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From causes to consequences, from chat to crisis. The different climate changes of science and Wikipedia

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ABSTRACT

Understanding how society reacts to climate change means understanding how different societal subsystems approach the challenge. With the help of a heuristic of systems theory two subsystems of society – science and mass media – are compared with respect to communications about climate change over the last 20 years. With text mining methods metadata of documents from two databases – OpenAlex and Wikipedia – are generated, analyzed, and visualized. We find substantial differences as well as similarities in the social, factual, and temporal dimensions. While Wikipedia shows a much greater variety of concrete organizations, social movements, media outlets, and persons, science is more concerned with abstract interrelations of human action. In both systems, there is a shift in attention from describing the very phenomenon to questioning how to deal with this fact. This demonstrates for science a discursive shift from causes to consequences and for mass media a shift from chat to crisis. Science shows an ongoing growth process, while the attention of mass media appears cyclical.

1. Introduction

Climate change is a "multifarious" phenomenon (Hulme, 2022). Its complexity meets the complexity of world society. Understanding climate change therefore entails understanding the multifariousness of climate change entangled with the multifarious dealings of the different parts of world society. To approach this challenge in the following, we use a heuristic based on sociological systems theory to make sense of the societal ways of dealing with climate change. We will test the plausibility of this by developing a framework for a comparison of how different areas of society conceptualize climate change. For demonstration purposes, we apply the framework using text mining methods on scientific and mass medial discourses about climate change. This also provides profound insight into the history of climate change conceptualization of the last 20 years.[7] The underlying premise is that the subsystems of society develop their very own conception of climate change, subject to their own constraints. Therefore, none of these conceptions can account for every aspect of the multifarious climate change by itself. Because there is no center of world society that could react to the threat, we can only observe the effects of the interplay of the mutually

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observing subsystems.

While the theoretical question is how a functionally differentiated society (*funktional differenzierte Gesellschaft*)[8] handles a threat like climate change, the empirical question is what themes or aspects get the most attention from the various subsystems. Attention is measured on the basis of the count of communications found in a system represented here by two corpora. To approach these links, we use text mining methods to get detailed insights into two function systems (*Funktionssysteme*) – science and mass media – and how they conceptualize climate change over a period of twenty years (compare for the basic assumptions: Azzam and Beckmann, 2022). To describe the constructing of and dealing with climate change in the systems, we focus on documents that contain system-internal communications and analyze them quantitatively with regard to their metadata and contents. To access the communications, we use two digital databases: OpenAlex for scientific works and Wikipedia for encyclopedic article pages. The internal structure of these databases determines the compilation of our corpora: all climate change-related Wikipedia pages and scientific works collected on OpenAlex between 2001 and 2021. In the comparison of the two corpora, we analyze synchronously and diachronously the social, factual, and temporal dimensions of the two different climate change discourses.

The insights of these analyses give a profound comparative overview of the variety and development of the knowledge of two essential subsystems. While to our knowledge this task has not been addressed in previous studies, we are also able to address several other open questions: For social scientific climate change research (Weingart et al., 2000; Engels, 2019), climate change is a challenge to society, and understanding the interplay of different areas and aspects is crucial. This is particularly important because the simple imagination of a scientific consensus leads to political action that solves the climate problem appears highly unrealistic (Sarewitz, 2011). Despite this, the development of climate change research is an interesting case for quantitative science studies (as well as their comparison to other areas: Wyatt et al., 2016). The need for a comparison of different corpora is also stated in natural language processing research in climate change (Stede and Patz, 2021). The theoretical foundation answers to some reservations towards computational methods in the field (Schäfer and Hase, 2023). For Wikipedia-studies, the long-term investigation of attention to climate change is of particular interest as a case study (Fichman and Hara, 2014). And lastly, empirical accounts with systems theory as their backbone remain a question under discussion, because there is no tight coupling of the theory to a method, and text mining methods are comparatively new (John et al., 2010).

2. Climate change as a problem of world society

We use as a heuristic the theory of society by Niklas Luhmann (2012, 2013) and his elaboration on environmental hazards (1989). Luhmann's system theory provides a highly abstract vocabulary that allows us to analyze different societal communications like scientific reasoning and edit wars with the same vocabulary: a second-order observation, that observes communications participants as first-order observers. To get Luhmann's theory right, one abstract but highly important point has to be made as a precursor to what follows: social systems only consist of communications, not of people.[9] The foremost problem each system faces in order to fulfil its function is overwhelmingly high complexity. To create meaning for the system the signal has to be separated from the noise. The necessary reduction of complexity is done by communicating in a specific way. Communicating, the system distinguishes itself from its even more complex environment. In other words, by fulfilling its tasks the system at the same time recreates itself as a system. Thus, social systems can be thought of as information processing systems using interconnected communication operations. To study them, the way how information is processed has to be taken into focus (Luhmann, 1995; see also Azzam and Beckmann, 2022: 4 f.).

World society is the "horizon" of all global communication (Luhmann, 1997). We compare communications about climate change in mass media and science as part of the same world society. On a structural level, sociological systems theory describes the world society as functionally differentiated (Luhmann, 2012). In an evolutionary process, the changes in society are led by differentiation to an ensemble of function systems like polity, economics, science, law, or art, which autonomously fulfill foundational functions of society. Although this diversity increases the efficiency and performance of the function systems, it entails different worldviews and a lack of a center that could react to threats that endanger society on a global level (Luhmann, 1989). More precisely, each function system develops its own perception of climate change and its risks in terms of its intrinsic logic.

In order to reduce social complexity, systems have historically developed a number of elaborated procedural and structural in-

Table 1
Core concepts of the theoretical heuristic.

Notion	Definition	Science	Mass Media
Function	Performance for society	Providing sound knowledge, techniques/ technologies	Providing actual pictures of society, orientation for everyday life
Symbolically generalized medium	Medium in which systemic communication flows	Truth	Newness
Code	Fundamental orientation for further communications	True/false	New/known
Programs	Rules how to attribute the sides of the code to communications	Theories and methods	News, entertainment, advertisement, encyclopedic information
Temporal structure	Temporal frames for communication flow like rhythms and durations	Slow, cumulative	Fast, cyclical
Roles	Set of expected behaviors of persons communicating in the system	Scientists	Journalists, Wikipedia users
Communicates	Documents that contain system-internal communications	Works collected in OpenAlex	Wikipedia pages

[8] The language of systems theory is not always easy to understand and difficult to translate. When appropriate we give the German words and quotation marks to remind that some concepts in systems theory have a slightly different meaning than in other theories. As recommended by the reviewers, we summarize some concepts also in Table 1.

[9] "But who communicates?" one may ask. Luhmann's conceptual answer is that people's thought processes, also being systems, are coupled to the communication systems. Still, the communication systems develop a dynamic of their own. Empirically, this can be seen by remarkable structural stability of social systems even when "key personnel" changes.

struments like communication "codes", "symbolically generalized media" of communication, "programs", roles, and hierarchies (Table 1). In the context of this paper, symbolically generalized media of communication like "truth", "love", or "power" are especially relevant. By using these, subsystems differentiate themselves from their environment. Further communication is oriented on this media as a frame of reference of the system which provides a simple "code" to channel the flow of communication (in science: true/false, in mass media: new/known). "Programs" (theories or Wikipedia guidelines) specify rules in which way communications are to be put on which side of the code. In such ways the communication organizes itself.

From a methodological perspective, we expose this to empirical investigation by identifying communications as belonging to specific function systems, so that their aggregation reveals signs of the working of the system. The methodological point of view from systems theory for the study of science and mass media is, in terms of systems observing observers on their own, a third-order observation. Less abstractly speaking, communications using a language of "truth", for example, can be identified as belonging to the subsystem of science. The development of research problems and consecutive attempts of solving them are central to this discourse. As a communication, a scientific work proposes scientific "truth" to be tested by the scientific community. As a communication, a Wikipedia page summarizes the recent state of the art regarding the page's subject to be cross-checked by every Wikipedia user to correct. This does not mean, that in science "truth" is a quality criterion, e.g. for the selection of publications. Instead, Luhmann's theory points out that social systems have created certain communication patterns, that enable them to filter relevant information of high complexity and process them according to their intrinsic logic that organizes further communication on the positive side but reflects its medium on the negative side (Luhmann, 1992: 200–204). By logic, we mean its own vocabulary and conceptualization, but also its own time-horizon. Whereas scientific communications can have very long time-horizons (think of space missions yielding results after 30 years), the mass media operate under much tighter time constraints. The interest of the public for certain topics ebbs and flows often in weeks or months rather than years or decades.

The theoretical framework discussed in this paper forms the basis for the empirical analysis in the following chapters. Its vantage point is that of a challenge to a system. We take as our use case the situation in which the entire world society has been challenged by one severe problem in the physical (not social!) environment: climate change (Luhmann, 1989). The world society can only react to this problem in its differentiated form. The question arising from such a challenge is how different function systems of society construct this reality by their specific communicative operations. In particular, we are addressing the question whether we can identify the expected common patterns of language use in each subsystem? Furthermore, questions to be addressed are: What kind of solutions do they put forward on the basis of their perception of the situation? In which ways do they observe each other in taking up communications from other function systems and working them according to their own logic? An important consideration in this context is that the two corpora remain fundamentally different, so not everything possible in one is reasonable in the other. Thus, for the analysis we focus on the three dimensions of meaning systems theory is focused on: social, factual, and temporal. We extract communications on the topic under study from the documents, identify the authors of the communications, map the topics of the communications and observe the developments of these topics as indicators of the situation enfolding over time. A further challenge arising in this analysis is the generation of comprehensible results and interpretations on the level of function systems.

Problems in each of the subsystems will be reformulated according to their specific construction of reality, materialized by the use of a system specific vocabulary and language. The challenge of comparing such differences is not to be underestimated. Text mining methods offer a unique possibility to unlock the construction of social reality of a system, because they allow the identification of communication structures in vast amounts of text data (Azzam and Beckmann, 2022: 6). While discourse analytic works are sensitive to differences inside systemic communications (Grundmann and Krishnamurthy, 2010; Tereick, 2016), we aim for an even more abstract level of differences between systemic communications. Empirically, this is elaborated to collect and analyze the semantics worth preserving (*bewahrenswerte Semantik*). This is classically used to show differences in historical semantics from pre-modern hierarchical and modern functionally differentiated societies (Ahlers et al., 2021). We use the analysis framework to analyze recent texts in a distant reading approach (Stulpe and Lemke, 2016), which entails focusing not on the contents of single documents (close reading), but by aggregating features of texts. The combination with text mining procedures allows the extraction of semantic features from an amount of data whose manual processing and systematic close reading is beyond human capacity. To operationalize the different function systems, we construct corpora collecting similar documents for a set span of time. This collection of corpora is the foundation for a quantitative account of the sociology of knowledge and the analysis of semantics at a given point of time.

In this paper, we compare the discourses on climate change in the two functional subsystems of science and mass media. By doing so, we can, firstly demonstrate the fruitfulness of our data driven methodology. Secondly, we shed light on a central arena of social communications on climate change: the system of science produces the core knowledge on climate change and its causes; the system of the mass media takes up this abstract knowledge and distributes a transformed state of this knowledge to larger audiences. With these rather illustrative use cases we want to examine whether the main assumptions of the theory of social communication systems can be partially or fully confirmed.

This perspective of theory of society pinpoints the importance of function systems in understanding the societal handling of climate change (Grundmann and Rödder, 2019), which is crucial in planning adaptation to or mitigation of climate change consequences as well. The function systems generate capacities for handling the challenge of climate change, for example, in parallel to the exponential growth of scientific literature (s. 3.2), global reporting (Broadbent et al., 2016), the rise of climate change litigations (Kahl and Weller, 2021), or the establishment of the global policy field (Gupta, 2016). But these communications only handle the problems of the respective systems in more and more detail – thus not necessarily tackling the problems of world society. The scientific problem of climate change is a question of "truth", whereas the mass medial problem is one of "actuality" and of connecting with the audience. The function systems are mutually observant of the other function systems, because the developments in one has consequences in the other (e.g., political changes may lead to different opportunities of securing research funding, while scientific proof of climate change may make the topic crucial for voters). The conceptions of climate change in the different systems are resonating with each other, but develop autonomously as Weingart et al. (2000) describe. For example, the consensus about the anthropogenic causes of climate change in science is not to be shared in polity. It cannot determine political decisions because collectively binding decisions are found in the means of "power", not of "truth". But resonances do change as well, constant Cassandra calls are receiving less and less attention in other systems and may even damage the credibility of the caller (Weingart et al., 2000). Societal reactions to such constellations can be moralization and heightened expectations which are specifically addressed to the political system and in turn pose a challenge to processes of achieving political consensus. The laid out heuristic therefore helps to understand why we see spirals of moral demands on politics and disenchantments while the challenge is simultaneously addressed in a myriad of actions by different actors despite of which we can only hope that the effects of climate change do not turn out unpredictably and uncontrollably. It also casts doubt on the simple idea that mass media delivering the right knowledge to people in need of education has the capacity of putting an

end to the political struggle.

3. Climate change in OpenAlex

3.1. OpenAlex and science

As a function system, science provides sound and true knowledge for society (Luhmann, 1992). Therefore, the generalized communication medium of "truth" is the foundation of scientific communication. The attribution of "true" or "false" to scientific findings obeys to the scientific community and the different "programs" of theories and methods. There is no central hierarchy but a heterarchy in science, which means that prestige is collected in subsystems of science (disciplines), but an expert in one subsystem is not often one in another. The temporal structure of science is slow, correctness and comprehensiveness are epistemic norms that are deemed to be more important than fast results. The flow of communication is directed towards identifying "truth", which means it would end, if all theoretical puzzles were solved. New knowledge is usually produced in a cumulative manner and over longer periods of time.

Climate change is a veritable and, by now, established subject of science. The literature in the field is overwhelming as our analyses below are able to show (compare the history and sociology of climate research: Weart, 2008; Hulme, 2022; the state of climate change research is also found in the recent IPCC report). In a bibliographic account, Haunschild et al. (2016) show the growth of scientific literature on climate change since the 1980 s. They base their findings on about 220,000 articles listed in the Web of Science database. Exponential growth starts in 2005 and while the whole database doubles its entries, the climate change part expands tenfold. Especially the IPCC Reports are analyzed as being dominated by physics and economics (Bjurström and Polk, 2011a). As disciplinary clusters, we find the natural sciences, medicine and the social sciences somewhat differentiated from each other with only few interdisciplinary fields such as geography between them (Bjurström and Polk, 2011b).

As the successor of Microsoft Academic Graph (MAG; Sinha et al., 2015), OpenAlex is an online database collecting about 170 million entries of scientific works (Priem et al., 2022). Visser et al. (2021) show in a comparison of different bibliographic databases, that MAG outdoes Web of Science and Scopus especially for works beyond journals (books and proceedings). In a comparison of MAG and OpenAlex, Scheidsteger and Haunschild (2022) asses OpenAlex as a sound base for bibliographic studies, yet cautioning at the same time that all databases have their flaws and limitations. But more comparison and evaluation are needed for OpenAlex. It is, thus, for example not entirely clear, to what extent the data basis changes over time and how ongoing updates will change the results presented below. Following the "fields of study" of MAG the concepts of OpenAlex works are tagged with an algorithm that uses as key components work title, venue title, abstract, and document type (OpenAlex, 2022). There are about 65,000 different concepts organized in a hierarchical graph and all are connected to a Wikidata concept. The concept "climate change" is found on the third of seven levels in the concept graph. Because of the automatic tagging of higher order hierarchies, these have a greater likelihood to be tagged. However, a score is given from OpenAlex for all concepts, we use the recommended 0.3 threshold for all concepts in the analyses.

3.2. Tremendous growth – structural trends in climate change research[10]

Climate change sees tremendous growth as a topic of science: Between 2001 and 2021 we find 166,856,571 entries in OpenAlex, 409,337 of these contain the concept "climate change" (0.25%). We find a nearly tenfold increase in works from 4,145 in 2001 to 41,093 in 2021 and a quadrupling of this proportion from 0.11 (2001) to 0.43 (2021). Fig. 1 displays the different developments of the climate change related works and their proportion of all works with indexed scales. Both see strong increases between 2006 and 2009 and again from 2019 to 2021, but the growth of the works is greater than the proportion.

As the number of works increases, so do the number of persons involved as well as the interrelation of the research. In 2001 there are 2.6 authors per work. This figure grows to 4.2 in 2021. There are not only more people producing more work on the topic, but more people are also taking notice of this work: The average number of references referring to an article in 2001 was 10.8. In 2021, this increases to 29.5. The development of these numbers over time are displayed in Fig. 2 again with indexed scales. The increases of the authors and references per work see a step backwards in the phase between 2006 and 2009, where the number of works strongly increase. Afterwards there is a steady growth and the second intense growth phase (2019–2021) is matched.

Overall the quantitative analysis of structural features of the scientific discourse predominantly reveals growth in all dimensions. Climate change can thus be shown to have evolved into an important and growing field of the scientific knowledge production of society.

3.3. From causes to consequences – trends in scientific research topics

To cover the topics of the scientific research found in the works collected in OpenAlex we further investigate the concept tags that are used in OpenAlex. As described above, these are assigned to all works through a machine learning algorithm. On average, each work is tagged with labels for about 9 concepts. This is relatively stable over the years, but sees a small increase in the last two years (compare Fig. 2).

Each work in our collection has the tagged label "climate change", followed by 61% (average over the 21 years) of all works labeled "environmental science", "geography" (38%), "climatology" (37%), and "environmental resource management" (21%). Ten other concepts show a proportion of over 10%. Over time, we see a relative decline of "environmental science", "climatology", "physical geology", and "geology" in favor of "geography", "environmental resource management", and concepts with lower frequency. This reflects a differentiation in the concepts that we also find looking at the developments of different concepts that occur each year: These more than triple from 2,705 in 2001 to 9,051 in 2021 in a steady way.

In Table 2, we show the 20 concepts with the highest proportion per year. This allows getting a view of how the attention and the focus of science changes over time in more detail. Firstly, we can stress a very stable set of relevant topics regarding climate change. Of the top twenty topics in 2001, 15 are in this set in each year until 2021.

But there are some changes in the tableau and the ranking as well. To describe the changes, we divide the timespan into three phases of seven years each and break down the concepts into three clusters. The first phase (2001–2007) sees a majority of earth- and climate-science concepts (white shape) in the top 20. Concepts like "climatology", "atmospheric science", "oceanography", or "precipitation" make up half of all ranks in this phase; an even higher proportion is found in the top 10 (58%). But there is also a shift predictable. Most of these concepts lose ranks over the years. In dark grey, we find concepts of the social ("environmental resource management", "political science") as well as agricultural sciences ("hydrology (agriculture)"). These make up about a third of all ranks, 20% in the top 10, and the concepts see an ascent in ranks over the years. The last cluster (light grey) contains topics that are more interdisciplinary and more inclined towards human interaction with nature-oriented sciences in connection to climate change: "environmental science", "geography", and "ecology". These concepts make up 15% of all ranks, 23% of the top 10, and see a slight upwards trend.

[10] We used the OpenAlex API at the 4.5.23, to download the entries of every work with the concept "climate change" and the recommended threshold on the concept score. We use quotation marks whenever we cite words from the corpora to demonstrate the difference in the notions.

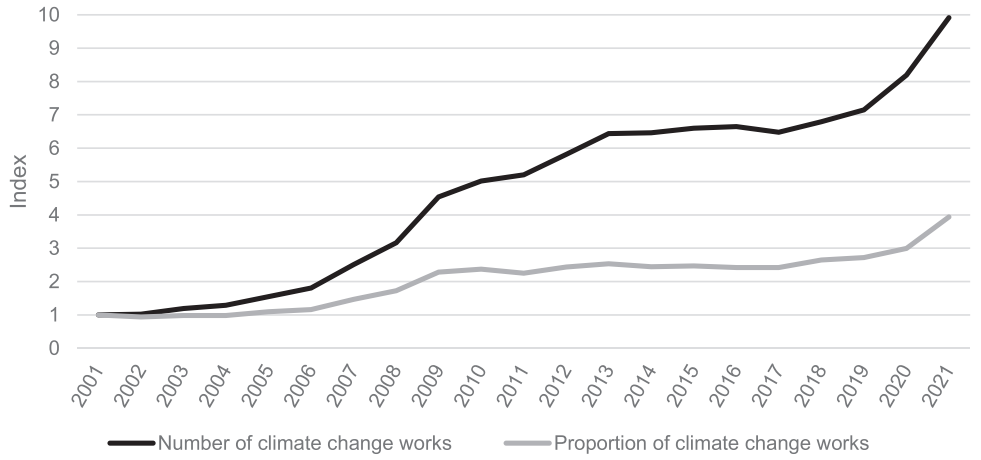

Fig. 1. *Climate change works and their proportion of all works in OpenAlex per year (index: 2001 =1).*

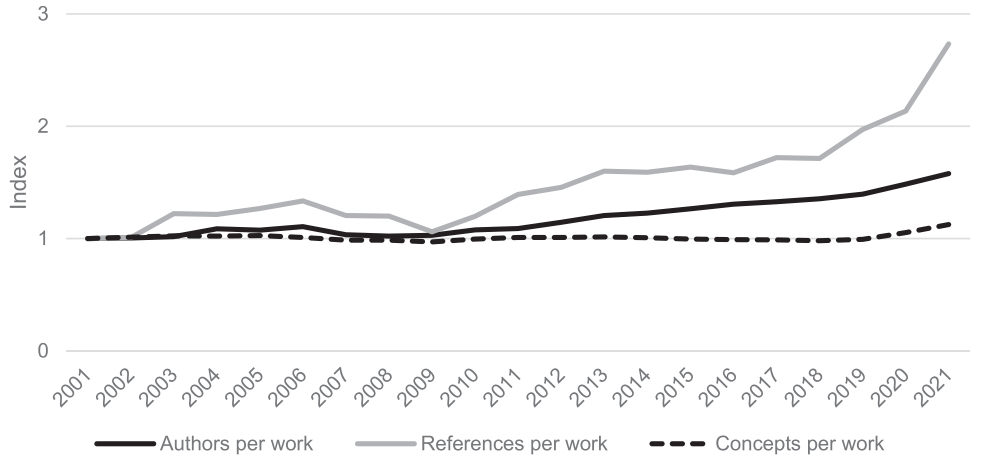

Fig. 2. Authors, references, and concepts of OpenAlex per work per year (index: 2001 =1).

Table 2
The 20 most common concepts in OpenAlex per year (white shading: athmosperic and earth sciences; light grey: ecological sciences; dark grey: social sciences).

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science	Environmental science
Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography	Geography
Geography	Geography	Geography	Geography	Geography	Geography	Geography	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology	Climatology
Physical geography	Physical geography	Physical geography	Physical geography	Physical geography	Physical geography	Physical geography	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management
Geology	Geology	Geology	Geology	Geology	Geology	Environmental resource management	Physical geography	Natural resource economics	Natural resource economics	Natural resource economics	Natural resource economics	Physical geography	Political science	Political science	Political science	Political science	Political science	Political science	Business	Ecology
Global warming	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Environmental resource management	Global warming	Global warming	Political science	Political science	Business	Political science	Political science	Physical geography	Physical geography	Physical geography	Physical geography	Environmental planning	Natural resource economics	Political science	Business
Environmental resource management	Atmospheric sciences	Global warming	Global warming	Global warming	Global warming	Natural resource economics	Natural resource economics	Business	Business	Political science	Physical geography	Natural resource economics	Natural resource economics	Natural resource economics	Natural resource economics	Business	Natural resource economics	Business	Ecology	Physical geography
Atmospheric sciences	Global warming	Atmospheric sciences	Atmospheric sciences	Atmospheric sciences	Natural resource economics	Geology	Political science	Physical geography	Physical geography	Physical geography	Business	Business	Environmental planning	Business	Environmental planning	Natural resource economics	Physical geography	Ecology	Physical geography	Political science
Meteorology	Meteorology	Meteorology	Meteorology	Natural resource economics	Atmospheric sciences	Political science	Business	Environmental planning	Global warming	Environmental planning	Environmental planning	Environmental planning	Business	Environmental planning	Business	Environmental planning	Business	Physical geography	Natural resource economics	Natural resource economics
Natural resource economics	Natural resource economics	Oceanography	Ecology	Ecology	Meteorology	Business	Geology	Global warming	Environmental planning	Global warming	Global warming	Global warming	Ecology	Ecology	Ecology	Ecology	Ecology	Environmental planning	Environmental planning	Global warming
Oceanography	Climate model	Natural resource economics	Oceanography	Meteorology	Climate model	Ecology	Ecology	Geology	Geology	Ecology	Ecology	Ecology	Global warming	Global warming	Global warming	Global warming	Global warming	Global warming	Global warming	Environmental planning
Ecology	Oceanography	Climate model	Natural resource economics	Climate model	Ecology	Meteorology	Environmental planning	Ecology	Ecology	Geology	Geology	Geology	Geology	Geology	Geology	Geology	Geology	Meteorology	Atmospheric sciences	Precipitation
Climate model	Ecology	Ecology	Climate model	Oceanography	Oceanography	Atmospheric sciences	Meteorology	Meteorology	Meteorology	Meteorology	Atmospheric sciences	Atmospheric sciences	Meteorology	Meteorology	Meteorology	Meteorology	Meteorology	Geology	Climate model	Atmospheric sciences
Political science	Greenhouse gas	Greenhouse gas	Greenhouse gas	Precipitation	Political science	Oceanography	Atmospheric sciences	Atmospheric sciences	Greenhouse gas	Greenhouse gas	Meteorology	Climate model	Atmospheric sciences	Atmospheric sciences	Atmospheric sciences	Atmospheric sciences	Atmospheric sciences	Atmospheric sciences	Precipitation	Climate model
Greenhouse gas	Political science	Business	Political science	Greenhouse gas	Business	Environmental planning	Greenhouse gas	Greenhouse gas	Atmospheric sciences	Atmospheric sciences	Climate model	Meteorology	Climate model	Climate model	Climate model	Climate model	Climate model	Climate model	Meteorology	Agriculture
Business	Business	Precipitation	Business	Political science	Precipitation	Greenhouse gas	Economics	Economics	Economics	Economics	Precipitation	Precipitation	Adaptation (eye)	Oceanography	Oceanography	Oceanography	Oceanography	Precipitation	Geology	Greenhouse gas
Precipitation	Environmental planning	Environmental planning	Precipitation	Business	Greenhouse gas	Climate model	Oceanography	Oceanography	Climate model	Climate model	Greenhouse gas	Oceanography	Precipitation	Precipitation	Hydrology (agriculture)	Hydrology (agriculture)	Hydrology (agriculture)	Hydrology (agriculture)	Hydrology (agriculture)	Geology
Environmental planning	Precipitation	Political science	Economics	Environmental planning	Environmental planning	Economics	Climate model	Climate model	Precipitation	Precipitation	Oceanography	Greenhouse gas	Oceanography	Agriculture	Economics	Agriculture	Agriculture	Agriculture	Agriculture	Hydrology (agriculture)
Economics	Economics	Hydrology (agriculture)	Hydrology (agriculture)	Hydrology (agriculture)	Economics	Precipitation	Precipitation	Precipitation	Oceanography	Hydrology (agriculture)	Economics	Adaptation (eye)	Greenhouse gas	Adaptation (eye)	Adaptation (eye)	Precipitation	Adaptation (eye)	Oceanography	Oceanography	Ecosystem
Hydrology (agriculture)	Hydrology (agriculture)	Economics	Environmental planning	Economics	Hydrology (agriculture)	Hydrology (agriculture)	Hydrology (agriculture)	Adaptation (eye)	Hydrology (agriculture)	Oceanography	Hydrology (agriculture)	Hydrology (agriculture)	Agriculture	Hydrology (agriculture)	Agriculture	Adaptation (eye)	Precipitation	Adaptation (eye)	Greenhouse gas	Meteorology

The next phase (2008–2014) sees the tipping point from causes oriented earth- and climate-sciences towards consequences oriented sciences. There is a lot of changing of positions in this time of strong growth (see 3.2). The earth- and climate sciences topics take up the half of the possible ranks again, but only 30% feature in the top 10. At the opposite end of the scale are the social sciences. While there is a small decrease in the proportion of all ranks ("economics" leaving the top 20), most of the concepts rising and the top 10 containing now nearly half of the ranks with social science. The ecological cluster gets 17% of all ranks and 21% in the top 10.

In the last phase (2015–2021) the picture remains largely the same. Especially in the last and most recent years, ecological and agricultural concepts see an upwards trend. The social sciences nearly hold 36% of all ranks and 49% of the top 10 ranks. The earth and climate science concepts now hold 46% of all ranks and only 21% of the top 10. The ecological concepts take up 19% of all ranks and 30% of the top 10. In comparison to the first seven years the natural and social sciences switch their proportions in the top 10, while the ecological concepts see a smaller increase.

3.4. Disciplinary division of labor – co-occurrences of OpenAlex concepts 2001 and 2021

To broaden the view on the development of scientific subjects related to climate change, we generated two co-occurrence networks for 2001 and 2021 with the help of the software VosViewer (compare Figs. 3 and 4).[11] VosViewer is a visualization tool and we limit our analysis of the networks to this aspect. The bigger the label in the maps, the more often the concept occurs, the nearer the concepts are, the more often they co-occur as concepts of scientific works: that is why "climate change" is found in the middle, because it co-occurs with every other concept.

The scientific climate change discourse in 2001 (Fig. 3) reveals itself as a differentiation of climate change research in the disciplines dimension: social (right) and natural sciences (left) are two more separated than joint endeavors. And these two sides are also differentiated. On the left, natural science side located in the top area are concepts around "atmospheric science", which clusters works about gases, oceans, and meteorological models. These are somewhat differentiated from earth science (lower left). Here is research about "geology", "geological geography", and ice ("glacier", "ice sheet") combined with "ecology", and ecosystems ("steppe", "taiga"). For the social sciences there is a differentiation between "agriculture" and "environmental management" (lower right) against political mitigation ("law", "convention") (upper right).

For 2021, the map looks slightly different (Fig. 4): The core differentiation of natural (left) and social sciences (right) remains but the two poles see changes. On the natural science side there is now in the upper area a conglomeration of concepts from "biology", "ecology", and "biodiversity". In the lower area the earth and atmospheric science concepts are now much nearer to each other. In the upper right area, political mitigation and resource management along with agriculture are now closer together. In the lower area, there are concepts of health, psychology, and "data science". While the map is overall denser, we interpret the changes as an orientation of the scientific attention towards ecological and societal effects of climate change.

We summarize the observed scientific development as an indicator of a shift from causes to consequences of climate change.

4. Climate change in Wikipedia

4.1. Wikipedia and mass media

As a function system, the mass media provide an actual picture of the world for society (Luhmann, 2000). Events are going to be constructed into something tellable, some kind of narrative, and for that, it does not matter if the medial form is storytelling, a radio feature, or a messenger line. The foundational "code" of this communication system is "new" or already "known". We can see a certain family-similarity between science and mass media, because both systems highlight knowledge that is not already known. But in the end, we differentiate the communication flow as selecting towards "truth" or "novelty": a lie can be news but not truth. This provides an observation scheme for the analysis of how different mass media use different programs (most common: news, advertisement, entertainment) in structural couplings with different other function systems. But the "horizon" of mass medial communication is always focused on the everyday life of the recipients. What is new and what is already known is attributed in context of other mass media communications which is why new events occurring in the world are the foremost material for news media: they are new and thus not already reported somewhere else. The mass media communicate events that are crucial for other function systems. Wikipedia also covers knowledge and events of other systems and brings these into a unique common form which is not oriented towards special, but everyday life means. We borrow from the issue-attention cycle (Downs, 1972), the characterization of a cyclical temporal structure of mass media, which implies that we do not expect linear trends, but periodic effects and a certain rhythm. Every year provides the same opportunities for reporting of periodic events; a topic has a cyclical form of attention with latent, intense, and end phases. New knowledge is collected in a covering way, an encyclopedia such as Wikipedia covers all fields of knowledge with the same interest.

Wikipedia is a collaborative encyclopedia (O'Sullivan, 2011), a sociotechnical system (Niederer and van Dijck, 2010), and a mass medium (for an overview on Wikipedia research: Jullien, 2012). To understand Wikipedia as a mass medium unlocks the perspective on the communications on the same level as science communications as instantiated by OpenAlex. The empirical interpretation has to succeed in showing how the structural features of the mass media system (roles, "code", "program", and "temporal structure") organize the discourse on an aggregated level. While sometimes just as fast, Wikipedia is only partially a news medium and represents with its encyclopedic article pages a genre of its own (Markusson et al., 2016). The central differences are to be found in what is newsworthy and what is Wikipedia-worthy. Holloway et al. (2007) for instance show the semantic map of Wikipedia with an emphasis on companies, deaths of persons, games, vehicles, songs, law, and politics. The quality and grade of detail varies and sometimes the work is more bound to single users than communities as Gonçalves Da Costa and Cukierman (2019) show for the Portuguese Wikipedia page on climate change. And while Wikipedia is, in principle, open for contributions, this claim has to be restricted, because skills and resources are needed to contribute and some pages underly special protections that prohibit inexperienced or vandalizing users to contribute. Halavais and Lackaff (2008) stress that the focus of Wikipedia research lies in the question of comparable quality to other encyclopedias. They evaluate the thematic breadth for several areas and find clear differences: The natural sciences are better covered than social sciences or humanities (Halavais and Lackaff, 2008: 431). Other research evaluates Wikipedia in contrast to news media and asks how

[11] For visualizing the vast co-occurrence networks, we used VosViewer 1.6.19 (Van Eck and Waltman, 2010; http://www.vosviewer.com [last visited: 4.24.23]). This tool offers various parameters for influencing the layout of the network maps in order to enhance readability: One can restrict the number of nodes and links displayed, and the positioning of these elements is determined by an optimization algorithm, for which one can choose the number of iterations as well as two parameters, called "attraction" (the higher the tighter) and "repulsion" (the higher the sparser), which cause strongly interlinked nodes to be close to each other while keeping weakly interlinked nodes apart. Our choice of parameters aims at reaching good comparability of the various figures we show. For reproducibility, we report these parameter values in the footnotes of the figures. We increased the iterations of the layout algorithm by 10. VosViewer displays in its screenshots not all nodes, but a sample that is optimized to show as many as possible.

Fig. 3. OpenAlex concepts co-occurrence net 2001.[12]1

fast Wikipedia can react to events (Fetahu et al., 2015). In contrast, our endeavor asks about the development of climate change knowledge in Wikipedia and compares this with the scientific development. We also transcend from the question, to what extent these revisions are a mark

4.2. Two intense phases – *structural trends in Wikipedia pages on climate change*

Climate change is a growing topic in Wikipedia: Between 2001 and 2021 Wikipedia contains 6,312,236 pages, 2,960 of which belong to the

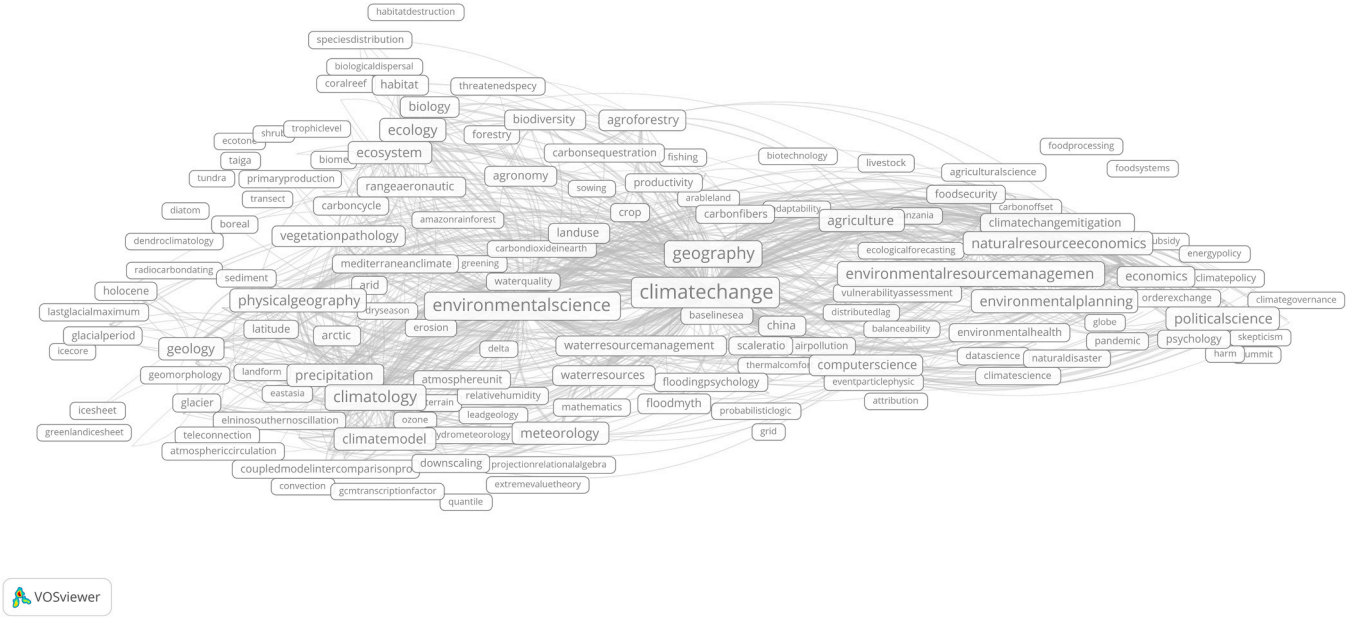

Fig. 4. OpenAlex concepts co-occurrence Net 2021.[13]1

for controversiality (Yasseri et al., 2013). Being agnostic when facing the question of what the revisions are, we just take them as a marker for attention by Wikipedia as a sociotechnical communication system. While the single revision may not be interesting or may even be misleading, the differences in revisions between the pages over one year show that some pages are more important in the system measured on Wikipedia's frame of relevance. And this very frame is based on the guidelines of Wikipedia (Oeberst et al., 2014). The categories of Wikipedia are also user generated. We use the category "climate change" to collect pages that deal with the general concept and meaning of climate change.

category "climate change" (0.04%).[14] On average there are 140 new climate change related Wikipedia pages per year. Edited climate change

[14] Each Wikipedia page is assigned to a category, which can have subcategories, which can be part of more than one category. Wikipedia categories have a hierarchical structure where a category can be a child/parent of another one (e.g., the category "climate change mitigation" is a child of the "climate change" category). Using the Wikimedia API, we fetch all English Wikipedia page revisions from 2001 to 2021 belonging to the climate change category and its children with depth three. We took the page count (content pages) for Wikipedia from Wikimedia Statistics (https://stats.wikimedia.org; last visit 11.15.22). We use the yearly average of the monthly provided counts.

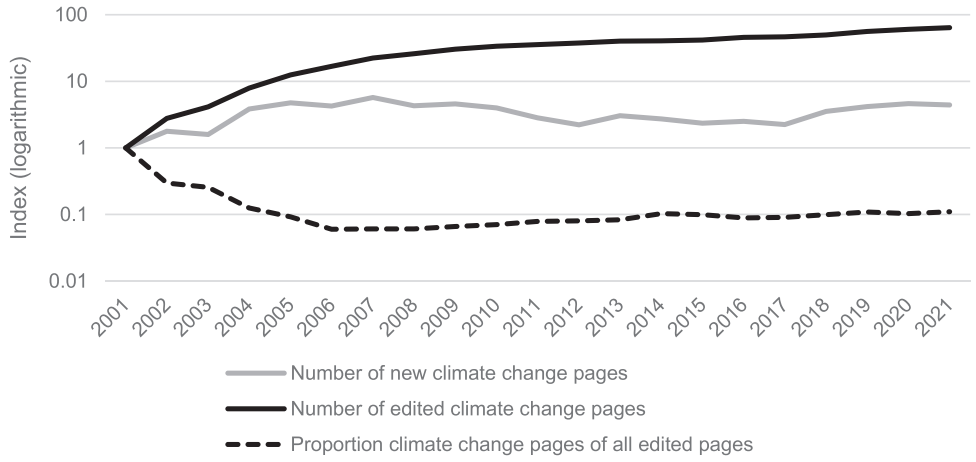

Fig. 5. New and edited climate change pages in Wikipedia and proportion of all edited pages per year (index: 1 =2001).

pages grow from 42 in 2001 to 2,686 in 2021. The proportion of these among all edited pages in Wikipedia (2001: 2,049; 2021: 1,189,200) is 0.3% on average. Fig. 5 shows the development of these three numbers on a logarithmically indexed scale. There are two phases that show greater attention of Wikipedia towards climate change: From 2004 to 2010 on average 189 new pages per year are created as compared to 176 in 2018 to 2021. For the edited pages, we find a steady growth: in 2011, 36 times as many pages are edited than 2001; in 2021 there are 64 times as many. But we also find two phases of greater attention: From 2004 to 2010 177 more pages are edited on average than the year before and from 2018 to 2021 these are 180, while the average amounts to 132 pages. The proportion of all edited pages first drop from 2% to 0.1% in 2006. This is because of the very small counts of pages in the formative years of Wikipedia which is also the reason for using logarithmic scale here. After that there is a steady growth to 0.22% in 2021. Again, the growth from 2006 to 2010 and from 2018 to 2021 is greater than in the intervening years.

Wikipedia has on average 389,963 authors per year, for the climate change pages we find 54,770 (14%).[15] For each page there is an average of 42 authors per year. The development of these metrics is displayed on Fig. 6, again because of the specifics of the counts on a logarithmic indexed scale. In the formative years of Wikipedia author counts skyrocket also for the climate change related pages: from 132 in 2001 to 110,775 in 2007. After 2007, authors decline by about half to 50,548 in 2013, only to stabilize on that level in the following years up to 2019 during which the authors rise to 78,018 (with small a decrease until 2021). A similar trend is found for the average author per page. Until 2007, the count increases to 118 author per page. After that we see a constant decline to 2018 (25). The following years see a rise (2019: 33), but it has been is declining again since then. The proportion of climate change page authors to all authors sees a different development. While there is an increase from 30% to 44% in 2002, the proportion declines constantly until 2012 (11%). The proportion stabilizes at about 12% in the following and there is also a rise in 2019 to 19%, which is stable until 2021.

In comparison to the cumulative growth of science, we see two intense phases of attention toward climate change in the quantitative analysis of structural features of Wikipedia. The first reflects a phase of high news media attention symbolized in the Nobel prizes for Al Gore and the IPCC in 2007 as well as the failure of COP-15 in 2009 (Broadbent et al., 2016). The second intense phase is clearly linked to the Fridays for Future movement. While the counts of authors and edits have seen are great growth, especially in contrast to the formative years of Wikipedia, the proportions of climate change related pages and authors are more stable after the formative years. This indicates that in contrast to science climate change is not a prominent driver for the development of Wikipedia, but especially in the last years the subject gets more attention.

4.3. *From chat to crisis – trends in the topics of Wikipedia pages on climate change*

To cover the attention and focus of Wikipedia as a whole, we look at the number of page revisions. Like the concept tags in OpenAlex, the revision rankings show the attention of Wikipedia as the sum of contributions. Revisions can have a number of reasons: new developments, improvements, debates (outside and inside the revisions), and vandalizing. It is also possible that the content of a page changes over time because some parts get their own pages or other structural changes occur. However, it allows a similar ranking per year that shows the topic shifts of climate change in Wikipedia over time. In analogy to 3.3, we use the proportion of revisions of all revisions per year to get a comparable ranking.

On average, there are about 55,000 revisions per year. The trend is similar to the one of the authors: the first years show a substantial growth of revisions that sees its climax in 2007 with over 100,000 revisions. This intense phase ends in 2010 when about 80,000 revisions are counted. After that there begins a phase of stagnation during which the revisions are very stable with around 52,500 revisions until 2018. The years 2019 to 2021 see a sustained increase in revisions (around 77,000) and are thus the second most intense phase.

We registered 1,150,179 revisions, 2.22% percent of them are revisions of the “climate change” page. With around 0.9% follows “wind power”, “UK independence party”, “Al Gore”, and “tropical cyclone”. Over 0.8% are “solar energy”, “Final Fantasy VII”, and “climate change in Mauritius”. Another 13 pages have percentages over 0.5%. 40 pages see revisions in all 21 years, another 57 see in 20 years, and another 61 in 19.

Table 3 shows the top Wikipedia pages in terms of revisions per year.

[13] The map contains all concepts (750 out of 8,952) that co-occur at least 57 times. It is generated with attraction = 2 and repulsion = 1, the maximal 10,000 links of 1562,972 are displayed.

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[15] Wikipedia calls the authors users in their self-description, we use ‘authors’ in the text synonymously. We took as user/author count from Wikimedia Statistics all users without differentiating between bots, registered or anonymous users, again as yearly averages of the monthly provided counts (compare Footnote 14).

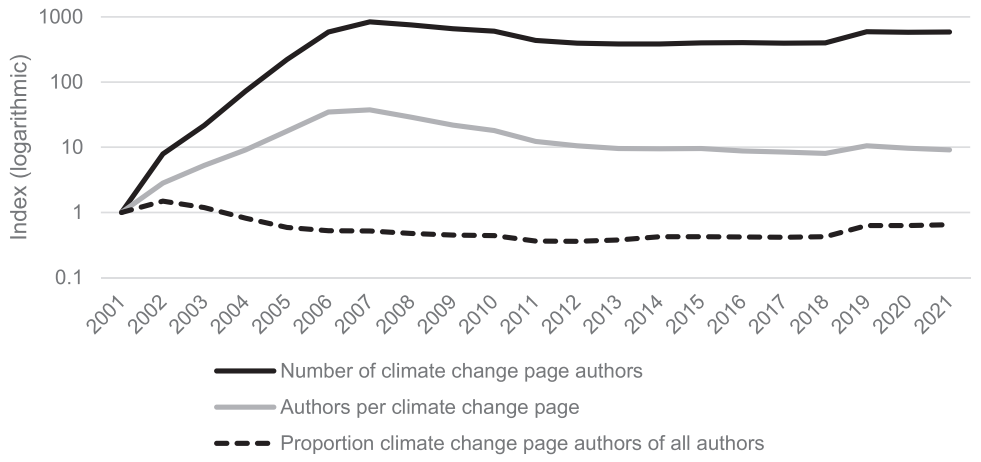

Fig. 6. Authors of climate change pages in Wikipedia per year.

Table 3
The 20 most revisioned pages in Wikipedia per year (shading in blues: Climate Change & Nature; greens: Politics; oranges: Energy; yellow: Cars; white: Media Products).

2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Renewable energy	Climate change	Water vapor	Al Gore	Climate change	Climate change	Climate change	Solar energy	Climatic Research Unit email controversy	Climatic Research Unit email controversy	UK Independence Party	Climate change in Southeast Asia	2013 Southeast Asian haze	UK Independence Party	Volkswagen emissions scandal	Dakota Access Pipeline protests	Blade Runner 2049	2018 California wildfires	Make the World Greta Again	2019-20 Australian bushfire season	Sustainable energy
Climate change	Kyoto Protocol	Climate change	Climate change	Tropical cyclone	Al Gore	Solar energy	Heat waves and climate change	Climate change	2010 Pakistan floods	Climate change	RT (TV network)	UK Independence Party	Early 2014 North American cold wave	2015 Southeast Asian haze	ExxonMobil climate change controversy	March for Science	Blade Runner 2049	Greta Thunberg	Climate change	Greenhouse gas emissions by Turkey
Solar energy	Al Gore	Al Gore	Kyoto Protocol	Kyoto Protocol	Solar energy	Heat waves and climate change	Wind power	Climate change in Mauritius	Bog turtle	Chevrolet Volt	Wind power	Alternative for Germany	RT (TV network)	UK Independence Party	Breitbart News	United States withdrawal from the Paris Agreement	People's Party of Canada	Climate change	2020 California wildfires	Don't Look Up
Al Gore	The Skeptical Environmentalist	Kyoto Protocol	Tropical cyclone	Final Fantasy VII	Tropical cyclone	Global warming controversy	Climate change	Climate change in Asia	Climate change	Climatic Research Unit email controversy	UK Independence Party	Climate change in Southeast Asia	2013-14 United Kingdom winter floods	Call of Duty: Black Ops III	UK Independence Party	Alternative for Germany	Climate change in Mauritius	Mary Ellis Stevens	Bushfires in Australia	Climate change
Flatulence	Blade Runner	Intergovernmental Panel on Climate Change	Views of Lyndon LaRouche and the LaRouche movement	Flatulence	Final Fantasy VII	Al Gore	Polar bear	Climate change and wildfires	UK Independence Party	Brink (video game)	Climate change in Mauritius	Tropical cyclone	2014 Southeast Europe floods	Climate change denial	National communication (Paris Agreement)	Breitbart News	Alternative for Germany	School Strike for Climate	Aviation and climate change	2021 United Nations Climate Change Conference
Energy storage	Renewable energy	Gaia hypothesis	Global warming controversy	Al Gore	Wind power	Polar bear	Al Gore	Wind power	Climate change in Mauritius	Blade Runner	Chevrolet Volt	Wind power	Climate change in Southeast Asia	Heartland Institute	Alternative for Germany	Geostorm	UK Independence Party	2019 Amazon rainforest wildfires	Greenhouse gas emissions by Turkey	2021 California wildfires
Albedo	Climate change and wildfires	Dune (novel)	UK Independence Party	Blade Runner	Climate change in Asia	The Great Global Warming Swindle	Biofuel	2009 United Nations Climate Change Conference	New Zealand Emissions Trading Scheme	Climate change in Asia	Mohamed Nasheed	Holistic management (agriculture)	Snowpiercer	RT (TV network)	Paris Agreement	National communication (Paris Agreement)	Sea level rise	Extinction Rebellion	Ronen Rubinstein	The Tomorrow War
Blade Runner	Carbon dioxide	Science & Environmental Policy Project	Climate change in Asia	Solar energy	Kyoto Protocol	Wind power	Greenhouse effect	Toyota Prius	Gore effect	Renewable energy	Family Research Council	RT (TV network)	Climate change in Mauritius	2015 United Nations Climate Change Conference	Global Climate Coalition	Paris Agreement	Climate change	September 2019 climate strikes	Make the World Greta Again	Bo Burnham: Inside
The Washington Times	Climate change in Asia	Renewable energy	Renewable energy	Climate change in Asia	Polar bear	Final Fantasy VII	Geothermal energy	Carbon dioxide	Toyota Prius	Climate change in Mauritius	Global warming controversy	Greenhouse gas	Climate change	Alternative for Germany	Climate change in Mauritius	New York Harbor Storm-Surge Barrier Agreement	The Washington Times	Greenhouse gas emissions by Turkey	Greta Thunberg	Paris Agreement
Gulf Stream	Methane	Greenhouse effect	Flatulence	Renewable energy	Renewable energy	Renewable energy	Greenhouse gas	Solar power	The Hockey Stick Illusion	Toyota Prius	Climate change	Climate change	Tropical cyclone	Climate change in Mauritius	Open energy system models	Climate change in Southeast Asia	PragerU	People's Party of Canada	Final Fantasy VII Remake	National communication (Paris Agreement)
Climate change in Asia	Attribution of recent climate change	Global warming controversy	Progress Party (Norway)	Greenhouse effect	Heat waves and climate change	Carbon dioxide	Climate change in Asia	Tropical cyclone	Wind power	Greenhouse gas	Tropical cyclone	Biomass	Fusion power	Final Fantasy VII	Call of Duty: Black Ops III	Blade Runner	Judicial Watch	Green New Deal	2020 Western United States wildfire season	Alternative for Germany
Methane	Intergovernmental Panel on Climate Change	Flatulence	Alexis de Tocqueville Institution	Carbon dioxide	Retreat of glaciers since 1850	Climate change in Asia	Oxyhydrogen	Kyoto Protocol	Chevrolet Volt	Solar cell	Carbon dioxide	Chevrolet Volt	Constitution Party (United States)	Wind power	Wind power	Final Fantasy VII	Cape Town water crisis	Climate change in Mauritius	Sustainable energy	Assisted migration of forests in North America
ExxonMobil	Greenhouse gas	Leipzig Declaration	Final Fantasy VII	Intergovernmental Panel on Climate Change	Flatulence	Effects of climate change	Flatulence	Solar cell	Solar water heating	Climate change in Southeast Asia	Greenhouse gas	Natural gas	Carbon dioxide in Earth's atmosphere	Climate change in Southeast Asia	Honda CR-V	Toyota Camry	Blade Runner	Sustainable energy	Planet of the Humans	Tipping points in the climate system
Kyoto Protocol	Global warming controversy	Climate change and wildfires	Dune (novel)	Solar cell	Fuel cell	Tropical cyclone	Kyoto Protocol	Biofuel	Earth Hour	Solar cooker	Heartland Institute	Carbon dioxide	Wind power	Climate change	El Niño	UK Independence Party	Kedarnath (film)	UK Independence Party	Climate change in Mauritius	Climate change in Mauritius
Climate change in Southeast Asia	Extreme weather	Carbon dioxide	Carbon dioxide	Environmental vegetarianism	Carbon dioxide	Greenhouse effect	Toyota Prius	Properties of water	Watts Up With That?	Carbon dioxide	Biofuel	Food security	Climate-friendly gardening	El Niño	Constitution Party (United States)	Downsizing (film)	2018 British Isles heat wave	Heat waves and climate change	Coal in Turkey	Climate change in Southeast Asia
Solar cell	Greenhouse effect	Climate change in Asia	Toyota Prius	Global warming controversy	Blade Runner	Lexus LS	Final Fantasy VII	Scientific consensus on climate change	Carbon dioxide	Tropical cyclone	Solar cell	Climate change in Mauritius	Fertilizer	Sea level rise	RT (TV network)	Climate change in Mauritius	Eric Garcetti	2019 California wildfires	Blade Runner 2049	Make the World Greta Again
Renewable energy and mining	Fuel cell	Distributed generation	ExxonMobil	Greenhouse gas	Lexus LS	Blade Runner	Carbon dioxide	Biomass	Tidal power	Fuel cell	2012 United Nations Climate Change Conference	Solar cell	Toyota Camry	Carbon dioxide	Properties of water	RT (TV network)	Wind power	Climate change in New Zealand	PragerU	2021 Turkey wildfires
Subaru Forester	Science & Environmental Policy Project	Earth Simulator	Solar energy	Fuel cell	Greenhouse effect	Biofuel	Solar cell	Alexis de Tocqueville Institution	Biomass	Biofuel	Biomass	Toyota Prius	Blade Runner	Tropical cyclone	Blade Runner 2049	Party for Freedom	Ford Focus	Team Trees	Aliza Ayaz	Greta Thunberg
Greenhouse effect	Fertilizer	The Skeptical Environmentalist	Fusion power	Wind power	Solar cell	Greenhouse gas	Chevrolet Volt	El Niño	Climate change in Southeast Asia	Biomass	Final Fantasy VII	Pollutant Standards Index	The Federalist (website)	Breitbart News	Toyota Prius	Carbon dioxide	Toyota RAV4	Toyota Corolla (E210)	Alternative for Germany	2021 Uttarakhand flood
Propane	Fusion power	Fuel cell	Volkswagen Golf	Climate change in Southeast Asia	Global warming controversy	Kyoto Protocol	Biomass	Final Fantasy VII	Kyoto Protocol	Final Fantasy VII	Geothermal energy	Climate change mitigation	Toyota Prius	Fusion power	Carbon dioxide	2017 People's Climate March	Climate change in Southeast Asia	Effects of climate change	Carrie Johnson	Disha Ravi

There we find 420[16] entries that appear to be much more diverse than in the science case. 109 pages appear only once. Not even "climate change" is in the top positions in each year (but in 19). This is followed by "carbon dioxide" (15), "climate change in Mauritius" (14), and "wind power" (12).

In analogy with the science case, we analyze the trends in the Wikipedia topics in three time spans of seven years (2001–2007, 2008–2014, 2015–2021) and with the help of thematic clusters. We put the pages in five different thematic clusters: NATURE (blues), POLITICS (greens), ENERGY (oranges), MEDIA (white), and CARS (yellow). These clusters sort the pages into a coarse framework, that makes the thematization of climate change in Wikipedia interpretable. We therefore distinguish all pages related to natural phenomena, climate change research (dark blue), climate change effects, and catastrophes (light blue) from pages related to international climate change mitigation, activists and protests (dark green), as well as denial and protagonists of climate change skepticism (light green). Thematizations of renewable energy forms (dark orange) and other energy themes (light orange) are distinguished from cars (light yellow) because the latter are single

[16] In 2001 the 16th rank is tied by 12 pages. Due to design restrictions we do not display all entries, omitted from the table are: "polar bear" (blue), "liquid propane" (light orange), "World Meteorological Organization" (blue), "global warming potential" (blue), "climate change in Mauritius" (blue), "cycling" (light orange), and "carbon dioxide" (blue). In the calculations these are taken into account.

product pages comparable to novels and films (together with media institutions: white). However, climate change denial media outlets are grouped inside the POLITICS cluster.

The first seven years of Wikipedia (2001–2007; this period contains the formative years and half of the first intense attention phase) are dominated by NATURE pages, which take 43% of all possible ranks and 40% of the top 10 ranks. We find pages related to greenhouse gases, some about climate change research, along with more general pages like "albedo" or "flatulence". There are only a few pages related to effects of climate change (5%). Only 2004 sees the most pages related to POLITICS, which takes about a quarter of the possible ranks (29% of the top 10). POLITICS is dominated by the Kyoto-Protocol page on the mitigation side, the page on Al Gore on the activists' side, and a variety of climate skeptic works, institutions, and populist right-wing parties (mostly from Europe). Especially in 2001, we also see a lot of ENERGY pages which overall make up 20% of all ranks as well as in the top 10. The pages are mostly tied to renewable energy, but also to "fusion power". We find few CARS (3%, no in the top 10) or MEDIA pages (8%, but 10% of the top 10). Notable is "Blade Runner" and "Dune (novel)" (a non-earth-related science fiction), next to the first appearances of the Toyota Prius- and the Final Fantasy VII-page, which appear often in the next years. This phase is characterized by the discussion of climate change and technical solutions mostly in the energy sector.

The next seven years (2008–2014; contain the second half of the first intense attention phase and most of the stagnation afterwards) see in first line of relative changes in Wikipedia's attention to climate change. Little change can be shown in the NATURE cluster: with 45% of all ranks it remains the most important cluster. Only in the top 10 do we find an increase in catastrophe pages (floods and hazes), but there are very few pages about climate research. While POLITICS is overall stable (22% of all ranks), we find a clear change in the subjects: there are now more pages about climate change skeptics with 23% of them in the top 10. The staples "Al Gore" and "Kyoto Protocol" both leave the top 20 in this phase. ENERGY remains at 19% and is in this phase almost exclusively connected to renewable energy. CARS and MEDIA somehow change places: CARS now take up 9% of all ranks and 7% of the top 10 (the hybrids: "Toyota Prius" and "Chevrolet Volt"), MEDIA gets only 5% of all ranks (remaining mostly non-earth related science fiction). We see in this phase a constant discussion of climate change in Wikipedia with somewhat contradicting features: there is an increasing spread of technical solutions beyond the energy problem e.g. in car pages as well as a detailed look on skeptical players.

In the last phase, 2015–2021, this leads to a very different picture. 44% of all ranks are now made up of POLITICS, even 57% in the top 10. While in the first years, skeptical pages remain dominant, activist pages around the Fridays for Future movement dominate the end of the phase. Another third of all ranks show NATURE, but now with a focus on the effects of climate change and concrete catastrophes (mainly bushfires), in the top 10; both subclusters make up over 10%. ENERGY is dwarfed to 7%, with "sustainable energy" as the new core page. What ENERGY loses is now found in MEDIA; here the proportion more than doubles to 13% especially in 2017 with a lot of pages on different products that are thematically closer to earth related science fiction (like "Downsizing (film)", "Geostorm", and "Blade Runner 2049").[17] The proportion of CARS is declining. This phase is marked by a politicization against the background of catastrophes.

4.4. Connect everything – co-occurrences of Wikipedia hyperlinks 2005 and 2021

But we find also another differentiation in Wikipedia that is not so much social in kind as factual. If we look at the networks of the co-occurrence of hyperlinks of all pages on the last revision of 2005 (Fig. 5) and 2021 (Fig. 6), we can interpret this as the encyclopedic side of Wikipedia. This means that the pages are connected through a wide variety of hyperlinks; their co-occurrences tend to build clusters beyond the discursive structures of climate change discussed in 4.3. The hyperlinks make use of the digital nature of the encyclopedia and are – in contrast to the concepts of OpenAlex – user generated (although not all Wikipedia users are humans), and depend on the existence of Wikipedia pages relating to the linking concepts. The maps give a snapshot of the whole climate change related Wikipedia to a given time, what widen the view over the most prominent pages. Like in the science case, the maps are interpreted towards an overview of the discursive structure and its change.

Because of the small sample sizes of the formative years of Wikipedia, we choose 2005 (9,041 terms) as the contrasting case to illustrate the development. We find in Fig. 7 a triangle form with the cornerstones energy (top), political climate change mitigation (bottom), and physical foundations of climate change (right). We interpret the map in a way that Wikipedia demonstrates climate change in 2005 as a matter of the physical foundations of global warming in connection to energy production and consumption and the politics of nation states on a global level. Hyperlinks to pages of climate change skeptics are found on the left side of the politics conglomerate, activists and effects hyperlinks on the right. While cars build a sub-cluster in the upper left, there is no match for the fictional thematization. The map shows the generality of the hyperlinks as well as the nature of the encyclopedia, that connects concepts not only by subject, but also by general categories and terminology (compare the clustering of the chemical terminology in the right).

The sample of 2021 is much larger (60,365 terms; Fig. 8). The shape is now more rectangular and the map is denser. However, the structuring logic remains: there are nature and natural science related hyperlinks strongly connected (top), societal climate change mitigation related hyperlinks (bottom left), and chemical, engineering, and electric mobility related hyperlinks (right). Overall, the depth of detail is now drastically increased: there are not only a huge amount of nation states, but also regions, and cities. There are concrete politicians ("Donald Trump" or "Banki Moon"), next to researchers ("James Hansen" or "Naomi Oreskes"), and activists ("Greta Thunberg") and NGOs ("Greenpeace"). There are a lot of concrete institutions like the IPCC, but also companies, and media outlets. But also abstract concepts such as "climate change denial" or "economic growth" next to concrete documents ("Stern report") or agreements ("Paris agreement"). In this way the network displays the interconnections of serval types of entities (persons, nation states, books, molecules, concepts, scientific disciplines, and so on).

Our understanding is that these maps reflect the structure of Wikipedia which has parts of enormous detail regarding engineering, chemistry, and biology, but also politics and media. The encyclopedic character of lists and hyperlinks affords a view of climate change embedded in engineering, natural science, and society. The change is, in first instance, one of enormous growth in detail, while also showing the complexity of the entanglement of worldwide climate change. The perspective remains one of mass media that works here on the foundation of a collaborative user base that is more structured by the logic of everyday life than a scientific one: we find exhaustive lists of nations, regions, and cities, next to cars and engines, video games and films next to abstract concepts.

We interpret the discursive shift in Wikipedia as one from chat to crisis. This is not meant in a disparaging way. At the beginning of Wikipedia, the variety of thematizations of climate change related pages is the most striking feature of the Wikipedia discourse: We find of cause "climate change", "carbon dioxide", and "greenhouse effect", however, there is also "polar bear", "bog turtle", and "flatulence". There are a lot of different renewable energy forms, but also "fusion power". Politics are

[17] We may interpret, that the withdrawal of the Paris Agreement by the USA leads the attention first to the fictional realm before the politics come back in even more intense.

Fig. 7. Wikipedia hyperlink co-occurrence net 2005.[18]1.

Fig. 8. Wikipedia hyperlink co-occurrence net 2021.[19]1.

dominated by the "Kyoto protocol" and the icon "Al Gore", but we find also a lot of skeptical pages. The fictional side contains non-earth-related science fiction. We characterize this tableau as chat about climate change. Over time the earth and nature related pages lose attention along with mitigation and activist pages, while skeptics, medial products (earth-related science fiction), and cars take up more attention. And this differentiation is succeeded by the Fridays for Future Movement alongside a series of catastrophic natural events. It is this tableau that we interpret as a sign of crisis.

5. The different climate changes of science and mass media

To capture the grand challenge of climate change, we approached the challenge of reconstructing and showing the differences of two systemic discourses about climate change. To test the plausibility of the heuristic we opted to reconstruct the logics of the systems in the aggregations of the observed communications, especially in the light of the constraints of a scientific journal article. Therefore, we used OpenAlex as a corpus representing science and Wikipedia as a phenomenon representative for mass media. In both corpora, climate change appears in the internal structure: as a concept in OpenAlex and as a category in Wikipedia. To summarize the findings, we show the differences in the social, factual, and temporal dimensions of meaning.

In Wikipedia, we find a personalization not found in science. Al Gore and Greta Thunberg, the PragerU, Extension Rebellion or the Alternative for Germany show a tableau of global celebrities, national or internationally known social movements, think tanks, and parties that represent a social structure of climate change. This social dimension of climate change is not present in science. While there is of course concrete human and organizational behavior implied in concepts like "environmental planning" or "political science", the first concept addressing something comparable to the examples above is "china" on rank 33 of the most often concepts. Abstracting from individuals and concrete entities in search of laws or general assumptions, science discards individual persons in favor of analyzing the roles they fulfill.

In the factual dimension, science and mass media are much more similar. Climate change is in both corpora a natural science topic that covers the changes in the atmosphere, land- and biomasses, oceans, glaciers, and precipitations. But while Wikipedia is much more concrete in addressing the catastrophic consequences (like the "2013 southeast Asian haze"), science shows more concrete concepts in adaption (like "agroforestry"). In both corpora, the political dispute over climate change mitigation plays an important role. In the case of economy, the strong representation of cars could be interpreted as a functional equivalent to "business" in science. But there are also differences in the relative weight of certain clusters. While climate change denial is an important topic in Wikipedia, this is not the case for science, where denial appears as a special case of general perceptions and attitudes. "Engineering" and "environmental resource management" are found to receive prominent attention by science, but the variety of energy forms discussed in Wikipedia is not found in science. Just as surprising is the fact that climate change research, especially the concomitant computer models, are not of much interest in Wikipedia. The same is true for climate litigations.

But both conceptualizations of climate change can also be shown to be changing over time. While in science the growth of the thematization of climate change is ongoing, the mass media show a more cyclical attention development. In science, we identify a shift of attention from causes to consequences with concepts describing the very phenomenon and its causes declining in relative importance in favor of those addressing mitigation and adaption. Also, ecological questions are becoming more prominent than climate science ones. This is in line with the sixth IPCC report which states that the science describing the causes of climate change is "unequivocal" (IPCC, 2021: V), and in line the whole structure of the IPCC report where the causes, the consequences, and the mitigation have their own sub-reports. In Wikipedia, we find two intense phases and a development that is characterized as from chat to crisis. At the beginning of Wikipedia, we find the discussion of climate change and its causes alongside alternative explications, fusion power next to solar power, and denial next to fictional cultural products – something we summarize boldly as "chat about climate change". However, especially in the last years, there is a notable shift to catastrophic events, climate change mitigation, and climate protests that we summarize as crisis.

The idea of contrasting the climate changes of science and mass media was designed to test the plausibility of the theoretic heuristic. World society's dealing with climate change is to be found in the contradicting dealings of the functions systems that handle some problems while producing irritations in other systems. But also because of this, we find climate change as a challenge to society recognized in both subsystems in a growing and more differentiated manner. In both systems, there is a shift in attention from describing the very phenomenon to questioning how to deal with this fact. An attempt has been made in this paper to employ sociological systems theory as a theoretical foundation to an empirical study to capture the development of the topic of climate change and society in the last 20 years.

Before we conclude with some summarizing thoughts, we would like to duely address the limitations of this study. We encounter these limitations in every single step of our research. We are dependent on the data provided by Wikipedia and OpenAlex, the comparability of metadata of scientific works (and authors) and encyclopedic pages (and users) is not a given, neither in Wikipedia not in the scientific realm: validation against developments of categories, concepts, the scope of OpenAlex and the history of Wikipedia pages and so on are of the essence. The interpretations are thus only to be read against the backdrop of such limitations. We focused on a highly abstract frame of comparison and on basic structural features and the only most prominent subjects. On the theoretical side, our heuristic is provocative, because it denies simple connections as e.g. a strong economical elite that manipulates scientific and mass media reporting in their interests. Instead, we postulate autonomously workings and developments of the function systems which produces side effects, but whose benefits are also threatened by demands of unanimous ends. What kind of insights this heuristic provides for the challenge of climate change we attempt to show in the concluding thoughts.

Both corpora have certain missing themes. Religion, education, and art beyond audiovisual mass products play no prominent role. This is surprising regarding the discussion of climate fiction in literary studies (Johns-Putra, 2016) or the thesis of the greening world religions (Chaplin, 2016). But this reflects maybe also the orthodox connex of climate change: science, politics, CO^2-reduction, and mass media. The other systems of world society appear not to be the focus of attention of the two function systems analyzed here, which is described elsewhere as part of the problem of climate change (Sarewitz, 2011; Hulme, 2022). For science, the development from causes to consequences reflects the perceived demand for theoretical and practical solutions for changing the world as well as the legitimization for political change – and of course the associated funding structures. The shift from causes to consequences also reflects the very temporal structure of science: accumulating results about the consequences of climate change. For mass media, the development from chat to crisis reflects the nucleus of a global public that nonetheless is oriented towards novelty. This promotes the latest car as well as the latest finding about climate change – and the latest denial. In the infrastructure of Wikipedia, there is room to

[19] The 2021 map contains all hyperlinks (753 out of 60,365) that co-occur at least 20 times, the map is generated with attraction = 1 and repulsion = 0, the maximal 10,000 of 147,766 links are displayed.

[19] The 2021 map contains all hyperlinks (753 out of 60,365) that co-occur at least 20 times, the map is generated with attraction = 1 and repulsion = 0, the maximal 10,000 of 147,766 links are displayed.

remember also scientifically refused theories and offbeat technological ideas – obscurity gains attention. And it shows how attention cycles also govern the activity on Wikipedia which the case of social movements underscores: the movements seek the publicity and reputation of Wikipedia, actuality drives Wikipedia to notice new movements, especially if they gain attention in other systems – but intense attention phases always end.

Of course, to get a complete picture of world society's tackling of the problem of climate change it would be necessary to analyze the communications of a number of functional systems, if not all of them. This cannot be done in this paper, but will require further and more research. We attempt to pursue more comprehensive analyses taking into account further subsystems like polity and also going deeper into questions of inter-system relations in future work resulting from our project InsightsNet (2023; Azzam and Beckmann, 2022; Bartsch et al., 2023; El Baff et al., 2023). Overall, regarding the handling of environmental hazards it must be remembered that the societal subsystems observe scientific knowledge (mostly via the mass media), but scientific knowledge can only cause changes in the transformed forms of the subsystems that lie beyond the control of science. One can be dissatisfied with the picture drawn here and also impatient, but one should not ignore society's ways of dealing with climate change in its differentiated forms.

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CRediT authorship contribution statement

Jasper W. Korte: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Visualization. **Sabine Bartsch:** Funding acquisition, Project administration, Writing - review & editing. **Rasmus Beckmann:** Conceptualization, Writing – review & editing, Funding acquisition. **Roxanne El Baff:** Formal analysis, Data curation. **Andreas Hamm:** Conceptualization. **Tobias Hecking:** Conceptualization, Project administration, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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