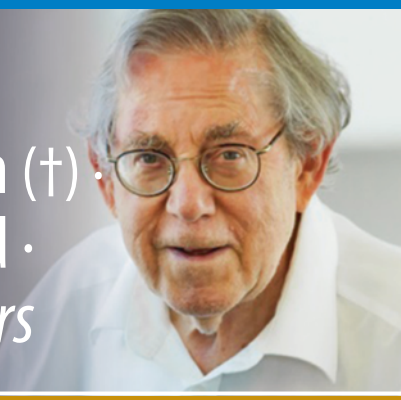
The Anthropocene: Politik–Economics–Society–Science

Susanne Benner · Gregor Lax · Paul J. Crutzen (†) · Ulrich Pöschl · Jos Lelieveld · Hans Günter Brauch *Editors*



Paul J. Crutzen and the Anthropocene: A New Epoch in Earth's History

With a Foreword by Klaus Töpfer and a Preface by Jürgen Renn

MAX PLANCK INSTITUTE FOR CHEMISTRY

Springer

The Anthropocene: Politik—Economics—Society—Science

Volume 1

Series Editor

Hans Günter Brauch, Peace Research and European Security Studies (AFES-PRESS), Mosbach, Baden-Württemberg, Germany

More information about this series at https://link.springer.com/bookseries/15232
http://www.afes-press-books.de/html/APESS_1.htm

Susanne Benner · Gregor Lax · Paul J. Crutzen ·
Ulrich Pöschl · Jos Lelieveld · Hans Günter Brauch
Editors

Paul J. Crutzen and the Anthropocene: A New Epoch in Earth's History

With a Foreword by Klaus Töpfer
and a Preface by Jürgen Renn

Springer

Editors
Susanne Benner
Max Planck Institute for Chemistry (MPIC)
Mainz, Rheinland-Pfalz, Germany

Paul J. Crutzen (deceased)
Max Planck Institute for Chemistry (MPIC)
Mainz, Rheinland-Pfalz, Germany

Jos Lelieveld
Max Planck Institute for Chemistry (MPIC)
Mainz, Rheinland-Pfalz, Germany

Gregor Lax
Max Planck Institute for the History of Science
Berlin, Germany

Ulrich Pöschl
Max Planck Institute for Chemistry (MPIC)
Mainz, Rheinland-Pfalz, Germany

Hans Günter Brauch
Free University of Berlin (Ret.),
Hans Günter Brauch Foundation on Peace and Ecology in the Anthropocene (HGBS)
Peace Research and European Security Studies (AFES-PRESS)
Mosbach, Baden-Württemberg, Germany

Acknowledgement The cover photograph was taken by Mr. Carsten Costard in July 2015 in the Max Planck Institute for Chemistry in Mainz who granted permission to use this photograph for this volume.

More on this book is at: http://www.afes-press-books.de/html/APESS_1.htm

ISSN 2367-4024 ISSN 2367-4032 (electronic)
The Anthropocene: Politik—Economics—Society—Science
ISBN 978-3-030-82201-9 ISBN 978-3-030-82202-6 (eBook)
https://doi.org/10.1007/978-3-030-82202-6

Copy-editing: PD Dr. Hans Günter Brauch, AFES-PRESS e.V., Mosbach, Germany
Proofreading: Susanne Benner, Max Planck Institute for Chemistry, Mainz and Hans Günter Brauch Foundation on Peace and Ecology in the Anthropocene (HGBS)

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

In memory of Paul

who sadly passed away on 28 January 2021

just before the completion of this book

Foreword

Thoughts, Memories, and Commemoration of Paul Crutzen the Man and His Work

Memories are awakened and come alive in three dimensions. Images and events merge with mine, do not stay isolated, are combined in an outstanding personality, a clever, wise person, an important scientist ahead of his time: Paul Crutzen.

These memories vividly bring back general conversations, scientific activities, and also socio-political actions. They are mingled with the results of scientific discoveries and cutting-edge research that never made Paul Crutzen, the man, complacent or vain. He always regarded his scientific contribution as the result of collegial collaborative work at the Max Planck Institute for Chemistry, the Scripps Institute in California, and countless scientific conferences. Paul Crutzen never punctuated these results with an exclamation mark or with the self-assurance of those who regard any scepticism about the results of their research as sacrilege. He himself always placed a question mark after these results, never an exclamation mark. For him science was a dynamic process, and his commitment to scientific endeavour meant he was more concerned with questioning his results than with verifying them. The question mark was dominant, not the exclamation mark.

Vivid Memories of the Flight around Mount Everest

This flight started from Kathmandu, the capital of Nepal, and was made for the purpose of conducting a scientific investigation into the particles in the atmosphere. Paul Crutzen and "Ram" Ramanathan were the scientific leaders on board. The scientists were responsible for the UNEP-initiated project "Atmospheric Brown Cloud" (ABC), linked to the major scientific research project "Indian Ocean Experiment" (INDOEX). As the Executive Director of UNEP at the time, I was there with them. The flight was as unforgettable for me as the subsequent scientific discussions to evaluate the results of this excursion.

The Flight around Mount Everest

We flew through the "Brown Cloud", composed of particles from all kinds of mass combustion processes. Lots of aerosols formed this "cloud".

The central scientific questions were: "How do these particle clouds, which are by no means limited to the Asian region, affect the climate and the Radiation Budget? Are they masking an even faster global warming process? Do they confirm the noticeable changes associated with the massive infiltration into the atmosphere of particles from gigantic volcanic eruptions such as Toba, which caused a volcanic winter over 75,000 years ago, and Tombora (in Indonesia), which erupted in 1815 and made 1816 the "year without a summer", triggering misery, hunger and mass emigrations as far away as Germany?

Or do these particle clouds have very different effects on the different regions of Planet Earth? Will the Arctic, in particular, be "heated up" more intensely with an accelerated thawing of the polar ice and the permafrost soils? Will climate change be further magnified by the additional methane emissions caused by this?

These were questions that would become an exclamation mark due to the topicality of the significantly above-average warming in the Arctic region.

For Crutzen, the graphic consequences posed challenging food for thought—hotly contested disputes about active human intervention in the Radiation Budget in the natural cycles of the Earth; Solar Radiation Management (SRM), such as Carbon Dioxide Removal (CDR); the importance of natural and artificial CO_2 sinks—in his essay, "Geology of Mankind" (*Nature*, 415, 23/2002).

This "Anthropocene article", which will be discussed later, ends with a reference to "internationally accepted, large-scale geo-engineering projects, for instance to 'optimize' climate. At this stage, however, we are still largely treading on terra incognita."

Again the question mark, not the exclamation mark.

Memories of the Joint Efforts in Scientific and Socio-Political Debate to Take Decisive Action Against the Expansion of the "Ozone Hole"

Crutzen's Research Results

Man-made emissions of CFC (chlorofluorocarbons) cause a "hole" in the ozone layer in the Antarctic region. Halogens and bromides are therefore a major threat to human health, especially in the southern hemisphere.

These scientific results were by no means accepted without opposition or criticism! There was opposition from science, opposition from commerce, and, initially, equally widespread lack of understanding in the community because these

substances were very cheap and could be used in a variety of ways. The CFCs in spray cans became the identifying feature in this debate.

Paul Crutzen's scientific wake-up call, reinforced in parallel by the scientific knowledge and results of Mario Molina and Frank Sherwood Rowland, prompted public demand for government action against these substances. Co-operation between science, non-governmental organizations and, increasingly, politicians led to success.

As early as 1986, the Vienna Convention for the Protection of the Ozone Layer was adopted as the basis for international law. It was also very quickly possible to successfully negotiate the Montreal Protocol in 1987 as the basis for specific interventions within the framework of the United Nations through the UNEP. What was still missing was solid funding for global action. This massive gap was finally bridged in 1990 with the establishment of the Multilateral Fund.

Without Paul Crutzen's almost agitatory activities, this success would not have been possible. Again the refrain: Paul Crutzen was never satisfied with the scientific result; he always felt it was his duty to share responsibility for social problems and to actively work to overcome them. Paul Crutzen, the staunch and convincing activist. For these contributions, which are crucial for successfully combating the threat to the ozone layer, the scientist Paul Crutzen was awarded the Nobel Prize in Chemistry in 1995, together with Mario Molina and Frank S. Rowland. Paul Crutzen's scientific interchanges, especially with Mario Molina, continued to be intensively maintained afterwards.

"Remembering is Only Fruitful When It Reminds You of What Still Needs to be Done"

This duty of remembering, which the philosopher Ernst Bloch urges, has an almost imperative quality in reminiscences of Paul Crutzen. How could it be otherwise when his scientific work ends with a question mark? So I must once more return to "Geology of Mankind", and the last two words of this most-cited scientific article of recent years, which I have already quoted: "terra incognita". Has man replaced nature? Has the natural age of the Holocene already ended, and have we already arrived at the first man-made age, the Anthropocene? Paul Crutzen accepted this finding—but not without the question mark mentioned above. Faced with a global catastrophe—Paul Crutzen cited as examples a meteorite impact, a world war, a pandemic—would mankind remain "a major environmental force for many millennia"? He exhorted scientists and engineers to lead mankind through the Anthropocene, stating, "This will require appropriate human behaviour". Crutzen left the question open as to who should enforce this human behaviour in a population that is rapidly advancing towards nine billion people. Above all, what this "appropriate human behaviour" looks like and how it is determined remains unanswered. The ultimate question that Paul Crutzen asked constitutes a challenge for society: can this "appropriate behaviour" be realized in an open parliamentary democracy? Does the ever-deeper foray of humans into the decoding of nature and

life lead to human action to control the expected and unexpected consequences of previous action; or does it lead to a lack of alternatives, to path dependency?

In the Encyclical, *Laudato Si'*, Pope Francis focuses this question on the "technocratic paradigm": Do people control technology or does technology control people?

These questions are part of Paul Crutzen's compelling legacy. Finding answers to them is essential to gain scientific understanding that is always mindful of the question marks over one's own research; this is part of the legacy that Paul Crutzen left behind as a task. Again and again, especially in the Anthropocene, people will be confronted with "terra incognita" and will have to cope with the unexpected consequences of previous actions.

Science cannot brush this legacy aside. Not least, the Coronavirus pandemic, a global catastrophe mentioned by Paul Crutzen, is a powerful reminder of this. So it is highly appropriate that the Max Planck Society has started to set up a new Institute for Geo-Anthropology. It will be a mark of respect for Paul Crutzen's incredible achievement when the development work led by Professor Jürgen Renn leads to success.

Remember what still needs to be done!

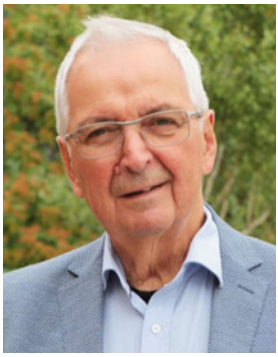
This is a general challenge for a science that is constantly questioning itself, a warning to society and politics not to misuse this dynamic of science as an excuse for postponing action.

To me, Paul Crutzen was, consciously and unconsciously, a teacher and a reminder:

Scientific knowledge is the basis for social and political action. It is indispensable. It is equally necessary to define "appropriate human behaviour" on the basis of normative, ethical action. For me, this link between science and politics has been repeatedly confirmed at the intersections of science and normative relationships in social politics, but rarely so clearly. Time and again these question marks will be an incentive for scientific research and political responsibility. That is the legacy I owe to Paul Crutzen.

Höxter, Germany
June 2021

Prof. Dr. Klaus Töpfer



Prof. Dr. Klaus Töpfer is the founding Director and until 30 September 2015 was Executive Director of the *Institute for Advanced Sustainability Studies* (IASS) based in Potsdam and Council Chair at Agora Energiewende. He is also the former Executive Director of the *United Nations Environment Programme* (UNEP) based in Nairobi and Under-Secretary-General of the United Nations (1998–2006). He graduated from Mainz, Frankfurt and Münster in 1964 with a degree in Economics. From 1965 to 1971 he was a Research Assistant at the Central Institute for Spatial Research and Planning at the University of Münster, where he graduated in 1968 with a Ph.D. in "Regional development and location decision". From 1971 to 1978 he was Head of Planning and Information in the State of Saarland, as well as a visiting Professor at the Academy of Administrative Sciences in Speyer. During this period he also served as a consultant on development policy for the following countries: Egypt, Malawi, Brazil and Jordan. From 1978 to 1979 he was Professor and Director of the Institute for Spatial Research and Planning at the University of Hanover. In 1985 he was appointed by the University of Mainz Economics Faculty as an Honorary Professor. Since 2007 he has been a Professor of Environment and Sustainable Development at Tongji University, Shanghai. He is also a visiting Professor at the Frank-Loeb Institute, University of Landau. Klaus Töpfer has been a member of the *Christian Democratic Union* (CDU) party in Germany since 1972. He is the former Minister for Environment and Health, Rheinland-Pfalz (1985–1987). He was Federal Minister for the Environment, Nature Conservation and Nuclear Safety from 1987 to 1994 and Federal Minister for Regional Planning, Housing and Urban Development from 1994 to 1998. He was also a member of the German Bundestag during the period 1990 to 1998. He has received numerous awards and honours, including the Federal Cross of Merit in 1986 and the German Sustainability Award in 2008 for his lifetime achievement in the field of sustainability. He received the German Award for Culture 2010 and the Wilhelmine von Bayreuth Award in 2012. In 2012 he was inducted into the "Kyoto Earth Hall of Fame".

Preface

Rethinking Science for the Anthropocene: The Perspective of Geoanthropology

This book offers a survey of the development of and current discussions about the Anthropocene concept introduced by Paul Crutzen in 2000. Sadly, Crutzen passed away just before the publication of this book, but it will nevertheless serve as a tribute to his lifetime achievements. He grew up in difficult times—in war-torn Amsterdam during the German occupation. His ambition to attend university and pursue an academic career was thwarted by economic conditions. True to his realist mindset, he decided to train as a civil engineer in order not to be a financial burden on his parents. He later applied for a position as a computer programmer at the Meteorological Institute of *Stockholm University* (MISU), an opportunity that would profoundly shape his future career. By the 1960s, environmental and political issues were already present in discussions of atmospheric chemistry, but Crutzen was primarily driven by his interests in basic science. He was first and foremost a passionate scientist, fascinated by intellectual challenges. But what is remarkable about his further intellectual pathway that led him to popularising the notion of the Anthropocene—and this is as a characteristic for his scientific persona as it is for the time in which it came to maturity—is the intertwinement between basic research and societal concerns.

Paul Crutzen had an acute sensibility for the implications of his research and pursued their political and practical consequences to the very end. His work in 1986 on the cause of the ozone hole in the atmosphere helped to save humanity from potentially catastrophic consequences of its interventions into nature. But the scope of his work was much larger. He also engaged with other entanglements between human activities and natural processes: biomass burning and biofuel production, nuclear winter, and geoengineering to mitigate climate change, to name just a few examples. Many of the phenomena Crutzen studied are, in fact, not separable into natural and human dimensions but are characteristic of the novel epoch that he spontaneously dubbed the "Anthropocene"—without being aware of its longer intellectual prehistory. He thus introduced not only a new geological epoch but also

a new era in which humanity, in general, and science, in particular, seek a more sustainable relationship with their home and habitat: planet Earth.

Crutzen's adoption of the term "Anthropocene" in 2000 had far-reaching consequences. It stimulated geologists to start examining the stratigraphic evidence for a new geological time period, a task taken up by the interdisciplinary *Anthropocene Working Group* (AWG) just a few years later. It encouraged Earth-system scientists to explore even more deeply the multiple entanglements between human activities and the various components of the Earth system. It shifted attention and stirred up profound discussions among the various disciplines of the humanities and social sciences that were now confronted with the repositioning of their genuine subject of interest: humans. Thanks to pioneering efforts such as *The Anthropocene Project* at the *Haus der Kulturen der Welt*, to which Paul Crutzen served as patron, the notion of the Anthropocene has triggered a wealth of cultural experiments in the arts, design, public engagement, and education. Innumerable publications, scientific as well as popular, have been dedicated to the notion of the Anthropocene, making it a familiar dictum in newspapers, political forums, and private conversations all around the world. Paul Crutzen has thus, in a significant way, contributed to the self-awareness of humans about their collective role as a geological agent. He has reminded us of what has been repressed by unstoppable progress due to the industrial implementations of science and technologies, namely, the need to deal with the externalities of an ever more expansive and extractive economy on a planetary scale. With his passing, we have lost an extraordinary researcher, but his legacy will surely continue to inspire future generations of scientists concerned with and concerned about the new planetary predicament that he helped to detect, describe, and analyse.

The ongoing transition into a new state of the Earth system, the Anthropocene, is the result of the nexus of multiple, human-induced crises that basically affect all living beings: rapid climatic change, an accelerating loss of biological and genetic diversity as well as critical habitats, the profound alteration of biogeochemical cycles, the introduction and dispersion of a plethora of novel synthetic materials, new mineral species, environmental toxins, radioactive elements, and many more such impacts that present an abrupt end—a shock—to the relatively steady state of the Holocene. This self-reinforcing nexus of planetary-wide environmental deterioration poses a number of challenges both to our understanding of it and our reactions to it. How did we get into this predicament? How can we survive and live in it? Does the Anthropocene perhaps even represent an opportunity to rethink and reshape our position as one among many species on this planet?

A key insight connected with the Anthropocene concept is the systemic nature of the ongoing changes and hence the need to take this systemic character into account when considering our actions. Partial improvements in environmental policy, economic incentives, and sociotechnical transformations are not only inadequate to cope with this systemic nature but also with the fundamental scale of the dynamics of the Anthropocene crisis. Improvements at one end risk becoming aggravations at other ends. To reduce the risk of systemic collapse of basic ecological, economic, and societal functions, it is vital to better understand the configuration and dynamic evolution of the crucial nexus between human agency

and the Earth system in its complex, highly interactive, interdependent, and time-critical nature.

The Anthropocene is therefore also a challenge to the transformation of our systems of knowledge. The geosciences bore Earth-system science as a unifying concept, conceiving our planet as a complex dynamic system with subsystems, such as the atmosphere, the hydrosphere, the lithosphere, and the biosphere. In the past two decades, the Anthropocene has likewise become a driver of a human-centred Earth-system science, coevolving with global environmental policy and governance, and central to the question of how to respond to emerging instabilities in Earth's metabolism. But avoiding global systemic catastrophes, lowering risks, and enabling a holistic transformation of human societies to sustainability requires an even deeper understanding of the human-Earth nexus.

It is particularly necessary to go beyond the notion of humans as part and parcel of the biosphere, especially as such a notion purports a picture of humans as a mere biological species with equally distributed powers and equally distributed effects on the global environment. Instead, it seems more appropriate to consider the technological empowerment, sociotechnical evolution, and high carbon intensity of *certain parts* of modern humanity as the decisive agent behind the dangerous dynamics now unleashed. In that sense, humans are a sociocultural and political species, but most importantly they are a "technological species," able to construct their own niche as well as internal power relations by using certain tools, transforming matter, and increasingly controlling the energy pathways that sustain them.

In recent times, these forms of human niche construction and social stratifications have resulted in the emergence of a qualitatively new planetary sphere, the technosphere: a human-created fabric of industrial technologies, infrastructures, harnessed energy sources, knowledge systems, social institutions, and powers that increasingly interact with and function on a magnitude equivalent to that of natural spheres like the biosphere or hydrosphere. The technosphere is both a catalyst of human powers and a new substrate upon which a vastly expanded human population now depends. Although the technosphere might turn out to be only a transient stage, it appears to be the most decisive addition to the Earth system since the emergence of the biosphere and represents thereby not just a quantitative but also a qualitative step change in both human and Earth-system history. While the pre-industrial *anthropos* was largely embedded within the biosphere, the emergence and rapid development of the technosphere has elevated human agency to its current, hugely outsized rank in the Earth system's architecture.

The intricate interactions among the different Earth spheres require entirely new forms of analysis, which have much to learn both from Earth system analysis, with its sophisticated and powerful methods of data collection, analysis, and simulation, and from the no less sophisticated and powerful traditional forms of historical investigation. But there can be little doubt that their integration will lead to something completely novel that is neither reducible to the principles and methods of the natural sciences as we know them, nor to those of the humanities. We have tentatively called this novel outlook, integrating the advancing tools of Earth system observation and analysis with innovative investigations of the technological, economic, and societal drivers of the Anthropocene, "geoanthropology."

The proposed approach of geoanthropology responds to the challenges of the multiple couplings between ecological, technological, and social evolution by merging an updated version of Earth system research (the *geo*, including the *bio*) with cultural theories, social science studies, and historical investigations of socio-material, energetic, and informational flows (the *anthropos*) by forming a new discipline (the *logos*). Through analytical and interpretative approaches, geoanthropology aims to study the various drivers, dynamics, and dilemmas that have led us onto an Anthropocenic path and applies these insights to cope with its further unfolding and rapid intensification. Cast into a research framework that studies the complex coevolution of natural and human systems, geoanthropology will investigate the concrete human-created conditions of ongoing Earth system and biosphere destabilisation, the limits of socio-ecological carrying capacities, possible system thresholds and tipping elements, as well as necessary socio-economic and cultural reaction times. All of this will be crucial to identify possible intervention points and novel geosocial opportunities in the Anthropocene.

Currently, the Max Planck Society is exploring the possibility of establishing an institute dedicated to geoanthropology as a new form of cross-disciplinary research between the natural and the human sciences—an ambitious approach through which the legacy of Paul Crutzen lives on. "I don't carry out 'pure science'," Paul remarked in an interview a few years ago, "although originally that was my goal. Until I discovered … this is more than science, since humans are involved."[1] The foundation of a new institute exploring the dynamics of the techno-Earth system with a focus on the human component would truly maintain the spirit of his work, both at the Max Planck Society and beyond, as an individual scholar and as a supporter of cross-disciplinary collaborations on the burning issues that he helped to identify.

This book brings together some of the milestones that mark the emergence of the current Anthropocene debate, with a focus on Paul Crutzen's contributions to it. In this sense, it is a fitting sequel to *Paul J. Crutzen: A Pioneer on Atmospheric Chemistry and Climate Change in the Anthropocene*, which offers a unique entry point into Crutzen's life and work.[2] I am convinced that the present volume will itself become a milestone publication and a most useful reference and guide in the debates on the Anthropocene to come.[3]

March 2021

Jürgen Renn
Max Planck Institute for the History of Science
Berlin, Germany

[1]Carsten Reinhardt and Gregor Lax: "Interview with Paul Crutzen", 17 November 2011 in Mainz.

[2]Paul J. Crutzen and Hans Günter Brauch (Eds.), 2016: *Paul J. Crutzen: A Pioneer on Atmospheric Chemistry and Climate Change in the Anthropocene* (Cham: Springer International Publishing).

[3]This text is partly based on an unpublished white paper on geoanthropology co-authored with Christoph Rosol.

Jürgen Renn born on 11th July 1956 in Moers, degree in physics at Freie Universität Berlin (1983), doctorate in mathematics at Technische Universität Berlin (1987), collaborator and co-editor of the Collected Papers of Albert Einstein (1986–1992), Assistant Professor (1989) and Associate Professor at Boston University (1993), Simon Silverman Visiting Professor of History of Science at Tel Aviv University (1993), Visiting Professor of Philosophy at ETH Zürich (1993–1994), Director and Scientific Member at the Max Planck Institute for the History of Science (since 1994), honorary professor for History of Science at Humboldt-Universität Berlin (since 1996). Member of the Deutsche Akademie der Naturforscher Leopoldina (the German National Academy of Sciences, since 2005), honorary professor for History of Science at Freie Universität Berlin (since 2006). *Address*: Prof. Dr. Jürgen Renn, Max Planck Institute for the History of Science, Boltzmannstr. 22, 14195 Berlin, Germany, +49 30 22667-101. *Email*: rennoffice@mpiwg-berlin.mpg.de.

Acknowledgements

We gratefully acknowledge stimulating discussions and exchange with numerous colleagues and friends from the scientific community, and we wish to express our gratitude to Astrid Kaltenbach, Tanja Pallien und Andreas Zimmer (all MPIC) for their help with the compilation and completion of this book.

We would also like to thank Dr. Christian Witschel, head of the Department of Earth Sciences, Geography and Environment, Ms. Marion Schneider and Ms. Birke Dalia with Springer Nature in Heidelberg (Germany) and Mr. Arulmurugan Venkatasalam and Ms. Priyadharshini Subramani with Springer Nature and Scientific Publishing Services Private Limited in Chennai, Tamil Nadu (India) who were responsible for the production of this book.

March 2021

Susanne Benner
Gregor Lax
Jos Lelieveld
Ulrich Pöschl
Hans Günter Brauch

Introduction: Aims and Approach of This Book

At an international scientific conference in the year 2000, Paul Crutzen realised and stated that we have progressed from the geological epoch of the Holocene into the Anthropocene, a new era of Earth history dominated by human influence. His rationale was that humankind has become a major force shaping planet Earth through globally pervasive effects of human activity on the composition and properties of the atmosphere, oceans and terrestrial environment.

While geologists still argue about the formal recognition and dating of the Anthropocene as a new geological epoch, the term is already widely accepted and used as a new approach and concept of describing the relationship between nature and humankind across the natural sciences, humanities, and arts. Over the past years, a large and rapidly growing number of studies, journal articles, books, films, and exhibitions have addressed the Anthropocene or are building on it.

Within two decades Paul Crutzen's concept of the 'Anthropocene' has triggered more than 10.000 publications according to the World Catalogue and more than 5000 peer-reviewed articles and in selected books that were indexed separately in the 'World of Science' and in 'Scopus' (2000–2020) with a primary focus on English language literature.

This book outlines the development and perspectives of the Anthropocene concept by Paul Crutzen and colleagues from its inception to its implications for sciences, humanities, society and politics. The main text consists primarily of articles from peer-reviewed scientific journals and other scholarly sources. It comprises most articles published by Paul Crutzen and colleagues with whom he collaborated closely on the Anthropocene.

For those texts the copyright holders did not grant a free licence for this Crutzen anthology the editors included the abstracts and links to the websites of the publishers from where these texts may be read, downloaded or purchased.

The introductory text by Gregor Lax (Chap. 1) portrays Paul Crutzen's scientific work and experience leading from investigations of human influence on atmospheric chemistry and physics, climate, and the Earth system, to the conception of the Anthropocene. The subsequent document is structured in two parts:

- Part I contains 19 texts by Paul J. Crutzen and his Co-authors on the Anthropocene;
- Part II includes texts by Abraham Horowitz with 'reflections on the Anthropocene' and a bibliometric analysis (2000–2020) by Hans Günter Brauch on the The Anthropocene Concept in the Natural and Social Sciences, in the Humanities and Law;

The book backmatter adds an appendix with additional materials on the Anthropocene and on Paul J. Crutzen such as a complete list of Paul Crutzen's scholarly publications and a brief professional biography.

March 2021

Susanne Benner
Gregor Lax
Jos Lelieveld
Ulrich Pöschl
Hans Günter Brauch

Contents

Abbreviations

^{14}C	Carbon-14, or radiocarbon
A&HCI	Arts & Humanities Citation Index
ACE-2	Aerosol Characterization Experiment
ACE-ASIA	Asian Pacific Regional Aerosol Characterization Experiment
AD (A.D.)	Anno domini (after Christ)
AERONET	AErosol RObotic NETwork
AFES-PRESS	Peace Research and European Security Studies
AI	Artificial intelligence
AMPG	Archives of the Max Planck Society
ANU	Austalian National University (Canberra, Australia),
AOD	Aerosol optical depth
Ar	Argon
ASI	Amsterdam Sustainability Institute
ASPO	Association of the Study of Peak Oil and Gas
ATSR	Along-Track Scanning Radiometer
AWG	Anthropocene Working Group
BC	Black carbon
BIBLE	International field research programme
BKCI-S	Book Citation Index–Science
BKCI-SSH	Book Citation Index–Social Sciences & Humanities
BNF	Biological N fixation
BP	Before Present
C	Carbon
Ca	Calcium
CC	Climate Change
CCS	Carbon capture and storage
CDIAC	Carbon Dioxide Information Analysis Center
CDR	Carbondioxide removal
CE	Climate engineering
CF_2Cl_2	Dichlordifluoromethane

CFC	Chlorofluorocarbon
$CFCl_3$	Trichlorofluoromethane
CFCs	Chlorofluorocarbons
CH_3CCI_3	Methyl chloroform
CH_4	Methane
CIAP	Climate Impact Assessment Program
ClO radicals	Chlor radicals
ClO_x	Chloroxide
ClO_x/NO_x	Chloroxides and nitrogen oxides
Cm	Cambrian
CMIP5	Coupled Model Intercomparison Project Phase 5
CMIP6	Coupled Model Intercomparison Project Phase 6
CNRS	Centre national de la recherche scientifique (French National Centre for Scientific Research)
CO	Carbon monoxide
CO_2	Carbon dioxide
COP15	Conference of Parties [of UNFCCC], Copenhagen, 2009
COP21	[UNFCCC] Conference of Parties No. 21 in Paris, 2015
Core Collection	A curated collection of Web of Science
COS	Carbonyl sulfide
CPCI-S	Conference Proceedings Citation Index-Science
CPCI-SSH	Conference Proceedings Citation Index-Social Science & Humanities
CPECC	The Committee to Prevent Extreme Climate Change
CRED	Centre for Research on the Epidemiology of Disasters
CSAB	Content Selection & Advisory Board
CSIC	Consejo Superior de Investigaciones Científicas (Spanish National Research Council)
D/O events	Dansgaard–Oeschger events
DGVMs	Dynamic Global Vegetation Models
DKN	German Committee Future Earth
DMSP	US Defense Meteorological Satellite Program
DNA	Deoxyribonucleic acid
DOAS	Different optical absorption spectrometer
EIA	Energy Information Agency
EJ	Exajoules
EMICs	Models of Intermediate Complexity
ENUWAR	Environmental Consequences of Nuclear War
ENVISAT	Environment Satellite
EPICA	European Project for Ice Coring in Antarctica
ERA-lab	PIK's laboratory
ESA	Earth System Analysis
ESCI	Emerging Sources Citation Index
ESS	Earth System Science
ESSP	Earth System Science Partnership

FAO	United Nations Food and Agriculture Organisation
FAOSTAT	UN Food and Agriculture Organisation, Statistics
FRG	Federal Republic of Germany
Ga	Giga annum (Billion years ago)
GCMs	General Circulation Models
GDP	Gross Domestic Product
GE	Genetic engineering
GEC	Global Environmental Change
GeoMIP	Geoengineering Model Intercomparison Project
GHGs	Greenhouse gases
GOME	Global Ozone Monitoring Experiment
GS	Geological Society, *London*
GSA	Geological Survey of America
GSSA	Global Standard Stratigraphic Age
GSSP	Global boundary Stratotype Section and Point
GWP	Global warming potential
H	Humanities
HCFC 31	Chlorofluoromethane
HCl	Hydrogen chloride
HDI	Human Development Index
HELSUS	Helsinki Institute of Sustainability Science in Finland
HFCs	Hydrofluorocarbons
HGBS	Hans Günter Brauch Foundation on Peace and Ecology in the Anthropocene
HNO_3	Nitric acid
IAHS Press	International Association of Hydrological Sciences Pubisher
IAHS	International Association of Hydrological Sciences
ICOLD	International Commission on Large Dams
ICS	International Commission on Stratigraphy
ICSU	International Council for Scientific Unions
IEA	International Energy Agency
IEEE	International Symposium on Electronics and the Environment
IGBP	International Geosphere Biosphere Programme
IGSD	Institute for Governance and Sustainable Development
IHDP	International Human Dimensions Programme on Global Environment Change
IHOPE	Integrated History and future of People on Earth
IMPLICC	Implications and Risks of Novel Options to Limit Climate Change
INDOEX	Indian Ocean Experiment
INQUA	International Union of Quaternary Studies
IPAT	Human Impact = Population × Affluence × Technology
IPCC	Intergovernmental Panel on Climate Change

IRD, France	Institut de Recherche pour le Développement (Research Institute for Development in France)
IRRI	International Rice Research Institute
ISI	Institute for Scientific Information
ISSN	International Standard Serial Number is registered with the ISSN International Centre
ITU	International Telecommunications Union
IUGS	International Union of Geological Sciences
IVM	Institute for Environmental Studies
K	Potassium
L	Law
LLL	Language, linguistics, literature
MA	Millennium Ecosystem Assessment
Ma	Million years ago
MEA	Millennium Ecosystem Assessment
Mg	Magnesium
MISU	Meteorological Institute of Stockholm University
MPIC	Max Planck Institute for Chemistry, Mainz, Germany
mPWP	Mid-Piacenzian Warm Period
N	Nitrogen
N_2	Nitrogen (diatomic gas)
N_2O	Nitrous oxide
Na	Sodium
NAS	National Academy of Science
NASA	US National Space Agency
NATO	North Atlantic Treaty Organisation
NCAR	National Center for Atmospheric Research, Boulder, USA
NERC	National Environment Research Council (in UK)
NH_3	Ammonia
NHx	Ammonia gas (NH_3) plus particulate ammonium (p-NH_4)
NKGCF	German National Committee on Global Change
NO	Nitrogen oxide
NO_3^-	Nitrate
Non-OECD	Developing and transitional countries
NO_x	Nitrogen oxides
NPP	Net primary production
NRC	National Research Council
NRW	North Rhine Westphalia, federal state in Germany
NS	Natural Science
$O(^1D)$	High-energy oxygen atom
O_2	Oxygen
O_3	Ozone
OC	Organic carbon
OCLC	Online Computer Library Center

OECD	Organisation for Economic Cooperation and Development
OFDA/CRED	Office of Foreign Disaster Assistance (OFDA-USAID) **a/** Centre for Research on the Epidemiology of Disasters
OH	OH (Hydroxyl)
P	Phosphorus
PAGES	Past Global Changes
PB	Planetary Boundaries
PCSHE	Personal, Cultural, Social, Health and Economic Education
PD	Privatdozent (German academic title without equivalence)
PETM	The Paleocene-Eocene Thermal Maximum
Pg	Petagram
PIK	Potsdam Institute of Climate Impact Research
ppm	Parts per million
PSC	Polar stratospheric clouds
R & D	Research and Development
RC	Resilience Centre in Stockholm
RIVM	[Rijksinstituut voor Volksgezondheid en Milieu] National Institute for Public Health and the Environment
S	Sulphur
SafMA	Southern African Millennium Assessment
SCI	Science Citation Index
SCOPE	Scientific Committee on Problems of the Environment
SDI	Strategic Defense Initiative
SKAD	A sociology of knowledge approach to discourse
SKC	Scientific Knowledge Community
SLA	Scientific Lead Authors
SLCPs	Short-lived climate-forcing pollutants
SO_2	Sulphur dioxide
SQS	Subcommission on Quaternary Stratigraphy
SRM	Solar radiation management
SS	Social Science(s)
SSA	Single scattering albedo
SSCI	Social Sciences Citation Index
SSTs	Super Sonic Transports
TARFOX	Tropospheric Aerosol Radiative Forcing Observational Experiment
Tg	Teragram
THC	Thermohaline circulation
TLA	Top Lead Authors
TOA	Top of the atmosphere
TTAPS Study	Surnames of the authors (R. P. Turco, O. B. Toon, T. P. Ackerman, J. B. Pollack, and Carl Sagan
UCLA	University of California in Los Angeles
UK	United Kingdom

UNAM	National Autonomous University of Mexico
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
UNFPA	United Nations Populations Fund
UNISDR	United Nations International Strategy for Disaster Reduction
US	United States
USDA	United States Department of Agriculture
USGS	United States Geological Service
USSR	Union of Socialist Soviet Republics
WBGU	Wissenschaftlicher Beirat Globale Umweltfragen (German Advisory Council on Global Change)
WCRP	World Climate Research Programme
WMO	World Meteorological Society
WorldCat	World Catalogue
WoS	Web of Science
WRI	World Resources Institute
WWF	World Wildlife Fund

List of Figures