be addressed but their discourse was interpreted differently by other actors, depending on their previous stances (Litfin, 1995). This firstly highlights the use of scientific narratives by the Political sphere and secondly corroborates the previously presented arguments of Boykoff (2007) and Dahlstrom (2014) that scientific findings are often misconstrued by external actors to fit into their previously constructed narratives.

An additional interesting aspect is the fact that the political sphere also took on the task of informing the public through narratives, as is highlighted by the publication of a comic book-style booklet to inform the public (mainly children) about the importance of ozone in 1993. This shows the use of a narrative tool as a mechanism of scientific communication, but it is also an example of the interplay between the Political and Cultural spheres.

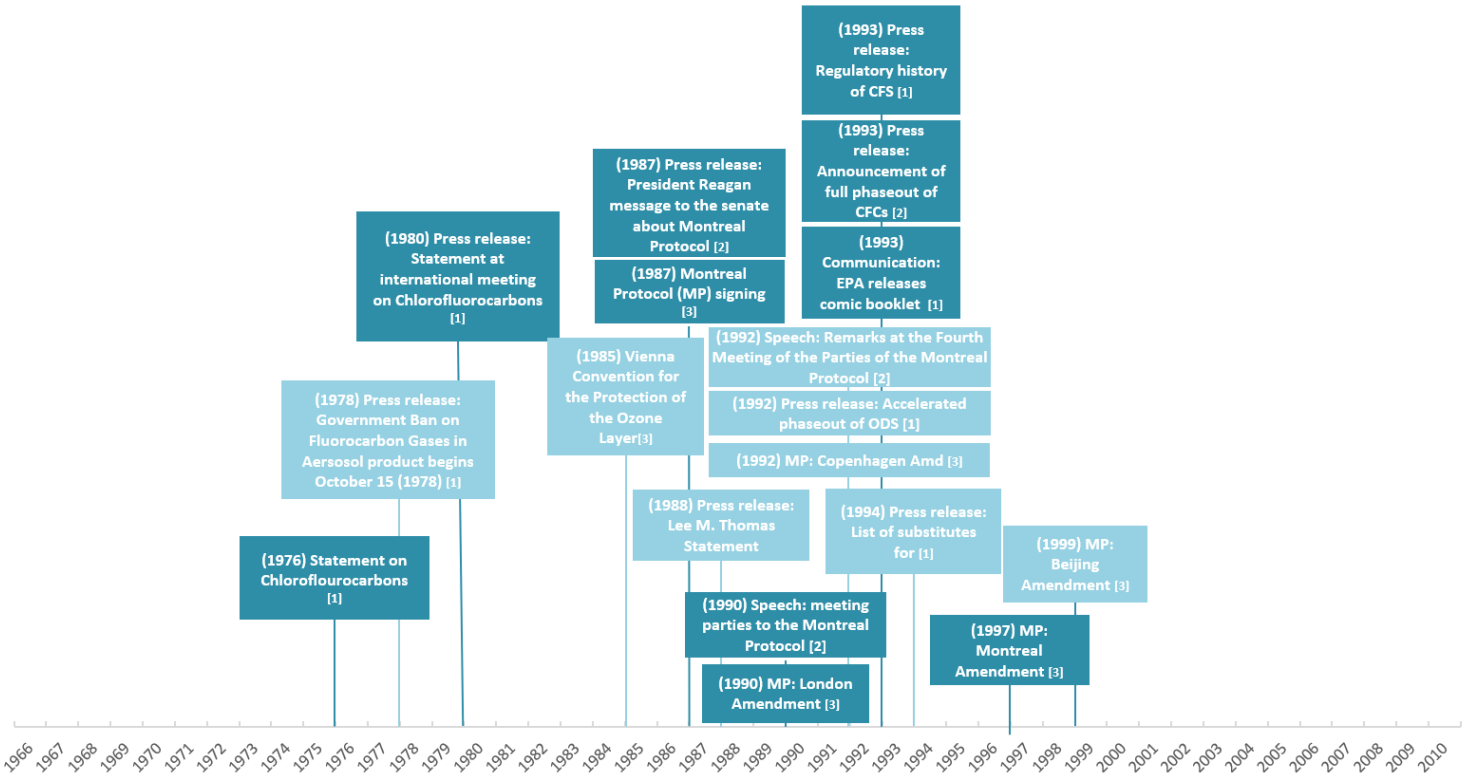

Figure 2 – Timeline of policy events related to the ozone layer in the US between 1966-2010 [1] - Environmental Protection Agency. (2024b, May 31). [2] - Environmental Protection Agency. (2024a, May 31). EPA History: Montreal Protocol. [3] - Environmental Protection Agency. (2021, August 30). Note: Color differences between events are merely for visualization purposes, and do not suggest differences between events.

5.1.2. Industry

The main producer of chlorofluorocarbons globally was the chemical manufacturing company DuPont, making them the main industry actor in this case. Other relevant producers of CFCs were S.C. Johnson, Allied Chemical, Union Carbide, Pennwalt and Kaiser Chemical. At the individual level, spokespersons and high-level executives for these companies put out statements and participated in political discussions. Examples of such actors include Mack McFarland, science advisor for CFC-related issues at Dupont and Irving Shapiro, Dupont's chief executive officer in 1974.

The technology of chlorofluorocarbons, branded with the name Freon, was one of DuPont's most successful products after its applications were expanded from refrigeration to propelling aerosols, cleaning metals and foam blowing for insulation (Maxwell & Briscoe, 1997). Together with other companies, the corporation established a research programme to provide scientific bases for phasing out CFCs, while at the same time persuading members of Congress to delay regulatory actions (Maxwell & Briscoe, 1997). In a statement, Joseph P. Glas (the Director of the Freon Products Division) mentioned that since the announcement of the hypothesis that CFCs contributed to the degradation of the ozone layer, DuPont had "actively promoted, sponsored and conducted research to develop a sound scientific understanding of the potential effects of chlorofluorocarbons on stratospheric ozone"(Glas, 1986).

Figure 3 shows the global production of CFC-11. After the initial, and rapid ban on aerosols using CFCs, production of this chemical showed a decreasing trend between 1974 and 1982. After this,

production increased again and reached levels higher than those of the mid-70s. This was admitted by the director of the Freon division in 1986, and followed up by the statement:

"Although we continue to believe that no immediate hazard to health or the environment exists from current levels of CFC emissions, the wisdom of permitting continued growth must be weighed against the existing inability of science to specify a safe long-term growth rate." (Glas, 1986)

Between the first report by Molina & Rowland (1974) and the Ozone Trends Panel Report in 1988 (Maxwell & Briscoe, 1997), the narrative advanced by actors behind CFC technologies was that of scepticism of the urgency for a phase-out, and of questioning the definitiveness of the science, to delay the regulations on the substance. A New York Times (NYT) article at the time (Glaberson, 1988) pointed out that DuPont executives had been writing combative letters for years and reported that the reason behind the company's shift towards a complete CFC phase-out was, as stated by the executives, "a result of pure, hard, cold science making its points in a company where […] science has always mattered as much as business".

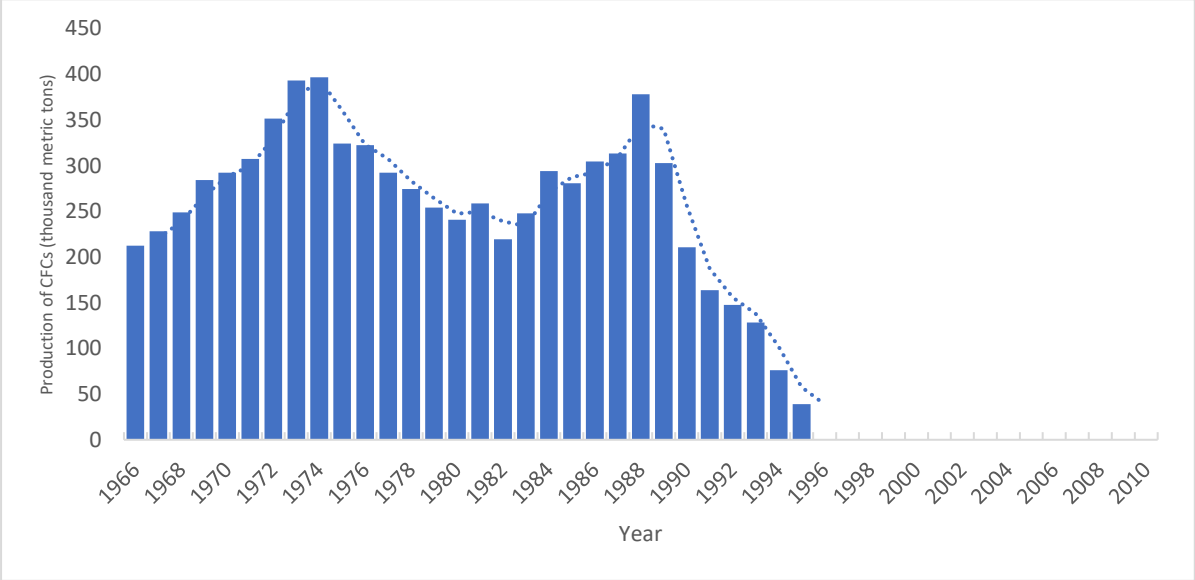

Figure 3 – Global production of CFCs (CFC-11, CFC-12, CFC-113) between 1966 and 2010, adapted from Cook et al. (1996).

5.1.3. Society

The role of civil society organisations and citizens is perhaps the least discussed aspect surrounding the ozone layer issue. However, NGOs and citizen actions were still highly relevant to the developments of the case, putting pressure on both businesses and political actors (Cook, 1990; Whitesides, 2020). At the institutional level the main actors were NGOs such as Friends of the Earth and the Environmental Defense Fund. Because CFCs were one of many components of consumer products, and not the final products themselves, identifying the role of citizens is relatively more difficult in the ozone layer issue. In socio-technical innovations such as electric vehicles, the adoption of a technology can be directly measured by the sales of the technological product, pointing to the citizens' behaviours as final consumers of said product (Sharpe & Lenton, 2021). Nevertheless, the individual level-actors of the Society sphere can be identified as consumers of aerosol, refrigerators and air conditioners during the case study timeframe.

In the US, several social action initiatives took place. For example, school children wrote letters to fast-food restaurant chain McDonald's urging them to stop using CFC-based packaging, which resulted in the company announcing its switch to non-CFC based packaging (Cook, 1990). Another example of discursive action came from Friends of the Earth-US, which launched the "Stratospheric Defense Initiative" seeking to eliminate CFCs from food packaging and pressuring restaurants by threatening to announce their responses during Montreal Protocol negotiations (Cook, 1990). Other initiatives included promotion of CFC recycling at car service shops, forming grassroots groups to mobilise citizens in support of the phase-out of ozone-depleting substances, and exposing companies for their ozone pollution by using public data available (Cook, 1990). Finally, boycotting aerosol products became popular, and polls showed that approximately half of the population was aware of the ozone issue, and sales dropped because of this (Bantham, 1975; Maxwell & Briscoe, 1997). In general, the narrative observed in the public sphere was that of understanding the issue of the ozone layer as a serious one, which is said to have garnered more public attention once the frightening image of the ozone hole became popularised (Maxwell & Briscoe, 1997). The image of the ozone hole may have acted as a contagious narrative which helped the public understand the severity of the issue (Grevsmühl, 2018; Maxwell & Briscoe, 1997). This points to a potential cascading effect triggered by a highly alarming narrative of a "hole in the sky" being spread throughout the population.

Figure 4 shows the United States' CFC consumption between 1966 and 2010. While the consumption metric is not a direct indicator of social change in this case, it still shows the dramatic shift in consumption patterns of CFCs between 1986 and 1996, driven in part by the work of NGOs, environmental groups and civil action on the issue.

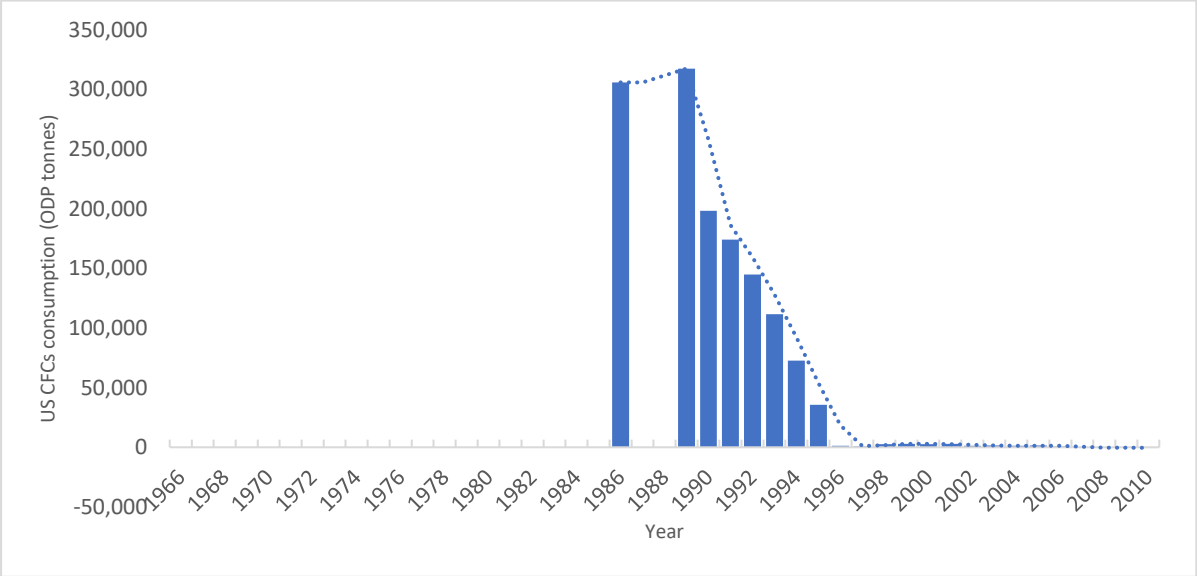

Figure 4 – Consumption of CFCs in the USA in ODP tonnes between 1966 and 2010 Source: UNEP

Note: Values before 1986, along with data for the years 1987 and 1988 missing from the original database.

5.1.4. Media

News media widely covered the ozone layer, both as a national and global issue. The main institutional actors identified were the New York Times, The Associated Press and other national and local newspapers. At the individual level, journalists reporting on the issue often contributed

to the ozone layer discourse by attempting to offer balanced views on the situation (Howland, 2006).

As early as September 1974, just three months after Molina & Rowland's publication in Nature, a news article was published in the NYT titled: "Tests Show Aerosol Gases May Pose Threat to Earth". In the article, Sullivan (1974) summarises the developments regarding the ozone layer, which begin with scientists warning about the potential for aerosol propellants to advance ozone breakdown in the atmosphere. Furthermore, it refers to Freon as the trade name used by DuPont, but also names other manufacturers of ODS. Lastly, the article presents the viewpoint of these manufacturers by reporting that the Manufacturing Chemists Association began its own program of laboratory studies and includes a statement by DuPont's product division spokesman which questioned the scientific assessment's validity.

This newspaper article highlights the role of media in presenting and amplifying discourse from other spheres, in a largely unbiased manner. However, there are also biased narratives presented by articles even within the same newspaper. Such is the case of a 1975 NYT article titled "Look Up and Live. (The Ozone Is Still There)" by Russel A. Bantham. This article is adapted from a speech before a cosmetics-industry trade group and Bantham is cited as being a legal counsel to a major aerosol marketing company. In contrast to the previous article mentioned, Bantham presents a starkly biased narrative of the ozone layer. It includes phrases such as "scientists have agreed to disagree on the validity of the theory" and ends with the following phrase, accompanied by a caricature of the Henny Penny story:

"Legend tells us that Henny Penny, who first postulated that the sky was falling when an acorn fell on her head, was subsequently proved wrong". (Bantham, 1975)

Figure 5 shows the trend of media coverage as a percentage of the total newspaper and magazine articles within the data. It can be observed that the first peak in coverage takes place around 1975, following the first scientific publication of the dangers of ODS in the atmosphere. After this, the coverage dies down until 1985, coinciding with the discovery of the ozone hole and subsequent Montreal Protocol enactment in 1987. This is consistent with the findings of Corbett (1993), who states that although ozone had been a topic of broad media coverage for nearly two decades, the focus of the stories is largely dependent on events such as conferences or alarming statements. The peak in mediatic discourse is reached in 1989 and 1990, where the main areas of focus are developments in scientific findings, with little mention of the policies needed to counteract the issue (Corbett, 1993).

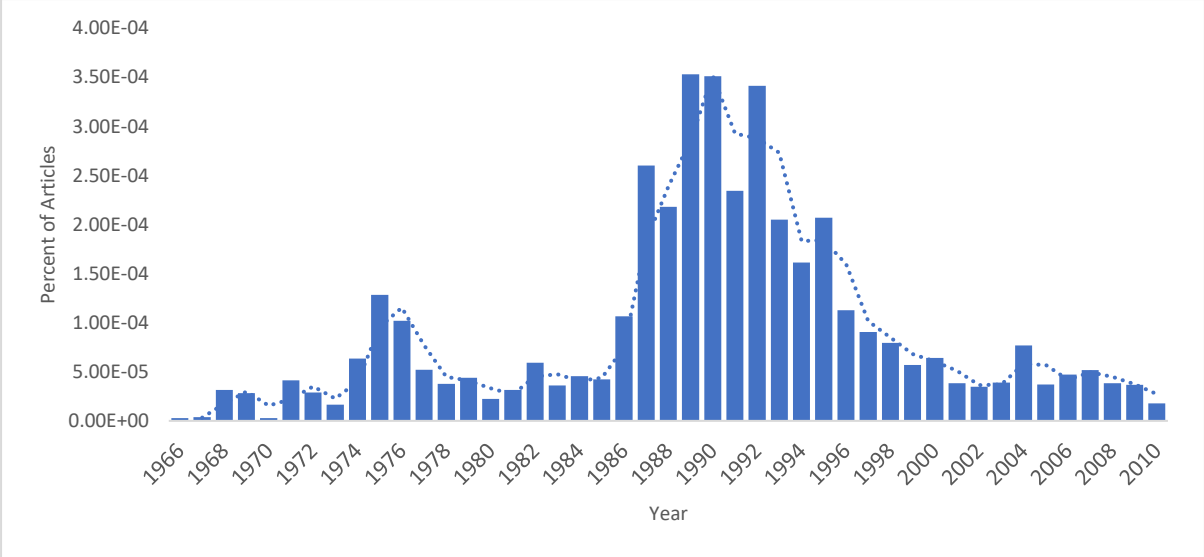

Figure 5 – Appearances of the term "ozone layer" in newspapers and magazines between 1966 and 2010, shown as a percentage of the total articles per year in the database Source: ProQuest

5.1.5. Science

Scientific actors were perhaps the most influential within the ozone layer issue, dominating the discourse surrounding it (for further proof of the Science sphere's prevalence in the ozone layer discourse, see Appendix A2). Identifying actors at the institutional level sometimes poses a problem, as scientific institutions were often part of both the Science and Politics spheres. Such is the case of the WMO/NASA or the Stratospheric Protection Task Force established under the EPA. However, scientific publications also came from more common scientific actors, such as the University of California at Irvine, Harvard University and the University of Michigan. At the individual level, scientists such as Mario Molina and Sherwood Rowland took a more active role in political activism outside of their scientific publications (Andersen et al., 2013; Howland, 2006).

The most often cited start to the chlorofluorocarbons scientific discourse, and indeed, to the issue in general, is the publishing of Rowland and Molina's 1974 report titled: "Stratospheric sink for chlorofluoromethanes: chlorine atom-catalysed destruction of ozone". While other publications that existed before also warned about possible damages to atmospheric ozone levels, they largely focused on issues caused by fertilisers and supersonic aviation (Andersen et al., 2013). After this first publication linking CFCs to ozone destruction was released, the scientific community focused on developing models and tests to come to definitive conclusions on the rates of ozone losses.

Litfin (1995) identifies knowledge brokers as important actors within the scientific sphere to frame information and translate scientific facts into language accessible by decision-makers. An example of such a knowledge broker was John Hoffman, the chairman of EPA Stratospheric Protection Task Force. Hoffman contributed a critical analysis to the scientific discourse: the "chlorine-loading" approach, which presented the idea that in order to stabilise chlorine concentrations, the emissions of CFCs required an immediate 85% cutback (Litfin, 1995). This idea presented a more urgent narrative, which competed with scientific models predicting modest ozone losses in the next years.

In 1985, an important development in the scientific sphere came when the British Antarctic Survey published a paper that reported major losses of stratospheric ozone in the Arctic, which was later confirmed by NASA satellite data (Litfin, 1995). The image of an ozone hole gave way to a new narrative, with a clear representation of critical damage to the Earth's ozone layer (Grevsmühl, 2018; Maxwell & Briscoe, 1997). However, this new piece of information was met with a further need to explain the phenomenon. Scientific actors within the political sphere such as President Reagan's Science Advisor William Graham, believed that the link between CFCs and ozone depletion was not clear enough to warrant decisive actions such as a 95% cut in CFC production, and some sceptics warned that rushing policy action would promote unsafe alternatives (Brune, 2015; Litfin, 1995). The issue with scientific narratives is therefore their interpretability. Within the sphere, scientific actors extracted different conclusions from the same information, which gave way to actors from the Industry to downplay the urgency of the situation (Litfin, 1995; Whitesides, 2020).

Figure 6 shows the scientific publications identified as a percentage of the total publications of that year. In contrast to what can be observed in other spheres, scientific publications continue to grow after 1993, and reach their peak in 2003. This behaviour could be explained by the fact that science continues to build upon previous knowledge and provides continuous measurements of an issue even after it has been resolved. Most of the publications in 2003 appear to be about data validations, measurements and analysis of past trends. Therefore, the science sphere mainly acts as an information broker, providing a baseline for other actors to interpret and extract narratives that cater to their specific views.

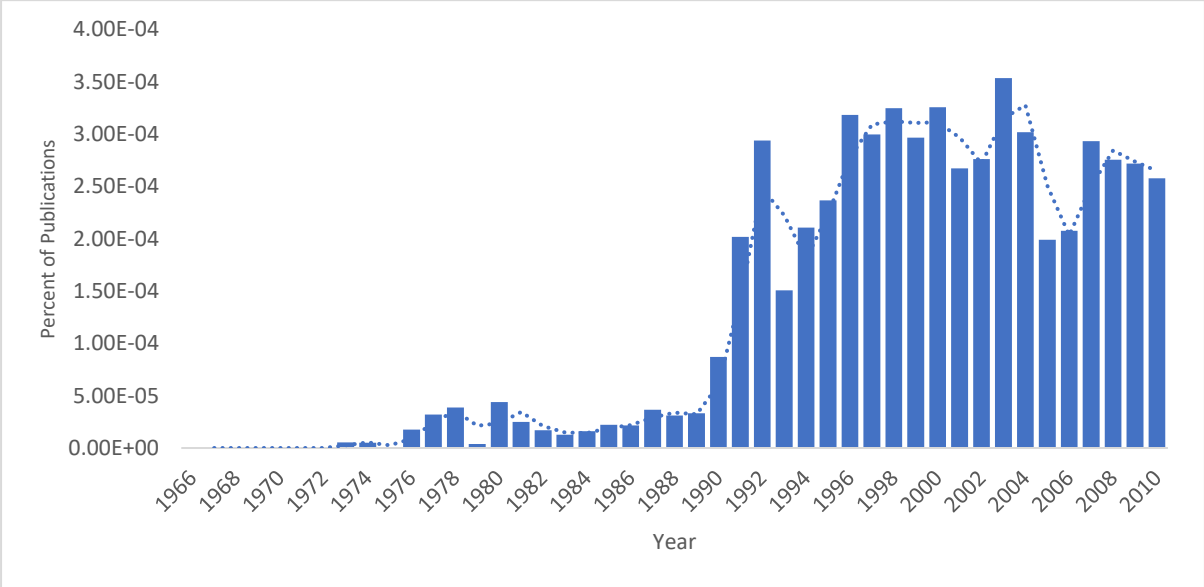

Figure 6 – Appearances of the term "ozone layer" in academic and scientific publications in the US between 1966 and 2010 shown as a percentage of the total publications in the US for that year Source: Web of Science core collection

5.1.6. Culture

The cultural dimension is often overlooked in studies of the ozone layer issue. However, as established in Section 4.1.6, it represents an instrumental avenue by which societal actors obtain and process information. At the institutional level, the Public Broadcasting Service (PBC) and the American Broadcasting Company (ABC) aired several highly popular TV shows during the ozone layer timeframe. While it is difficult to identify specific actors at the individual level, several artists and public figures played relevant roles in translating scientific information into narratives

through entertainment media. One such example is that of Carl Sagan, whose role in TV show "Cosmos" played an important role in disseminating scientific information to the masses (Sorensen, 2013).

The first mention of the ozone layer within the analysed database is found in an episode of Cosmos, aired in December 1980. The full phrase states "The surface of Mars, fried by ultraviolet light is also a reminder why it's important to keep our ozone layer intact". The series, though belonging to the documentary category, was important for scientific communication, exemplifying the intersection of science and popular culture. The series effectively conveyed scientific information to a larger audience by creating a type of "science fiction" from facts (Sorensen, 2013). In this case, the narrative being communicated is an informational one: the ozone layer as an important part of the Earth's system that must be protected. Later appearances of the term are observed in series such as MacGyver or The Golden Girls, which belong to the action and comedy genres, respectively. In the MacGyver Pilot episode aired in 1985, the dialogue reads: "Without the ozone layer, the sun's ultraviolet rays would kill everything on Earth. I think Carl here discovered the key to make the ozone layer self-destruct, didn't you, Carl?", while in the Golden Girls episode titled "The Accurate Conception", aired in 1989, one character says, "The sun's rays can be dangerous now there's a hole in the ozone layer", referring to another character tanning under the sun. These examples of the term in popular TV shows demonstrate how the ozone issue was presented within the cultural sphere. In general, whether it was through informative or more comedic programmes, the narrative being advanced is that of the ozone layer as an important protection mechanism for the Earth. Programmes informed the public and raised awareness of the issue, whether through the integration of the ozone layer as a fictional plot point within the storyline or as a statement of fact.

Figure 7 shows the frequency of the term within TV shows and movie transcripts. It can be observed that the term was only used once in the Cosmos episode in 1980, -which did not make a direct reference to the ozone layer as a current issue-. Afterwards, the term was rarely used until 1989, where it started to be more frequent. Mentions of the term reached the first peak in 1992, due to several instances in shows such as "Teenage Mutant Ninja Turtles" and "Baywatch", as well as six uses of the term in movies such as "Honeymoon in Vegas" and "Buffy the Vampire Slayer". In general, the use of the term in these instances advances the narrative of the hole in the ozone layer as a negative element which poses health risks.

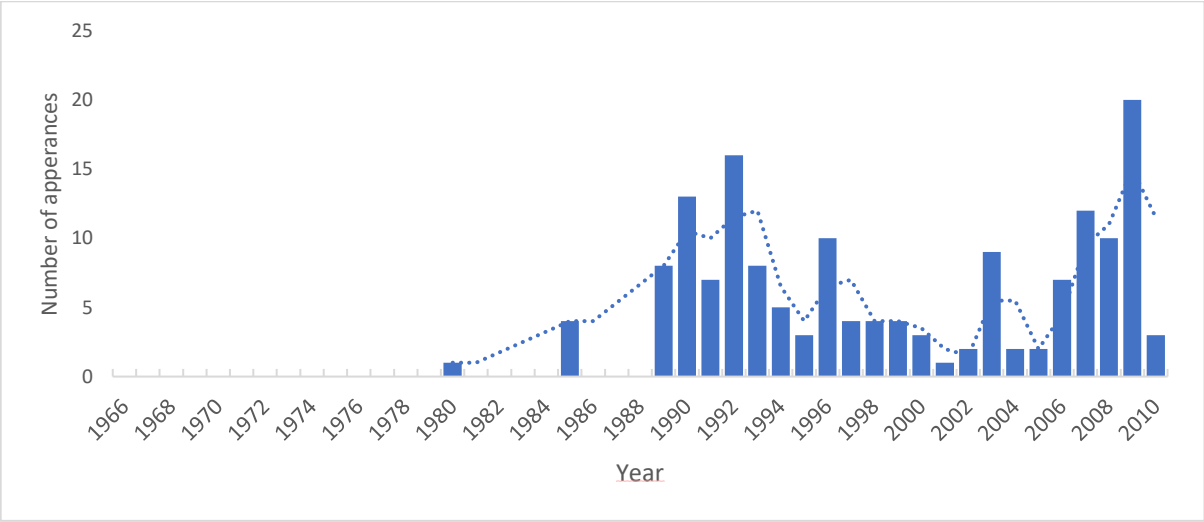

Figure 7 – Appearances of the term "ozone layer" in TV and Movie transcripts between 1966 and 2010 Source: Davies, Mark (2019) The TV Corpus & Davies, Mark (2019) The Movie Corpus

5.1.7. The "ozone hole" narrative

As mentioned earlier, a pivotal moment in the discursive developments of the ozone layer issue came in 1985 with the discovery of the ozone hole. This unveiled a new narrative that studies have identified as persuasive and more alarming (Grevsmühl, 2018; Maxwell & Briscoe, 1997). It is suggested that the idea of a "hole" in Earth's atmosphere was clearer and therefore a more impactful narrative that drove swift public and political action forward. Litfin (1995) states that the ozone hole was extensively covered in the media and contributed to the adoption of more precautionary measures within the Montreal Protocol. It is expected, then, that the narrative of the "ozone hole" would be used broadly in the Media, Science and Culture spheres to spread the message of the ozone hole's urgency. Figure 8 and Figure 9 show the mentions of the keywords "ozone layer", "ozone hole" and "hole in the ozone layer" in the Media and Science spheres, respectively. The data appears to contradict the idea that the media amplified the "ozone hole" narrative. Scientific publications widely began using the term immediately following the discovery of the ozone hole. Meanwhile, the Media sphere kept the use of the term "ozone layer" even after 1985. This could be explained by the fact that the scientific community immediately began looking for explanations regarding the cause of the ozone hole, its dimensions and implications. Meanwhile, the Media likely used the term that the public was already familiar with to report on the issue, and mainly reported on policy and scientific developments in general terms.

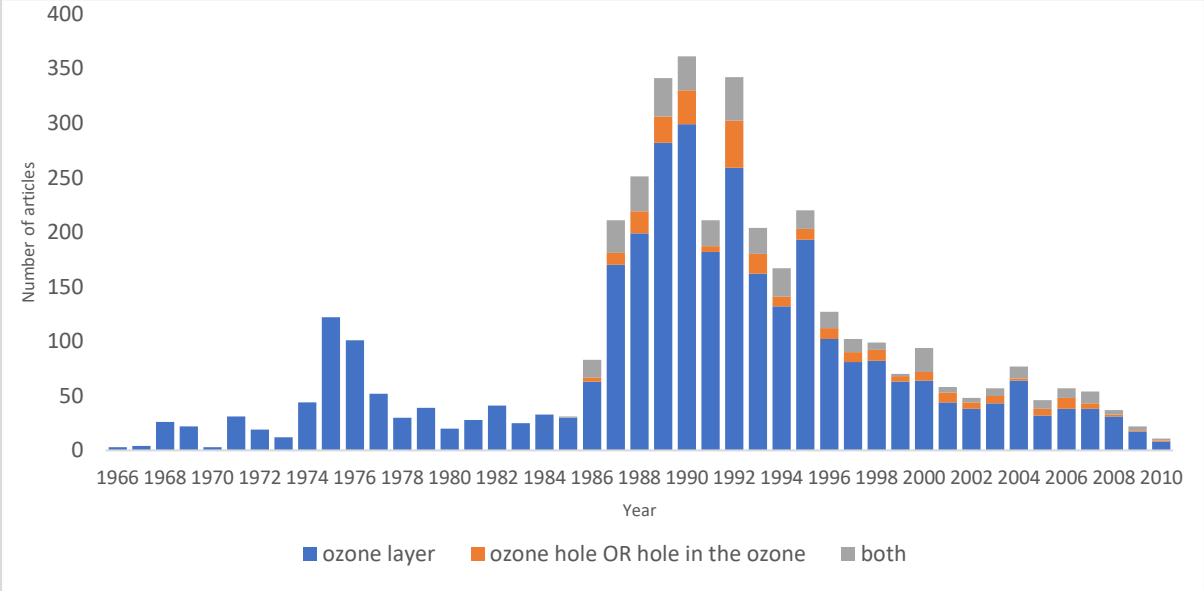

Figure 8 – Appearances of the terms "ozone layer", "ozone hole" or "hole in the ozone layer" in Media between 1966 and 2010 Note: Entries with duplicate terms categorised under "both"

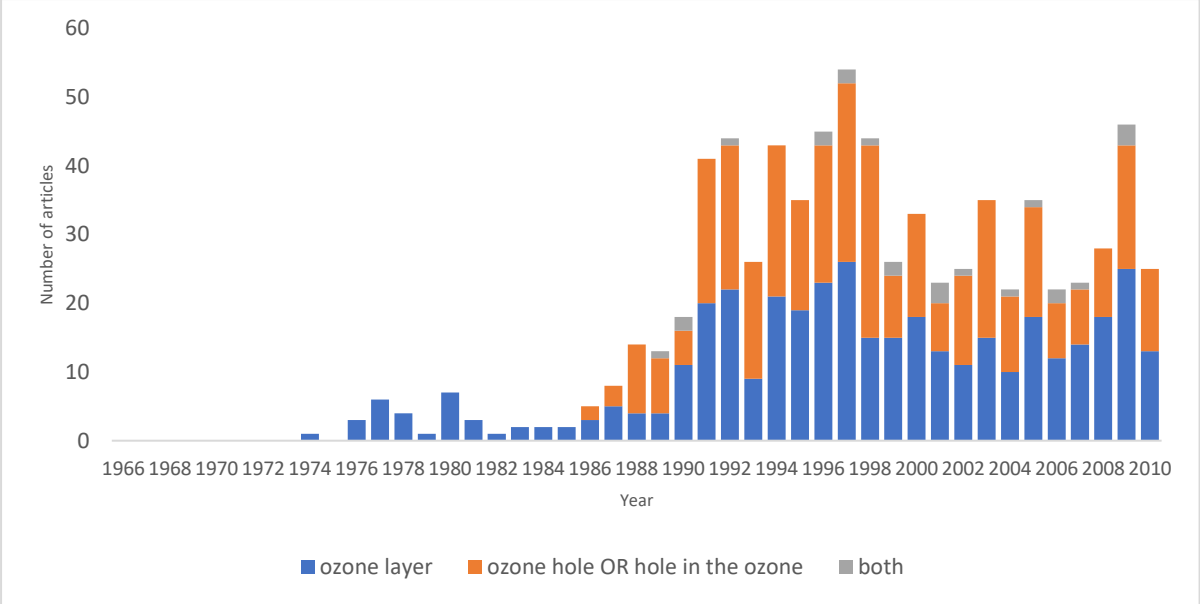

Figure 9 – Appearances of the terms "ozone layer", "ozone hole" or "hole in the ozone layer" in Science between 1966 and 2010 Note: Entries with duplicate terms categorised under "both"

5.1.8. Bringing it all together

To truly understand the complex interrelations of the spheres and the dynamics of the narratives with the broader issue, it is useful to observe them together. In Figure 10, the data for the six spheres of the DN-STP framework are plotted through normalised values. The first peak in media coverage of the issue came in 1975, one year after the first report on CFC damages to the ozone and three years before the US announcement of an aerosol ban. By this point, production of CFCs had already begun to slow down, primarily due to the actions of the company S.C. Johnson in stopping its use of CFC propellants immediately after the first warning signs by the Scientific sphere (Cook & Forte, 1996). Between 1988 and 1992, the Media, Science and Culture spheres all show important peaks in content, signifying the peak in general discourse around the matter. Specifically, 1992 shows a peak in all three spheres, coinciding with the Copenhagen amendment to the Montreal Protocol. The data suggests that general discourse and its embedded narratives lagged behind the developments of the issue, where the tipping point for the Industry and Social spheres can be empirically set around 1988. Therefore, Political and Industry actors appear to implement solutions earlier than the public is informed about them. Though science dominated the ozone layer discourse, its influence is disconnected from the number of publications made surrounding the topic, which also appear to peak long after the issue has been resolved (the peak in scientific publications took place in 2003).

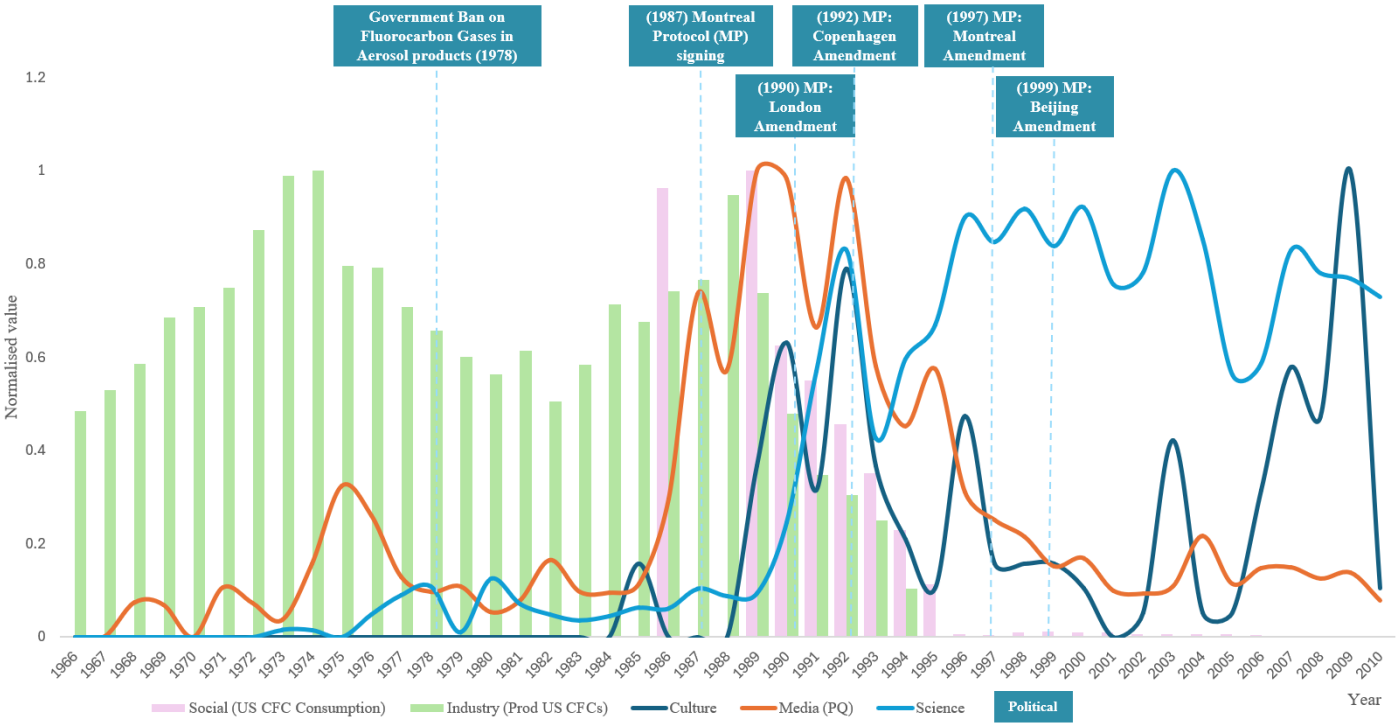

Figure 10 – Graph showing results for all spheres. The political sphere is represented by milestones in their respective years. Industry and Social spheres are shown as bar graphs and Culture, Media and Science spheres are shown as line graphs of normalised values.

6. Discussion

The DN-STP framework and subsequent case study highlight the interplay between all six actor spheres in constructing, disseminating and interpreting discourses and narratives. The framework presents a structured way of analysing STP issues through a comprehensive view of actor spheres within SESs. The framework therefore builds on the holistic and actor-centred approach of Stadelmann-Steffen et al. (2021), but expands on it by integrating the Media, Science and Culture spheres. I argue that these spheres are vital to analysing an STP issue through the scope of societal actors, and not including them risks leaving out important interlinkages at the system and sub-system levels. Additionally, the framework integrates clear pathways for identifying actors, namely at the institutional and individual levels, within each sphere. The combination of the six DN-STP framework spheres and the institutional and individual actors within them create a clearer and more comprehensive blueprint for STP analysis, facilitating the integration of empirical data and therefore responding to a current limitation of STP research (Milkoreit, 2023).

An interesting insight extracted from the case study comes from further analysis of Figure 10. Here, the discourse peak observed in the Media, Science and Culture spheres -which represent the main avenues for spreading knowledge to the general population- happened after the issue had been virtually resolved (see Section 5.1.2). Therefore, an interesting hypothesis for future research can be to test whether these three spheres can influence the speed at which an issue is resolved by taking earlier control of the discourse, and how this relates to behaviours within the Social sphere. That is to say, the Media, Science and Culture spheres could have potentially sped up the resolution of the ozone layer had their discursive peaks been observed earlier and had the consumer choices been more prevalent. This could be tested, for example, by applying the present framework to analyse social issues such as the Arab Spring or the civil rights movement, where

social and cultural narratives were highly influential (Harlow, 2013; Smidi & Shahin, 2017; Younas, 2023).

An important challenge, which at the same time highlights the complexity of the issues that the framework aims to analyse, arises when trying to place certain actors within the societal spheres. The dynamics of the ozone layer were complex, and the framework does not currently account for institutions or individuals acting within the intersections between spheres. Institutional actors such as WMO/NASA and the EPA operated at the intersection of the Science and Politics spheres, while companies within the Industry sphere created the Manufacturing Chemists Association to produce their own scientific knowledge on the issue. Likewise, at the individual level, actors such as William Graham, who acted as the science advisor to President Reagan, operated at positions which complicate the identification of their interests. This points to possible adjustments for the framework to further clarify the role of interests and power structures of the actors within an STP issue. While hegemonic processes and power are intrinsic to the study of discourse (Blommaert & Bulcaen, 2024; Souto-Manning, 2014), further expansions of the framework could establish this relationship more explicitly.

Another key difficulty arises when trying to pinpoint the cause-and-effect relationship between discourses and narratives and actor behaviours. Though the potential for discourses and narratives to affect network mechanisms is established, this becomes difficult to empirically test. Particularly, the link between specific narratives and the feedback effects of complex contagion and cascading effects is not yet convincingly established through the case study. For example, the "ozone hole" narrative is often mentioned as one that increased awareness of the issue and urgency among the general public (Grevsmühl, 2018; Maxwell & Briscoe, 1997), but the distinction between the "ozone hole" as a narrative and as irrefutable evidence of severe damage to an environmental system is hard to make. This is especially reinforced by the lack of prevalence of the term within the Media sphere (see Section 5.1.7), which would have suggested the adoption of the ozone hole as a stronger narrative. As Media acts as the main avenue for the dissemination of information across wider audiences, a larger prevalence of the ozone hole narrative would have indicated its role in initiating cascading effects (Boykoff & Yulsman, 2013; Lenton et al., 2022). While uncovering this link would have cemented the implications of this study, this issue points to a deeper discussion regarding the relationship between linguistic practices and the construction of reality, and whether this link can be credibly established. Centola (2021) posits that informational spread is not enough to trigger widespread behavioural change. While this may be true, the present study suggests that discourse and narratives are an important dimension both for understanding and facilitating societal change. Therefore, they are crucial mechanisms to be included within STP research to contextualise and understand societal behaviours to face an Ecological issue. Further research should aim to integrate additional societal mechanisms in addition to discourses and narratives to create a comprehensive theory of change for the field of STPs.

An additional limitation of the study relates to the collection and use of empirical data. While the ozone layer case is appropriate for its wide documentation and role as a successful example of global environmental management, gaps in available data remain. Acceptable time series data for visualising either discourse intensity or behaviours for most spheres was accessible and readily available but difficulties sometimes arose in obtaining relevant information, particularly for the Society sphere. The data on consumption obtained for this sphere only presented data for eight out of the 45 years included in the study timeframe. More importantly, the data relates to country-level consumption of CFCs, calculated as the sum of production and imports of the material, minus its exports. This data is not ideal for observing the behaviours of social actors, as consumers were not directly buying CFCs but rather refrigerators, air conditioning units and

aerosols. As the technological changes to CFCs happened almost seamlessly and without many changes to prices and product specifications (Maxwell & Briscoe, 1997), this data more appropriately shows the behaviours of CFC producers in phasing out the material from their products. Furthermore, little data was found related to the spread of discourses and narratives within the Society sphere, requiring assumptions about their role in influencing behaviours. Later studies using the DN-STP framework could seek information on direct consumption metrics or public opinions as empirical data for the social sphere. For more recent cases, social media data can be used to unveil discourses and narratives spread by social actors, as observed in studies on narratives and the Arab Spring (Comunello & Anzera, 2012; Smidi & Shahin, 2017).

Finally, this study touches on a broader question posed by Milkoreit (2023) about how agency, knowledge and navigational capacities are distributed in the current system. I argue that the DN-STP framework can aid in responding to the first two aspects of this question. Both agency and knowledge are closely related to discourses and narratives, which, as linguistic practices, serve as mechanisms for actors to exercise their agency and share knowledge. While the framework offers insights into the distribution of agency and knowledge, further research is needed to fully uncover their underlying mechanisms. The framework can therefore be further expanded to explore the relationships between agency, knowledge and navigational capacities to enhance its usefulness for future STP studies.

7. Conclusion

This study integrates discourse and narratives within the field of STPs as key mechanisms for understanding and enabling societal change. The first sub-research question guiding this study is:

What are the major spheres of a socio-ecological system, and how do discourses and narratives influence actor behaviours within and across these spheres?

To answer this question, I first identified six spheres: Politics, Industry, Society, Media, Science and Culture and synthesised them into the DN-STP framework. By identifying the six major spheres composing an SES, the DN-STP framework offers a comprehensive view of critical societal actors that interact within an SES to affect an ecological system. This approach bridges critical gaps in previous STP studies, where important societal actors related to the dissemination of information and knowledge in society were left out.

Secondly, drawing from studies on social network dynamics and STP studies, I propose complex contagion and cascading effects as the critical feedback mechanisms that are relevant for the study of discourse and narratives within SESs. These mechanisms point to critical pathways for the spread of social behaviours, making them crucial elements to understanding how discourse and narratives can influence behaviours with the speed and reach necessary to trigger social tipping dynamics.

Finally, I establish the role of discourse and narratives in shaping social behaviours in the context of each sphere of the DN-STP framework. Discourse and narratives represent some of the primary ways in which humans interact, share meanings and construct their understanding of the world (Litfin, 1995; Nyman et al., 2021; Roos & Reccius, 2024; Souto-Manning, 2014). Therefore, I draw on literature from a wide range of fields such as social psychology, economics, and linguistics, to establish these concepts as central to enabling social change within each sphere. This firstly highlights the interdisciplinary nature of the study, which is a critical aspect of the field of Industrial Ecology and for expanding our knowledge of complex systems such as the ones studied herein. Secondly, this approach points to relevant research gaps to guide future studies. As interest in STPs (Milkoreit, 2023) and narratives (Roos & Reccius, 2024) has been growing in recent years, so has the need to establish comprehensive frameworks and definitions to guide them and effectively synthesise their concepts.

The second sub-research question presented at the beginning of this study is:

How does the proposed DN-STP framework help explain the developments and dynamics in the ozone layer issue?

The ozone layer issue is interesting for the study of STPs and discourse and narratives since it exemplifies a complete transition where an ecological issue was solved through social tipping dynamics. Having been studied in both natural (Lenton et al., 2008) and social tipping points (Stadelmann-Steffen et al., 2021) literature, it serves as the ideal case study to deepen our understanding of the underlying mechanisms of social change, which can be influenced by discourse and narratives. The application of the DN-STP framework to this case therefore unveils insights into the societal developments and dynamics that took place during the case study period. First, the DN-STP framework establishes a structured mechanism for identifying actors within a societal system. The framework delineates the spheres of an SES, their actors at institutional and individual levels, and their communication pathways. This facilitates the identification of actors such as DuPont or William Graham and places them within their corresponding sphere to account for their interests and power structures within the issue. Then, the DN-STP framework provides a blueprint for analysing discourse and narratives empirically within each sphere and links to the mechanisms that can explain changes in behaviours. Through this, the ozone layer case reveals insights such as the Science sphere's importance in driving the broader discourse while showing that the lack of strong narratives presented by scientific actors often facilitated the undermining of their message, particularly by actors in the Industry and Politics spheres. Additionally, the study underpins the role of the Media sphere as an amplifier of discourses from other spheres. Actors within the Media sphere presented the competing narratives of the issue on an equal level – similar to what can be observed in the climate change case (Boykoff, 2007)-, undermining the urgency and consensus communicated by the Science sphere. Finally, the case study identifies the Social and Culture spheres as the least impactful in influencing the outcomes of the issue, pointing to the potential for future studies to use the DN-STP framework on issues where social and cultural actors' importance has been established.

To conclude this study, I hereby answer the main research question presented at the start:

What role do discourses and narratives play in shaping behavioural change towards social tipping points?

The study has shown that discourse and narratives play a critical role in influencing the behaviours of actors within an SES towards an STP in two ways: First, discourse and narratives act as a way of constructing reality through their role in meaning-making. This relates to how individual actors understand an issue and shape their reactions. As such, discourse and narratives act as powerful tools to analyse and understand the behaviours of societal actors throughout a certain period. Through analysing the competing narratives existing within a sphere, and the discourse that these create, we can deepen our understanding of why certain actors behave as they do.

Secondly, discourse and narratives act as enablers for the network mechanisms of complex contagion and cascading effects. As important mechanisms for communicating information and sharing knowledge, discourse and narratives aid in the creation of shared identities. The DN-STP framework can aid in deepening our understanding on how actors relate to each other, disseminate information and create shared knowledge. The implications of this are relevant for the use of discourse and narratives to encourage positive social change. For example, insights from the Scientific sphere suggest that scientific actors can create stronger narratives and take ownership of communication pathways to bolster the implications of their findings. This has meaningful implications for solving the ecological crises humanity currently faces. As the timeframe to

implement meaningful solutions for preventing tipping points in Earth's systems shortens (Lenton et al., 2019), we must use every tool at our disposal to attempt to trigger positive tipping dynamics in our society. Discourse and narratives might be a useful tool in this endeavour.

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9. Appendix A

1. Methodological Annex

1.1. Data Sources

For the empirical layer, different sources and data types are used. Table A1 lists the databases used for each sphere, the data type and additional comments.

Table A1 – Databases used for ozone layer case study

Sphere	**Type**	**Database(s)**	**Comment(s)**
Politics	Press releases and policies	• Environmental Protection Agency • United Nations Environment Programme	
Industry	Historical production of CFCs	• Cook, Elizabeth., & Forte, Reynaldo. (1996). *Ozone protection in the United States : elements of success*. World Resources Institute.	Data extracted from Figure 2: U.S. Production of Major CFCs and Policy Developments (thousand metric tons) using OriginPro software
Social	Historical consumption of CFCs	• United Nations Environment Programme: Data Centre	Consumption is defined by UNEP as production + imports – exports. Values for 1987 and 1988 are missing
Media	Newspaper and magazine articles	• ProQuest	Databases selected: Historical newspapers, newspapers and magazines
Science	Scientific journal articles	• Web of Science Core Collection	
Culture	TV Show and Movie transcripts	• Davies, Mark. (2019) *The TV Corpus*. Available online at https://www.english-corpora.org/tv/. • Davies, Mark. (2019) *The Movie Corpus*. Available online at https://www.english-corpora.org/movies/.	

1.2. Data Processing

1.2.1. Political

Data was gathered from the Environmental Protection Agency official press website (accessible at: https://www.epa.gov/history/epa-history-ozone-layer-depletion) and United Nations Environment Programme (UNEP) Ozone Secretariat (accessible at: https://ozone.unep.org/ozone-timeline). Developments in the policy sphere related to the United States were selected manually. Global developments such as the Montreal Protocol and its amendments were also included due to their importance for the United States. In total, 38 relevant elements were gathered. Due to the nature of the data, a timeline visualisation was preferred for this sphere. Table A2 shows all Political data gathered for the case study. The data can be further consulted in Appendix B sheet 1.

Table A2 – Political discourse developments from 1966 – 2010 related to the ozone layer in the USA. Source: EPA, UNEP

Year	**Event**
1976	Statement at a Public Meeting on Chloroflourocarbons
1977	World plan of action
1978	Government Ban on Fluorocarbon Gases in Aerosol Products Begins October 15
1980	Statement at International Meeting on Chlorofluorocarbons
1985	Vienna Convention for the Protection of the Ozone Layer
1987	EPA Press Release - President Reagan message to the senate
1987	Montreal Protocol Signing
1988	The U.S. honors its commitment to the Protocol when EPA issues final rules cutting domestic production and importing by 50 percent, through a system of tradable allowances.
1989	Montreal Protocol enters into force
1989	Congress levies excise tax on sale of CFCs and other ozone depleters. This program is handled by the Internal Revenue Service.
1990	Phase out of ODS is set for 2000 for A2 countries and 2010 for A5 countries
1990	In London, Parties to the Montreal Protocol pass amendments calling for total phaseout of production and importation of CFCs by 2000.
1990	Clean Air Act Amendments of 1990 signed, and include phaseout controls similar to London Amendments, although interim phaseout timetable more stringent. CFCs, halons and carbon tetrachloride must be phased out by 2000; methyl chloroform by 2002; and hydrochlorofluorocarbons (HCFCs) by 2030. Statute also requires rules restricting use of ozone-depleting substances in society, through such means as recycling and reducing emissions to the atmosphere.
1991	EPA proposes rule implementing Clean Air Act production and importing phaseout schedule for CFCs, halons, carbon tetrachloride and methyl chloroform.
1991	Adjustments to the Montreal Protocol agreed in 1990 in London at the Second Meeting of the Parties enter into force.
1992	Phase out of CFC accelerated to 1996
1992	EPA issues final rule for mandatory recycling of CFCs in motor vehicle air conditioners.
1992	The Parties to the Montreal Protocol meet in Copenhagen and agree to accelerate the phaseout of CFCs, carbon tetrachloride and methyl chloroform to Jan. 1, 1996, and halons to Jan. 1, 1994. (By April 1993, 107 nations were party to the Protocol).
1992	London Amendment enters into force
1993	EPA Issues First Safe Substitutes List for CFCs and Other Ozone Depleters
1993	EPA issues final rule banning use of ozone depleters in certain nonessential products, such as aerosol spray cans.
1993	EPA issues final rule requiring warning labels on products containing or manufactured

	with CFCs and other ozone depleters.
1993	EPA proposes rule to accelerate the phaseout of halons to Jan. 1, 1994, CFCs, methyl chloroform and carbon tetrachloride to Jan. 1, 1996, some forms of HCFCs to 2003; also adds methyl bromide and hydrobromofluorocarbons (HBFCs) to list of ozone-depleting substances, the former due for phaseout Jan. 1, 2000, and latter due by Jan. 1, 1996.
1993	EPA proposes rule requiring federal agencies to change contracting practices to minimize purchases of goods containing ozone depleters and to maximize use of safe alternatives. EPA proposes safe substitutes rule listing acceptable and unacceptable alternatives to ozone depleters, and lays out procedure for future listings. EPA issues final rule prohibiting venting of ozone depleters into atmosphere during servicing and disposal of residential and commercial air conditioners and refrigerators.
1993	Adjustments to the Montreal Protocol agreed in 1992 in Copenhagen at the Fourth Meeting of the Parties enter into force.
1994	Copenhagen Amendment enters into force
1994	Developed countries phase out halons used in products such as fire-fighting equipment, followed by developing countries in 2010.
1996	Developing countries freeze HCFCs
1996	Developing countries freeze the production and consumption of HCFCs.
1997	First developing country control measures take effect
1998	Adjustments to the Montreal Protocol agreed in 1997 in Montreal at the Ninth Meeting of the Parties enter into force.
1999	Montreal Amendment enters into force
2002	Beijing Amendment enters into force
2004	Developed countries phase out methyl bromide, followed by developing countries by 2015.
2007	The Montreal Protocol is adjusted to accelerate the phase-out of HCFCs by developing countries.
2008	The Vienna Convention and the Montreal Protocol become the first multilateral environmental treaties to achieve universal ratification.
2008	Adjustments to the Montreal Protocol agreed in 2007 in Montreal at the Nineteenth Meeting of the Parties enter into force.
2010	All parties to the Montreal Protocol phase out the consumption and production of chlorofluorocarbons (CFCs), halons, carbon tetrachloride and other fully hydrogenated ozone depleting substances.

1.2.2. Industry

Industry data is represented by the total CFC production in the US between 1958 and 1995. The data is extracted from *Figure 2: U.S. Production of Major CFCs and Policy Developments (Thousand Metric Tons)* as shown in Ozone Protection in the United States: Elements of Success (Cook et al., 1996). The figure uses data from the U.S International Trade Commission and the EPA, however, the primary data source was not located. The data points for the totals of CFC production per year were extracted from the figure using Origin Pro's digitizer tool. Figure A1 shows the figure as presented in the original study. The data can be further consulted in Appendix B sheet 2

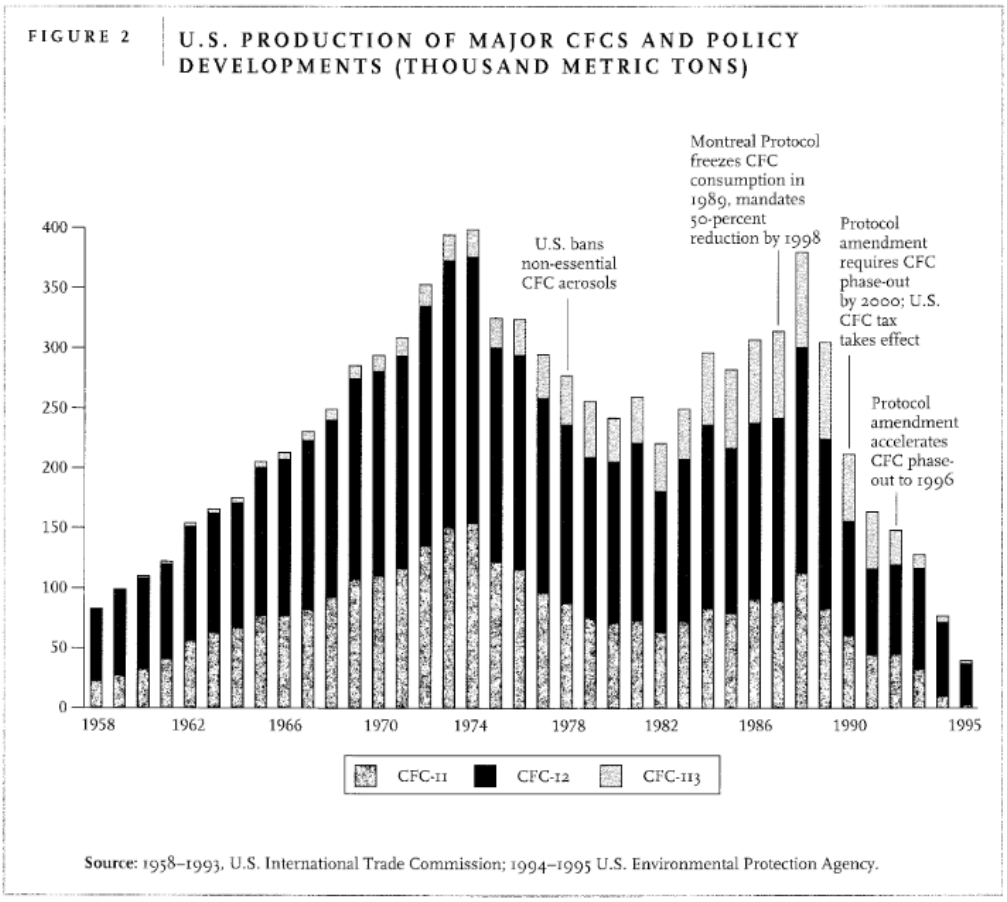

Figure A1 – Data for major CFC production and Policy developments in the U.S. Source: Cook et al. (1996)

1.2.3. Society

Data for the social sphere was gathered from the United Nations Environment Programme Data Centre. Data for CFC consumption in the USA was selected using the UNEP website filters. As per the UNEP's definition, consumption is defined as the sum of production and imports, minus exports. While this is not ideal data to represent the Social sphere, it is considered a proxy for Table A3 shows the data extracted from the website in tabular format. An important consideration is that data for the years 1987 and 1988 is missing from the source. The data can be further consulted in Appendix B sheet 3.

Table A3 – CFC consumption in the USA between 1986 and 2023 in ODP tonnes. Source: UNEP
**Data not available from source*

Year	**Chlorofluorocarbons (CFCs)**
1986	305,963.60
1987	N.A*
1988	N.A*
1989	317,543.00
1990	198,308.20
1991	174,261.80
1992	144,855.80
1993	111,458.80

1994	72,534.40
1995	35,529.60
1996	1,331.00
1997	745.70
1998	2,709.20
1999	2,903.80
2000	2,614.60
2001	2,806.80
2002	1,357.20
2003	1,605.20
2004	1,153.60
2005	1,496.60
2006	752.70
2007	-68.60
2008	-569.20
2009	-223.60
2010	-661.80
2011	-1,374.60
2012	-1,050.30
2013	-498.60
2014	-459.90
2015	-328.20
2016	-353.90
2017	-418.50
2018	-292.50
2019	-647.80
2020	-300.10
2021	-161.60
2022	-186.00
2023	N.A*

1.2.4. Media

For the media sphere, a search of the key words “ozone layer” was performed on the ProQuest databases. Figure A2 shows the data processing flow diagram for this sphere. Data was filtered to include Newspaper and Magazine articles containing the keywords “ozone layer” in the USA within the selected period. For the study, the articles were graphed as a percentage of the total publications within the Historical Newspapers, Newspapers and Magazines databases for each specific year. This data can be consulted in Appendix B sheet 4.

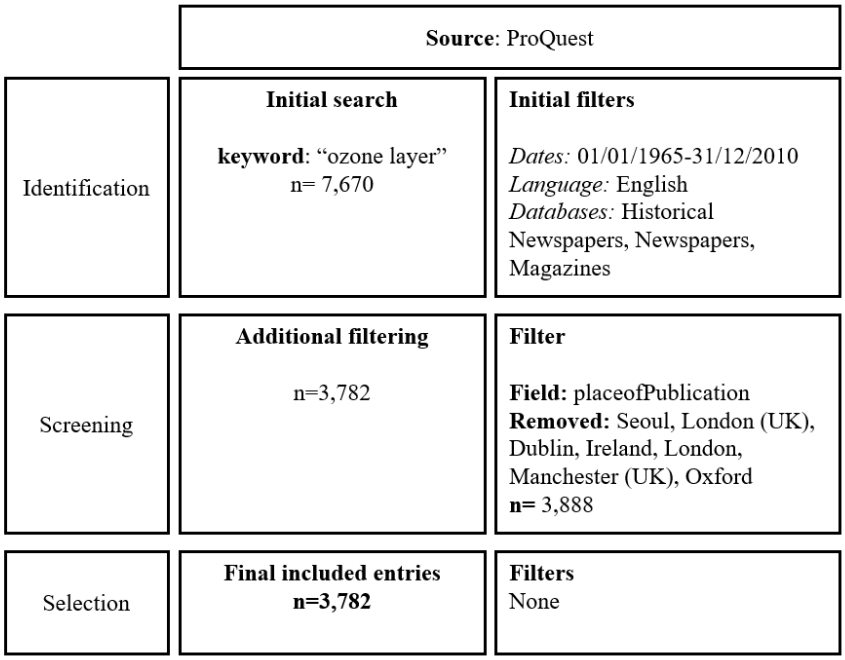

Figure A2 – Data processing flow diagram for Media sphere, showing identification, screening and selection of articles

1.2.5. Science

The Web of Science Core Collection database was used to identify scientific publications for the science sphere. The keywords "ozone layer" were used to search in all fields, and further filters were applied to obtain papers within the US and selected period. Figure A3 shows the data processing flow diagram for the papers obtained. Additionally, the total number of publications per year within the US were consulted to visualise the data as a percentage of total publications. This data can be consulted in Appendix B sheets 5.1, 5.2 & 5.3.

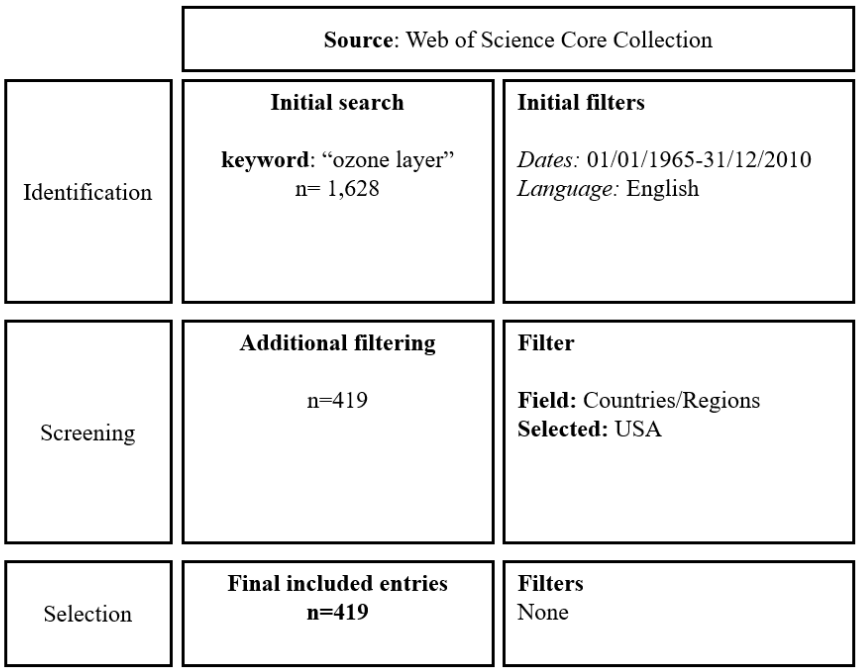

Figure A3 – Data processing flow diagram for Science sphere, showing identification, screening and selection of publications

1.2.6. Culture

Data for the Culture sphere was gathered from the English-Corpora.org website, which hosts a wide range of corpus data useful for linguistic analysis. Two databases were selected: The TV Corpus (Davies, 2019) and The Movie corpus (Davies, 2019). Figure A4 shows the data processing flow diagram for Culture data. Additional data can be consulted in Appendix B sheet 6.1 & 6.2.

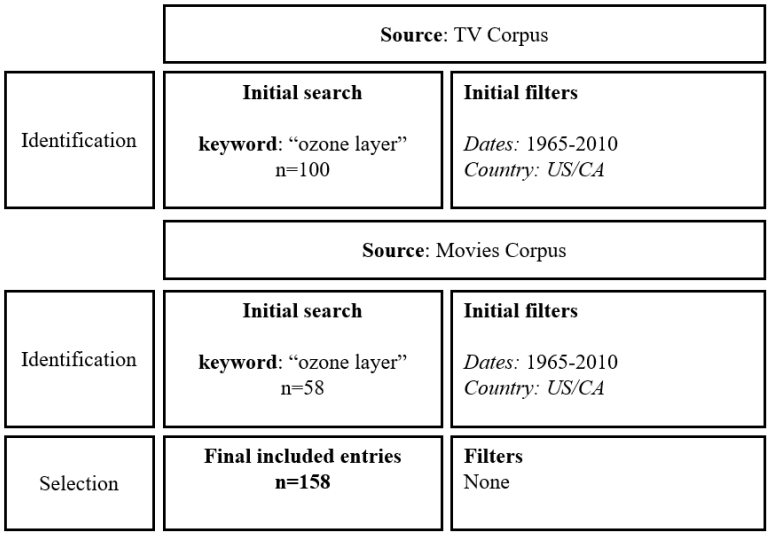

Figure A4– Data processing flow diagram for Culture sphere, showing identification, screening and selection of publications

1.2.7. The "ozone hole" narrative

For the "ozone hole" narrative analysis, the keywords "ozone hole" or "hole in the ozone" were added to the Media and Science spheres. The Culture sphere was omitted from this study due to a lack of data. Figure A5 shows the data processing flow diagram for the Media sphere, while Figure A6 shows the same diagram for the Science sphere. After the new keyword data was gathered, a cross-reference search was done to account for entries that appeared in more than one keyword search by searching for duplicate titles. Once duplicates were tagged as "both", the data was used for the analysis. The database can be found in Appendix B sheets 9.1-9.8.

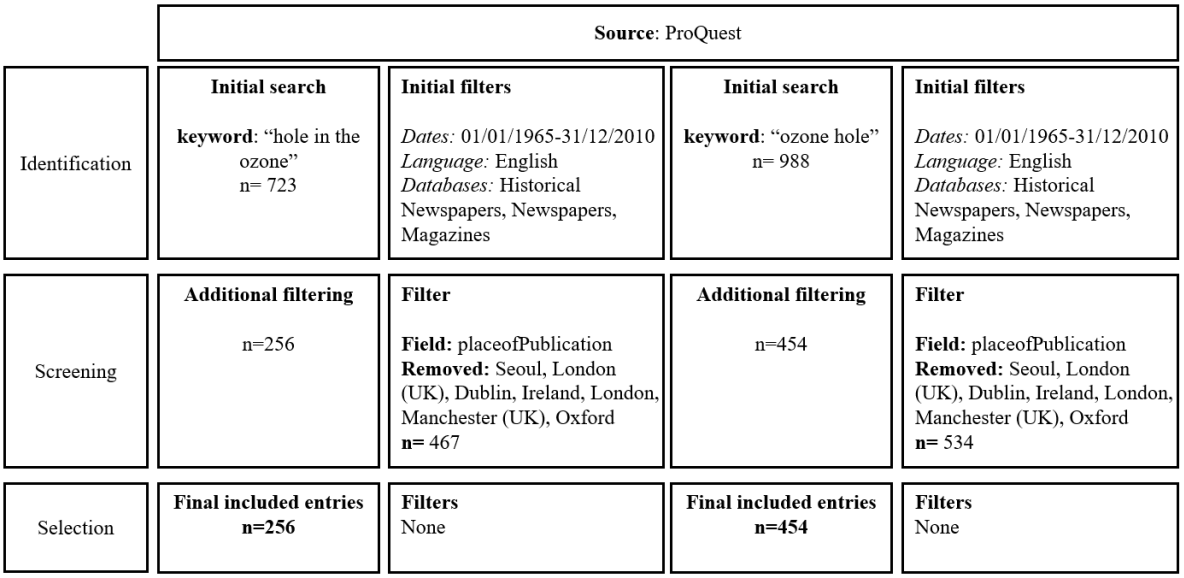

Figure A5– Data processing flow diagram for Media sphere for keywords "hole in the ozone" and "ozone hole"

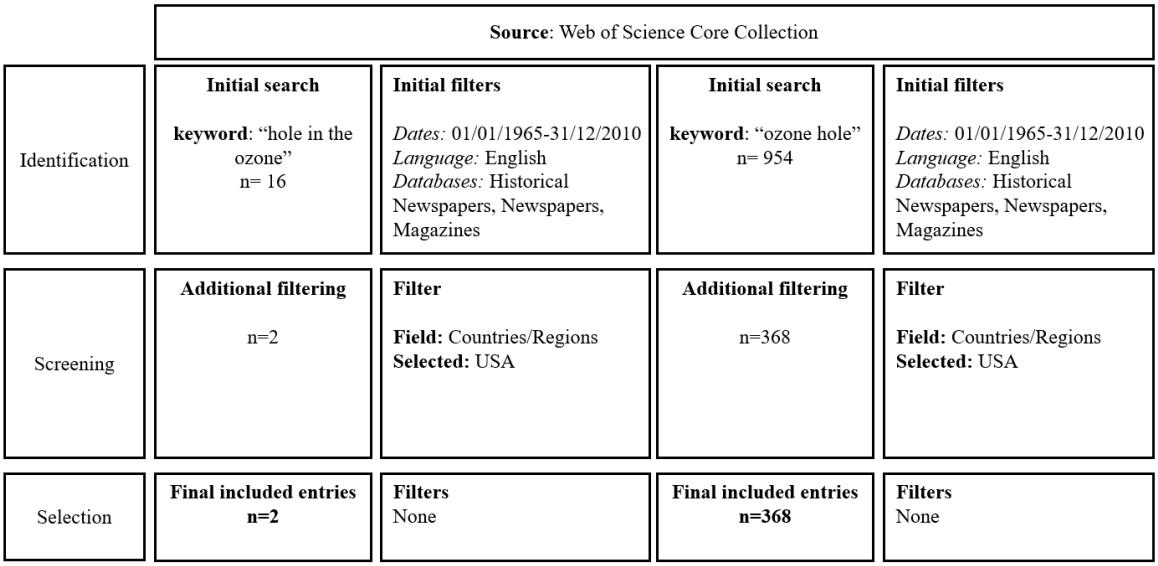

Figure A6– Data processing flow diagram for Science sphere for keywords "hole in the ozone" and "ozone hole"

1.2.8. The Media narratives

For the Media narratives section, different keywords were searched for in combination with the keyword "ozone layer" within the ProQuest database. Table A4 shows the keywords used to search to represent each sphere. In some cases, no full text search was preferred due to the amount of noise in the data. The database containing the results can be consulted in Appendix B sheets 10.1-10.6

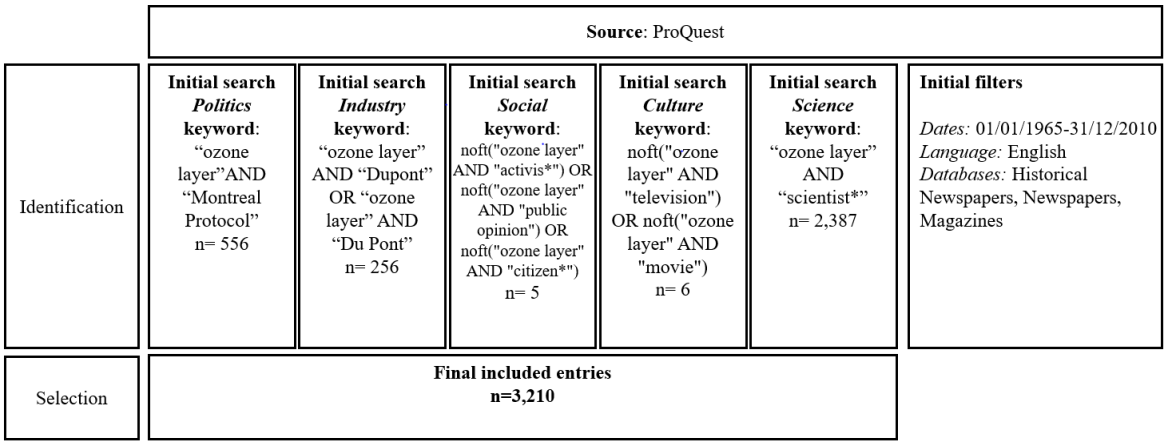

Figure A7– Data processing flow diagram for Media sphere inter-sphere analysis.

2. Additional Analyses

2.1. The media narratives

The Media sphere can illustrate the narratives that were being broadcast to the general public by newspapers and magazines at the time. By searching for specific keywords within articles related to the ozone layer, we can observe the interconnections between the spheres and gain an understanding of the most important actors for communicating the issue. Figure A8 shows the mentions of selected keywords representing the Politics, Industry, Social, Science and Culture spheres within the Media. It can be observed that the discourse was dominated by mentions of scientists throughout the whole timeframe. Mentions of DuPont as the main industry actor reach a first peak in 1975, but quickly die down between 1976 and 1986. In 1986, it again becomes prevalent, but is overtaken by reports on the Montreal Protocol. Another important observation is the fact that mentions of "activists" representing the Social sphere only return five results in the whole timeframe, showing the virtually non-existent discourse surrounding activism during the ozone layer. The cultural sphere is similarly under-represented and articles mentioning TV or movies within the context of the ozone layer are mainly seen after 2005, well after the general discourse had passed its peak.

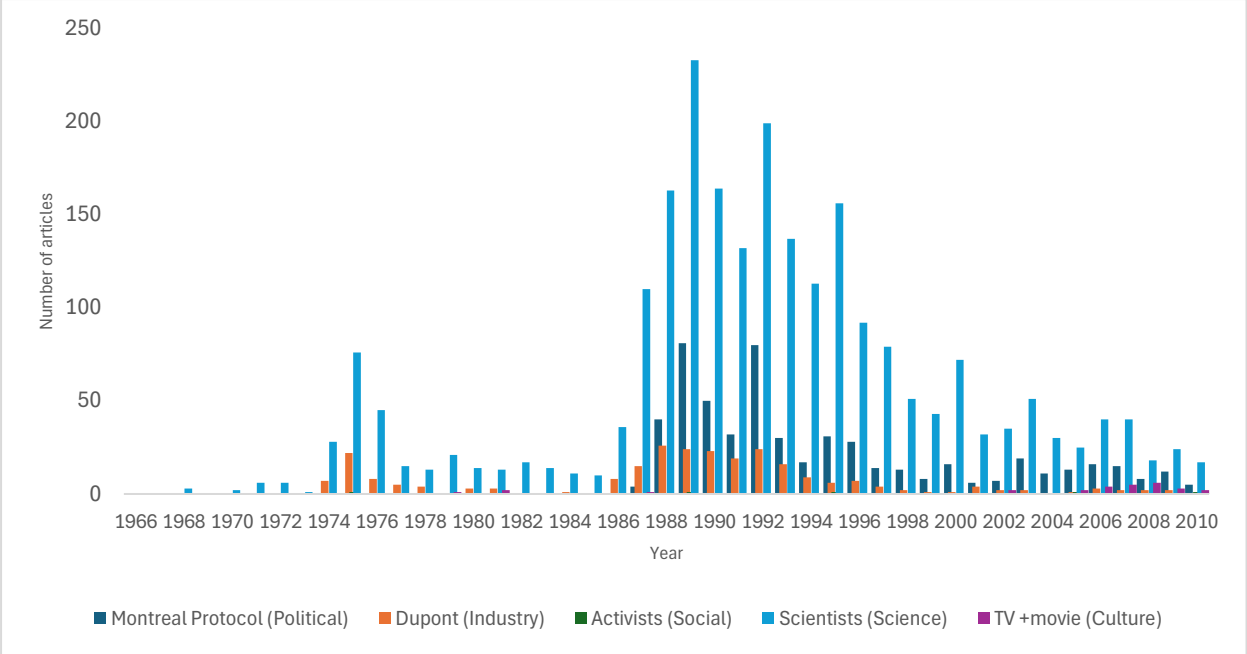

Figure A8 – Appearances of the terms "Montreal Protocol", "DuPont", "Activists", "Scientists", "TV + movie" in combination with "ozone layer" within the Media database