Chapter 1
"The Reacting Atmosphere": A Systemic Approach to Atmospheric Research

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The Research Network

The Research Network "The Reacting Atmosphere" is a trans-disciplinary consortium of natural and social scientists, economists and mathematicians. Its objective is to acquire a systemic view of the role of the atmosphere for air quality and climate change. This systemic view is mandatory to understand the interactions of atmospheric change with political measures, societal and economic developments and their feedbacks.

Motivation

In a changing world our traditional approaches for solving environmental problems, taken alone, are doomed to fail. Accordingly, new thinking and new actions are needed to prevent us from destroying ourselves. Human-made changes of climate and the interaction with air-quality endanger the social and economic basis of all people around the world. This implies a strong need to promptly develop efficient sustainable mitigation and adaption strategies in response to the already caused changes.

The Intergovernmental Panel on Climate Change (IPCC) has identified the interactions between atmospheric composition (e.g. air quality) and climate to be a key uncertainty in our understanding of climate change, in particular on decadal time scales. Therefore, it is of utmost importance to gain a sound understanding of the complex global and regional interdependencies between human activities, climate and air-quality. This requires the development of a systemic view that

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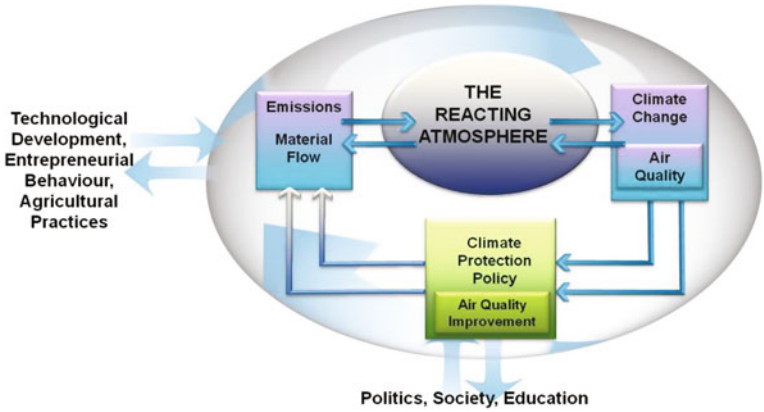

Fig. 1.1 Systemic view of air quality and climate change including the interactions of atmospheric change with political measures, societal and economic developments and their feedbacks

includes societal and economic processes as well as physical and chemical processes in the atmosphere (cf. Fig. 1.1), leading also to improved predictive capabilities and normative implications.

Our Vision: The Systemic View

Today, the scientific community agrees that global temperatures will increase in the next 100 or 200 years, although the predictions based on the results of various climate models under the consideration of different scenarios show tremendous variations, reaching from an increase of the mean global temperature of 2–6.5 °C until the end of this century. Despite of this general agreement nobody knows how the Earth system will respond to these changes. We are not even rudimentary able to obtain a conclusive statement, what the feedbacks on land use, agricultural practices, and energy or food supply will be.

Our research aims at a quantitative understanding of the key processes of the system as a whole, both the interdependencies of atmospheric processes and parameters and the interaction between physico-chemical and socio-economic processes. This quantitative understanding will help to assess previous political and technical measures and will provide the basis for the development of new sustainable strategies for economic and societal developments.

Only a systemic approach can initiate technology and policy measures as well as societal and educational developments to improve air quality and counteract climate change in a sustainable manner, in Europe and worldwide.

Our vision is to achieve this objective by a trans-disciplinary research approach covering atmospheric sciences, scientific computing and mathematics as well as economic and social sciences.

Why a "Systemic View"?

The Earth system as a whole is what we would call a really complex system. General attributes of complex systems are the large numbers of characteristics, which are not easily accessible, which develop individually in a very dynamical way and which mutually interact. Another property of complex systems is a—sometimes large—time delay between cause and effect. Generally, from their evolutionary development human beings are not suited to handle complex systems. Humans usually tend to think and act in a linear way and, thus, to solve problems systematically; one step after the other, assuming that one problem has only one solution. In doing so, immediate effects may be considered. Cascading effects, feedbacks or different specific effects as a result of a singular cause are usually not considered at all. Our causality understanding, which is obviously an inherited behaviour, presupposes some principal rules: (1) the cause occurs before the effect, (2) cause and effect occur together, (3) cause and effect occur close in time and space and (4) cause and effect resemble each other. This human pattern of behaviour makes it difficult if not impossible to act well-directed in situations where at a first glance causes and effects seem to be not directly related to each other or the time lag between causes and effects is counted in decades or centuries.

Another aspect to solve problems in complex systems is that usually the seemingly most important problem is solved first, very often controlled by its conspicuity or by the available competences. If problems encompass different disciplines, often the methods of one subject area are used to solve problems that are outside one's subject area. And, last but not least, the importance to monitor the results and the reactions of a system to a specific measure is often neglected.

These are exactly the main problems with processes such as climate change. The temporal and spatial course of processes within the Earth system following global change is not within the reach of the rules stated above. In addition, there are many disciplines involved, and monitoring effects need a lot of time, large efforts and sometimes cause high costs. Although numerical models as well as their spatial resolution were getting significantly better in the last years and computing power increased considerably, the predictability of future developments regarding global change is still extremely low and uncertainties are high. Nevertheless, assessing developments in the past should make us aware of the fact that we face complex problems. We have no choice but to accept the challenge and to learn how to deal with this complex system and its compulsory complex solutions.

The Case of Chlorofluorocarbons

The invention of chlorofluorocarbons (CFCs) in the 1920s may be taken as an example. These chemicals have excellent properties: they are nontoxic, chemically inert, inflammable, and offer a wide field of applications such as refrigerants, foaming agents and degreasing solvents. 50 years after the start of industrial production and use of these compounds James Lovelock, a British chemist, invented the electron capture detector, a special instrument to detect halogenated trace gases in the atmosphere. While measuring the CFCs in the atmosphere he quickly recognized that the total atmospheric burden corresponded more or less to the total amount produced up to that time. A few years later Sherwood Rowland and Mario Molina, two atmospheric chemists at the University of California, detected that the only way to remove these compounds from the atmosphere is the transport from the troposphere into the stratosphere followed by the breakdown of the molecules due to the solar ultraviolet radiation. This process, however, led to the production of chlorine, which in turn in a catalytic process is able to destroy ozone. Rowland and Molina warned that the increasing concentrations of CFCs will lead to a significant destruction of the ozone layer, which protects all life forms (including humans) against ultraviolet radiation. However, this warning was not taken seriously. Another 10 years later the ozone hole over Antarctica was discovered. Following four years of intensive research, halogens such as chlorine and bromine originating from CFCs were identified to be the cause of ozone destruction. These findings finally led to the Montreal Protocol, which entered into force in January 1989, banning the production and use of these environmentally hazardous compounds.

On the one hand, this is a classic example for the temporal and spatial behaviour of causes and effects in atmospheric processes. The time lag between the invention of CFCs and the effect in form of severe ozone depletion is counted in decades. While the vast amount of these compounds were emitted in the northern hemisphere, the most significant and visible effect occurred over Antarctica. On the other hand, this is an optimistic-provoking example for the capability of mankind to act well-directed under the urge to save the protective shield against the life-destructive ultraviolet radiation.

The Time Delay of Climate Effects

Climate effects behave in a very similar way. We are significantly increasing the concentration of greenhouse gases. With the change in land use we change the albedo of the Earth's surface. With increasing emissions of other gases and particulate matter we change the radiative transfer in the Earth's atmosphere. As a consequence, the temperature started to increase and will continue to do so. It may take decades before noticeable and hazardous effects will occur. Regarding the oceans, reaction times are even longer, in some instances hundreds of years. Some of these reactions will have positive feedbacks still increasing the impacts. And some of these reactions will lead to so called tipping points, where parts of our Earth system will irreversible migrate into a new steady state. The loss of the rain forests due to continuous droughts, the deglaciation of the northern hemispheric ice cap, or the disappearance of the Asian monsoon would be such tipping points.

Climate Reductionism

There are a number of key issues in the context of the complex phenomena connected with climate change and our response to it. Presently, there are a number of weaknesses in our behaviour regarding the obvious changes in the Earth system.

Greenhouse gases are naturally and anthropogenically emitted infrared active trace gases in the atmosphere. The most important greenhouse gas is water vapour, the concentration of which is affected by climate change leading to a so called positive feedback mechanism. A warmer atmosphere can take up more water vapour leading to an increase in global warming. Other greenhouse gases are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). Additionally, there is a large variety of entirely anthropogenic greenhouse gases like SF_6, the chlorofluorocarbons (CFC), and a number of other gases. The global warming potentials of these compounds are by orders of magnitude larger than those of the also naturally emitted gases. The fully halogenated compounds were abandoned by the Montreal Protocol and the follow up protocols leading to significant depletions of the gases since then. CO_2 and a few other greenhouse gases are under the restrictions of the Kyoto Protocol with more or less questionable results.

However, despite of these facts and the meanwhile profound knowledge of the concentrations and distribution of these gases and their effects on the Earth system, the discussion of necessary political and societal responses to climate change with respect to environmental issues, changes in energy "production" and consumption, transport strategies, is usually reduced to the carbon dioxide emissions.

Integrating Natural and Social Scientific Work

If we talk about a "complex system" such as the Earth system we actually have to be aware that we have to deal with two different types of complexity, a structural complexity and a behavioural complexity. The structural complexity of a system increases with an increasing number of components and interactions. This type of complexity can be described by quantitative characteristics. The number of elements or subsystems and the number of interconnections are measurable and can eventually be described by a reduction to key parameters determining the interactions.

Behavioural complexity has a qualitative characteristic. Here properties of the system as a whole and the relationships and processes between the subsystems have to be considered. These relationships and processes are characterised by a non-linear behaviour. They are dependent of their previous history, and, usually, not predictable. Furthermore, the structure and the state of the system can be significantly altered by dynamical interactions as well as feedback mechanisms. This becomes especially noticeable as soon as human interactions come into play. These interactions cannot be described by a linear approach and simple "cause and effect" processes, because they occur on different temporal and spatial scales. Furthermore, local interaction can lead to emergent phenomena in the global structure of the system as a whole.

To account for these facts, both quantitative and quantitative approaches to an understanding of the system as a whole have to be considered. This means, natural sciences describing physical and chemical processes and interactions are necessary but not sufficient to increase our understanding of the system. Social and economic science has to be included in order to investigate and assess also the interactions between humans and the environment.

All present studies and projects mainly focus on natural scientific work, investigating the on-going changes in our atmosphere and the processes responsible for these changes. If ever, an integration of social or economic science is only realized to a very small extent. The transfer of theoretical knowledge into practical actions has not at all been investigated up to now. The question, if researchers give the right information in the right way to the right addressees is not even partially answered. At the same time an assessment, if and how decision makers make use of scientific results in the development of actions and measures is also lacking, as is an assessment of the measures taken so far. The question in which way specific measures affect the atmosphere and, even more important, if these measures probably produce unwanted trade-offs, seems not to be asked.

To understand today's climate it is, of course, necessary to understand the development of climate in the past. However, this knowledge is not simply transferable to the future. Small variations in the initial conditions, incalculable positive or negative feedbacks, unforeseeable variations in external forcings, and unpredictable human behaviour may considerably change the development of the system. Any decision or measure aiming at a (positive) influence on the climate system depends on a vast variety of processes, parameters and interactions. In a complex and non-linear system it is impossible to generate planning reliability. However, predictions that usually are based on different potential scenarios can be improved if we take into account dynamical interactions as well as non-linear behaviour, and also simulate possible surprising effects. In addition, it is indispensable to continuously assess measures and decisions regarding their impact on air quality and climate.

One of the objectives of the Research Network is the development of concepts to successfully build a bridge between natural and socio-economic sciences.

The Systemic Approach

Our research aims at a as far as possible quantitative understanding of the key processes of the system as a whole, both the interdependencies of atmospheric processes and parameters and the interaction between physico-chemical and socio-economic processes. This will help to assess previous political and technical measures and will provide the basis for the development of new sustainable strategies for economic and societal developments. Only a systemic approach can initiate technology and policy measures as well as societal and educational developments to improve air quality and counteract climate change in a sustainable manner, in Europe and worldwide.

Our vision is to achieve this objective by a trans-disciplinary research approach covering atmospheric sciences, scientific computing and mathematics as well as economic and social sciences. Thus, we need to apply a highly non-linear, cross-linked thinking to take the challenge of counteracting climate change. We need a new degree of abstraction. We have to abandon well established strategies and break new grounds.

An Example of Unconsidered Interdependencies

The conflict between air pollution mitigation measures, economic and technological measures and chemical processes in the atmosphere is shown taking the air pollutant nitrogen dioxide (NO_2) as an example. The NO_2 issue became evident through the introduction of new European limiting values in January 2010, which are currently still exceeded in many European areas. The reason for this is manifold and partly caused by unconsidered interdependencies:

- The introduction of continuously regenerating particle traps, e.g. in public busses in the city of London, led to reduced particle emissions but unexpectedly to increased emissions of nitrogen dioxide (NO_2).
- During the economic crisis in 2008 Germany subsidised purchasing new cars in order to support car manufactures. Accordingly, the introduction of low emission vehicles, such as EURO-6 cars, into the car fleet is now delayed several years. Thus the compliance of new NO_2 limiting values will be achieved much later than expected.
- Not even taken into account is the fact that increasing NO_2 concentrations are also caused by the yet unexplained increase of background ozone concentrations.

The example of NO_2 shows impressively in a nutshell the impact of so far disregarded interdependencies on the "reacting atmosphere" and the necessity of a systemic approach.

A First Step Towards a Systemic Approach

Currently, hydrogen (H_2) is intensively discussed as a major element of future energy supply in order to reduce the emission of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4). However, the production and supply chain of hydrogen in a future global hydrogen economy is inevitably accompanied by leakages leading to an increase of hydrogen in the atmosphere. As a consequence, this could yield a significant increase of water vapour concentrations in the stratosphere, which impacts the ozone layer and surface climate, two areas of high societal relevance.

Previous studies focused only on particular aspects, but did not consider the whole supply chain and its impacts. Therefore, the possible impact of a future hydrogen economy was investigated as a first attempt in a systemic approach. A sophisticated atmospheric model was combined with available scenarios for future economic, population growth and implementation of a future hydrogen economy. In addition, the range of possible production and leakage rates of hydrogen was analysed in a technical assessment considering the complete process chain from production to utilization.

In contrast to previous studies the systemic approach showed that the impact of a future hydrogen economy on stratospheric ozone will be most likely of minor importance. Thus, hydrogen may be used as a promising future energy carrier. This example shows that only through the systemic approach a more realistic assessment of the potential impacts of a hydrogen economy was achieved.

The Strategy of the Research Network

More than half of mankind is living in urban areas being responsible for almost 80 % of global greenhouse gas (GHG) emissions. To cut emissions, technological solutions are not sufficient as their effects may be overcompensated by economic growth and rebound effects. Therefore achieving ambitious GHG reduction goals requires a holistic approach, including the consideration of consumer behaviour and social innovations as important topics. Additionally, urban climate protection strategies can only be successful if they pay attention to additional ecological (e.g. air quality) and societal targets besides the climate issue.

Being aware that a systemic view is not an easy task, but inevitable to enhance our understanding and prediction capabilities, the Research Network will start by focusing its research activities on two regions.

The Rhine-Ruhr Metropolitan Area as a First Focus

One research focus will be the Rhine-Ruhr Metropolitan Area as a typical example of a large sprawling urban area. This region, which is possibly the biggest European agglomeration, is comparably well understood in terms of anthropogenic emissions and looks back on a 50 years record of corresponding political and technological measures. In addition, the Research Network "The Reacting Atmosphere" can build on a high-quality database for air quality issues as well as a profound understanding of the socio-economic system in this area. It is thus an ideal starting point for the development of a systemic approach.

Innovation City

Shaping sustainable urban infrastructures is a complex process and experience is scarce. The project "Innovation City Ruhr" was started as a multi-dimensional and transdisciplinary real world experiment, which has a crucial role in the transition cycle. The aim is to learn more about achievable urban transition goals, socio-economic system interactions, alternative transition options and their characteristics and impacts.

In November 2010 the city of Bottrop located in the middle of the industrial heart of Germany was appointed "Innovation City Ruhr". The aim is to cut GHG emissions in a representative district with about 69.000 inhabitants by 50 % within 10 years. Additionally "better living" conditions shall be achieved.

Compared to many other projects "Innovation City" is going a step further. Society and technology are inextricably intertwined and science has the role to support the transition process, to help developing experiments and to trigger learning projects. The comprehensive accompanying research programme is being organized by one partner of the Research Network. The project brings together different disciplines and experiences. It works as a transmission belt between researchers, the planning team, investors, and political decision makers. Thus, research provides first-hand information and insights, which are absolutely crucial for national and international transfer of practical experience.

East Asian Megacities: Towards a Quantitative Understanding of Chemistry-Climate Interactions

The results from the Rhine-Ruhr Metropolitan Area will be used for corresponding investigations in the East Asian megacities. There, population growth and economic developments lead to severe air pollution being significantly higher than in any European area. In addition, this region has a significant impact on global air quality-climate interactions. This is based on emissions of greenhouse gases and their precursors combined with a special meteorological condition known as the Asian monsoon circulation, which amplifies the impact of these emissions.

Recent studies show that this circulation leads to rapid transport of large amounts of pollutants from the lower to the upper atmosphere (up to 20 km), which is extremely climate sensitive. From there, pollutants are readily dispersed around the globe.

A good example for the importance of the Asian monsoon circulation is its impact on stratospheric aerosols (sulphuric acid droplets). This aerosol was recently observed to increase, though the global sulphur emissions are decreasing. The reason is obviously the tremendous increase of sulphur dioxide (SO_2) emissions in densely populated regions of China since 2002, most likely in connection with the effective transport into the stratosphere via the Asian Monsoon circulation.

This convincing example underlines the importance of investigating physico-chemical processes in the atmosphere simultaneously with socio-economic processes determining important emissions of greenhouse gases and their precursors.

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