BELGIAN SCIENCE POLICY

Belgian global change research 1990-2002

Synthesis of the assessment and integration report

Main editors:
G. den Ouden, M. Vanderstraeten

Science writer:
P. Raeymaekers

.be

Results of global change research activities realised between 1990 and 2002, supported by the Belgian Federal Science Policy Office (BELSPO), were subject to an assessment and integration in 2003 and 2004. This process focussed on a selection of scientific information, based on data voluntarily provided by Belgian researchers, and resulted in two reports:

- ✓ Belgian global change research 1990 – 2002: Assessment and integration report
- ✓ Belgian global change research 1990 – 2002: Synthesis of the assessment and integration report

This report is the synthesis of the assessment and integration report, and is also available in Dutch and French. Those who wish to go deeper can go to this complete report. Both reports emphasise the following four topics:

- ✓ Atmospheric composition changes
- ✓ Climate changes
- ✓ The role of the ocean in global change
- ✓ Global change impacts on ecosystems

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Note of the Minister

Global changes have important consequences, both social and economic, in fields of action such as renewable energies, transport management, industrial emissions, ...

This is why, as the Minister in charge of Science Policy but also Energy, the Economy, and Foreign Trade, I base my actions on close interaction between my areas of competence.

At the societal level, global changes caused by human activities have led to soil depletion, disturbances in ocean currents, reduced biodiversity, changes in the atmosphere, ... These changes mean that it is necessary to transform our patterns of production, consumption and organisation within society. Here, science and technology have an essential role to play in the elaboration of strategies for preventing changes, attenuating them, or adapting to them.

At the economic level, summits like those of Kyoto, Buenos Aires, and Johannesburg enable us to reconsider the economy in a global perspective, integrating the sustainable development principle into our energy, environmental and mobility policies.

Lastly, it is increasingly clear that the environment will become an asset giving Europe a competitive edge. Well-designed environmental policies favour innovation, create new markets, and reinforce competitiveness through more efficient use of resources and via new investment opportunities. In this sense they can contribute to reaching fundamental objectives of the Lisbon strategy: growth stimulation and job creation.

A technological breakthrough is needed in order to meet the Kyoto challenge. The role of public authorities is to create a climate favouring innovative advances in the fight against climate change. By generating economic niches, such a policy induces a win-win synergy between the three pillars of sustainable development.

Today at all levels - national, European and international - only an integrated policy associating scientists, industrialists, policy-makers and citizens will make it possible to assure the survival of our planet so that we can pass on to future generations this exceptional heritage.

I wish to thank all the authors of the report 'Belgian global change research 1990-2002: Assessment and integration report' for their excellent work. This report contributes to better understanding of the problems we must face. It will be a precious tool for policy-makers, pointing them towards the most appropriate solutions at the local, regional, national and supranational levels.

Marc Verwilghen,
Federal Minister of Economy,
Energy, Foreign Trade and Science Policy

Foreword

Research is the cornerstone of any science. Its goal is to improve our general understanding of things around us. With increasing understanding of relationships between natural and anthropogenic activities, global change research is crucial to selecting policy objectives related to environmental protection, human well-being and economic development. It is recognised as a major pillar of the European Sustainable Development Strategy (Göteborg 2001) and of the implementation plan of the UN World Summit on Sustainable Development (Johannesburg 2002). Current European research policy towards global change research tends to reinforce cooperation between European and global research initiatives.

Results of global change research activities realised between 1990 and 2002, supported by the Belgian Federal Science Policy Office (BELSPO), were subject to an assessment and integration. This process focussed on a selection of scientific information and resulted in the following two reports:

- ✓ Belgian global change research 1990 – 2002: Assessment and integration report
- ✓ Belgian global change research 1990 – 2002: Synthesis of the assessment and integration report

The thematic sections of the assessment and integration report are structured around policy-relevant questions and answers. Apart from policy-supporting tools and neutral advice, this 'state-of-the-art' knowledge document also provides an overview of the relevant scientific knowledge and expertise in Belgium. It seeks to explain what the challenges are that global change puts before us, what views Belgian and international scientists hold about global change and its impact, what their research results are and how these can contribute to better decision-making and policy development.

The active and enthusiastic involvement of so many scientists in producing this report and the good collaborative spirit among them proves that there is a 'Belgian global change research community', sharing knowledge and ideas. Although the task was complex and very different from their daily work, they experienced the translation process of research outputs into a policy-oriented document as interesting and instructive. A large proportion of the scientists that contributed to this process is unfamiliar with policy actors and views the area between these actors and themselves as a twilight zone. They have expressed the feeling that this report will contribute to bridging the gap.

To make this assessment and integration report accessible to both policymakers and the general public, an additional concise interpretation has been drafted by a science writer. This resulted in a synthesis report that has been further edited by the main editors G. den Ouden and M. Vanderstraeten in close co-operation with the science editors named hereafter.

Within Belgium, the 'Scientific support plan for a sustainable development policy' (SPSD) programme is one of the major initiatives funding global change research. The Belgian Federal Science Policy Office also acknowledges the importance of other partners, international or Belgian, that contribute to the funding of Belgian global change research.

I would like to thank the science editors from the complete 'Assessment and integration report': R. Zander (ULg-GIRPAS), M. De Mazière (BIRA / IASB), J.-P. van Ypersele (UCL-ASTR), R. Wollast and J.-P. Vanderborght (ULB-OCEAN), and R. Ceulemans and I. Nijs (UA-PLECO). In particular, I wish to pay tribute to Prof. Wollast, who passed away recently. His last contribution to the production of this report proved his scientific expertise, his skill at synthesizing, and his holistic view of global change issues. His death is a great loss to the international scientific community.

I wish to express my sincere gratitude to all the scientists on whose work the report is based and those who participated actively in the assessment and integration process, to the involved BELSPO colleagues, as well as to the science writer, reviewers, translators and language revisers. I hope that such fruitful collaboration will continue.

Dr. Philippe Mettens,
Chairman of the Board of Directors

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Introduction: global change, a world in motion

Background

It is becoming increasingly clear that man's impact on his environment is no longer limited to disturbances of a local or regional nature, but that he is changing the world in its entirety. All changes in the environment on a global scale – which, of course, can have a natural origin as well – are called 'Global Change'.

Changes that affect the entire planet include alterations in atmospheric composition, climate, water sources, land use, land cover, and ecosystems. According to many scientists, it is becoming increasingly clear that man plays a role in these changes, because humankind is taking up more and more space and moulding nature to its will. Man is consuming the earth's natural resources and emitting pollutants through industry, agriculture, transport and households. These change the composition of the soil, atmosphere, rivers, seas and oceans, which as such have an impact on the climate, ecosystems and biodiversity.

All these changes have repercussions on the living conditions and health of man himself. Natural goods and services that he consumes (food, water, air and a healthy environment) can be put under stress as a consequence of changes in the global environment. Thus, damage to the ozone layer leads to more harmful solar rays on earth; climatic changes induce droughts in some areas that lead to a disruption of agriculture or create extreme weather conditions with serious consequences such as floods; changes in ocean currents and temperature affect climate systems, transport routes, and fish stocks; and so forth.

Global environmental change impel policy- and decision makers to have appropriate tools to face this challenge. For developing these tools, the behaviour of the system earth needs first of all to be well understood.

Global change research

Complex interactions and uncertainties

The precise mechanisms with which human activities and natural processes influence the earth are not easy to understand. Indeed, the interactions between the various natural components and in particular between man and his environment are diverse and complex. It is even more difficult to assess or predict the impact of all these changes on ecosystems and our own lives.

Policy and science

An understanding of the world around us and the interactions between man and nature are an absolute necessity. Decision makers and policymakers need independent advice and access to research and its results. Research and science provide crucial insights into the functioning of the earth's ecological system; contribute to the assessment of the impact of global change; facilitate the prediction of risks; sound a timely alarm when problems emerge; develop indicators, measuring instruments and sustainable technologies; … and so much more. Research and science enable decision makers to constantly test their visions and decisions against reality and the expectations of how the future will evolve. Still, the scientist must remain cognizant of his limited role: scientific expertise and knowledge constitute only one element in the decision-making and policypreparing process. National and international political decisions and policy documents regarding global change that Belgian scientists have been involved in are recorded in Annex 5 of the full 'Assessment and integration report' and cover the topics: air quality, stratospheric ozone, climate change, Antarctica, protection of nature and biodiversity, water, land use, marine environment, agriculture and forestry, and sustainable development.

Organisation of research

Worldwide

Given that global change is a worldwide phenomenon with origins in, and impact on, a variety of domains, international policy and collaboration as well as research on this subject must be tackled from a global and interdisciplinary standpoint. Collaboration within international organisations and programmes is, therefore, the most effective approach. That is why global initiatives – such as the 'International Geosphere-Biosphere Programme' (IGBP), 'International Human Dimensions Programme on Global Environmental Change' (IHDP), 'World Climate Research Programme' (WCRP) and the 'international biodiversity programme' DIVERSITAS – are coordinating the research of scientists all over the world (see Box 1). Since 2001, these four primary research programmes have formalised their collaboration in the 'Earth System Science Partnership' (ESSP). The aim of this partnership is to find answers to fundamental questions about the earth as a system in order to formulate pro-active measures that underpin, in a scientific manner, decision- and policymaking regarding the global change issue. The organisations that sponsor research have also united themselves in a discussion platform called IGFA (International Group of Funding Agencies for Global Change Research).

Europe

Within the European research programmes, the environmental issue has evolved significantly. Initially, these programmes focused primarily on environmental protection, but in the 6th Framework Programme (FP6, 2002-2006) this research component has been integrated around sustainable development. One of the priorities is the research topic 'Global Change and Ecosystems', with the objective of directing the European strategy for sustainable development and the EU 6th Environment Action Programme (6EAP, 2001-2010) on the basis of scientific understanding.

At the European level, the European Science Foundation (ESF) is also a major player. With its 'Collaborative Research Programmes' (EUROCORES), the ESF seeks to bring together national organisations that subsidise fundamental research and have them collaborate on multidisciplinary topics that have relevance on a European scale. Global change is regarded as a major topic in this initiative.

Belgium

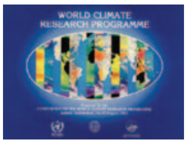
The existence of international research programmes does not exempt national institutions and political authorities from stimulating and continuing to support global change research at the national and regional levels. Although global change is a worldwide phenomenon, its impact will differ from one continent to another and among regions on the same continent. Research on a local scale thus remains a need, but it does not immediately provide answers to questions about the impact of global change on the global scale. Each individual researcher or research group can study only certain sub-aspects of global change. When it comes to getting a comprehensive picture of causes and impacts, general policy lines, and scientific support, it is necessary to access the international or global level, incorporating

Box 1: International research programmes regarding 'Global Change'

Because of the worldwide character of global change and its complex impact on a variety of domains, scientific research needs to be coordinated and integrated on a worldwide scale as well. This is happening through the following organisations:

The 'International Geosphere-Biosphere Programme' (IGBP) focuses primarily on the earth's geochemical components (ocean, land and atmosphere) and their connection. (www.igbp.kva.se)

The 'International Human Dimensions Programme on Global Environmental Change' (IHDP) is an international, interdisciplinary, non-governmental research programme promoting and coordinating research concerning the human dimensions of and in global change. (www.ihdp.uni-bonn.de)



The 'World Climate Research Programme' (WCRP) seeks to enlarge the fundamental scientific view of the climate system and processes to be able to forecast climate more accurately and to assess the impact of humankind on climate change. (www.wmo.ch/web/wcrp/wcrp-home.html)

DIVERSITAS is an international research programme concerning biodiversity, supporting policy regarding the preservation of species and sustainability. (www.diversitas-international.org)

The 'Earth System Science Partnership' (ESSP) is the platform in which the IGBP, IHDP, WRCP and DIVERSITAS have formalised their collaboration to answer fundamental questions about the earth, so that policy decisions can be supported by scientific evidence and a sustainable management of the environment worldwide becomes possible. (www.ess-p.org)

The European Sixth Framework Programme (FP6, 2002-2006) finances global change research, primarily funded under the thematic sub-priority "Global Change and Ecosystems". It is intended to develop the scientific, technological and socio-economic basis and tools necessary for the study and understanding of changes in the environment. It emphasizes global and regional environmental problems that may have a significant impact on Europe, such as climate change, ozone depletion, biodiversity loss and reduction in the fertility of the soil. (www.cordis.lu/sustdev/environment)

The European Science Foundation (ESF) promotes the development of European science at the forefront of knowledge by bringing together leading scientists and scholars and research and funding agencies to debate, plan and implement European research in all fields, including global change. One of its initiatives to implement research and networking is the ESF Collaborative Research Programmes (EUROCORES). (www.esf.org) the research results and interpretations of all individual scientists. For this reason it is important not only to support researchers in their research, but also to enable them to set up and develop national and international networks and give them the opportunity to acquire a place within international research programmes.

Belgian Federal Science Policy Office

In response to the international IGBP initiative, the Belgian Federal Science Policy Office (BELSPO) started its own 'Global Change' research programme in 1990. This programme supports global change research primarily via: multiannual research programmes, financing federal scientific research institutes, securing bilateral collaborative agreements, its space programme, and the activities that fit within the 'Scientific Support Plan for a Sustainable Development Policy' (SPSD).

Products and expertise in support of policymaking

Types of results

The full 'Belgian global change research 1990-2002: Assessment and integration report' contains an overview of the various BELSPO research activities regarding global change and examples of relevant results (e.g., Annexes 1, 2 and 3).

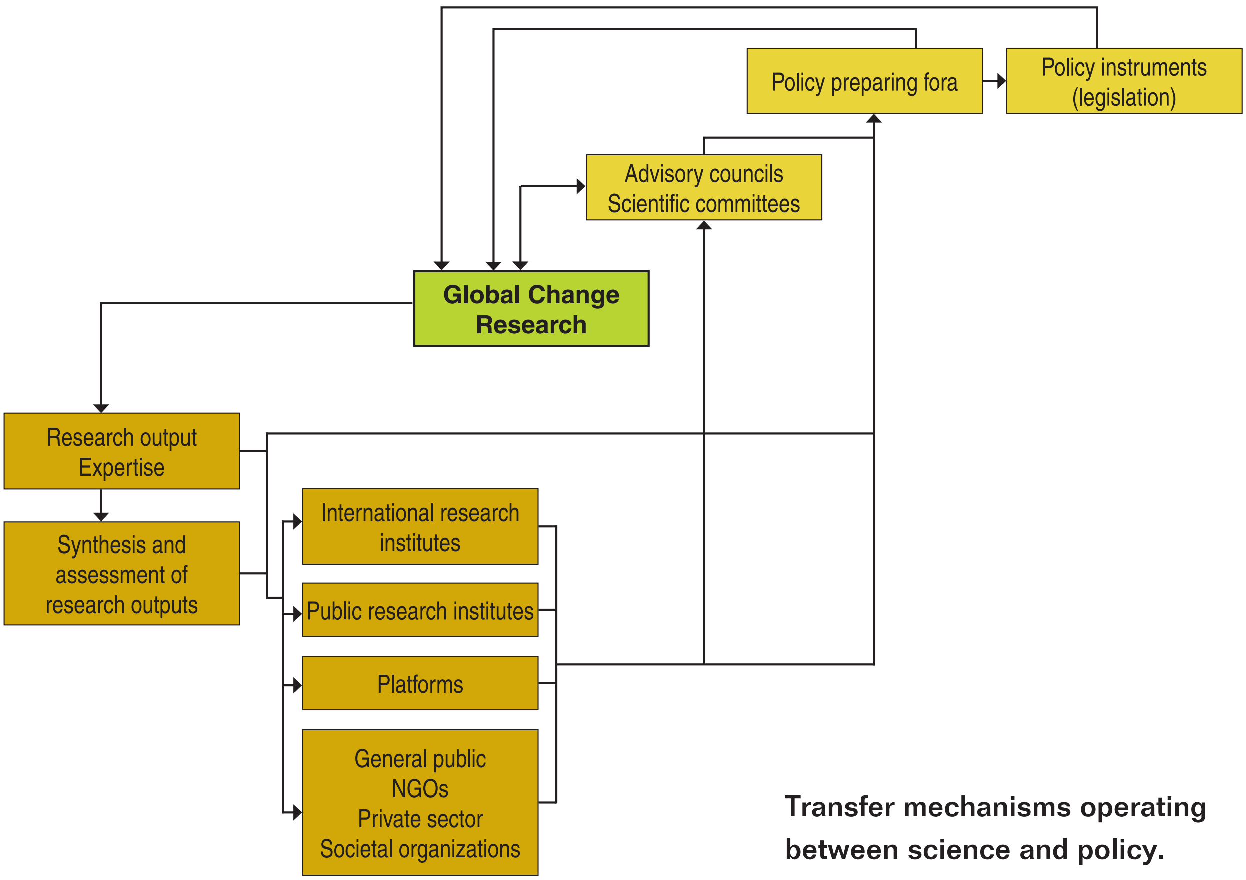
The research projects supported by BELSPO lead first of all to a broadening and deepening of knowledge. The scientific results of the projects are published in scientific journals and the general media, among others, and are integrated into international 'assessment' activities. In addition, they provide specific, practical products as well as expertise that are important for the development, implementation and monitoring of national and international policy.

The results and products that the research has generated can be classified as: measurements and inventories; analyses; demonstration projects and pilot studies; descriptive, predictive, and impact models; long-term data series; databases; maps; measuring instruments and calculation methods; standards; methodologies; manuals; indicators; information systems (incl. websites) and discussion platforms; policy instruments and recommendations; etc. Furthermore, the scientist is also indispensable as an expert both in translating and interpreting the research results with regard to policy as well as in scientific verification of policy.

Integration

Scientific results and expertise are only useable for policy support when they are integrated correctly into the decision-making process. That is why a worldwide, intensive dialogue between scientists and policymakers is essential. The current dialogue needs to be further formalised, consolidated and strengthened. At the same time, the knowledge base must be further developed to be able to respond quickly and effectively to the large challenges of global change. There are various transfer mechanisms for conducting this dialogue, as summarised in the figure on the next page.

Scientists' results are widely disseminated via a variety of communication channels: scientific journals, overview publications, general newspapers and magazines, conference presentations, participation in public debates, etc. Besides these traditional channels, there is also a lot of attention being paid internationally to assembling research results in synthesis and assessment reports. Scientific assessments contain detailed, but also integrated, state-of-the-art scientific and technical information in a particular domain. Frequently, a synthesis report and/or summary is attached for policymakers. Sometimes assessments are drawn up especially to meet the needs of an



Transfer mechanisms operating between science and policy.

international convention. That is the case for the 'Millennium Ecosystem Assessment' on behalf of the UN Convention on Biological Diversity (CBD) and the Ramsar Convention. The IPCC (Intergovernmental Panel on Climate Change) climate change assessment constituted the basis for developing the United Nations Framework Convention on Climate Change (UNFCCC), while the series of UNEP (United Nations Environment Programme) - WMO (World Meteorological Organization) scientific assessments regarding ozone depletion led to various amendments and adaptations to the Montreal Protocol.

In addition to national and international policymakers, synthesis and assessment reports also reach the general public, NGOs, industry and numerous other societal organisations, which in turn influence the decision-making process.

A recent phenomenon is bringing researchers together with potential users of research results in so-called thematic platforms. These are opportunities for scientists to interact with other scientists, the decision makers involved, and the general public. Finally, scientists are involved in policy support and development regarding the global change issue in various consultation structures (such as councils and committees) at the local, regional, national, European and global levels.

Role of BELSPO in research and dialogue

Acquiring all the scientific knowledge necessary to answer the questions about global change is far beyond the reach of the individual scientist, institute, community, country or research discipline. Therefore, as indicated above, BELSPO stimulates research programmes that fit within an international context. Emphasis is placed on topics in which Belgian scientists have, or can develop, expertise.

To fulfil this aim, the BELSPO global change research programmes have undergone profound change over the course of time – evolving from mono-disciplinary into multi-disciplinary programmes striving towards including user groups in projects and clustering projects (see Box 2).

Box 2: Objectives of global change research supported by BELSPO:

- ✓ To consolidate the scientific potential in Belgium.
- ✓ To support policy preparation and implementation on the regional, federal, and international scales.
- ✓ To stimulate participation of Belgian scientists in international research networks and international assessment and integration efforts.
- ✓ To promote multidisciplinarity and networking at project level.
- ✓ To integrate and synthesise research results for policy actors and the public at large.
- ✓ To enhance the dialogue between policy actors and scientists.

1. Changes in the atmosphere

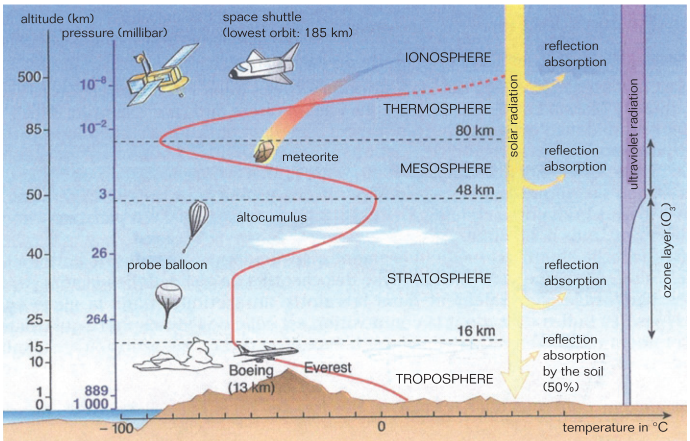



The earth is surrounded by a mixture of gases that together constitute the atmosphere (see Box 3). This atmosphere has several layers, each with specific properties. Without the atmosphere, life on earth would not be possible.

During the last 150 years (referred to as the industrial era), the composition of the earth's atmosphere has undergone relatively dramatic changes. These include a sharp increase in carbon dioxide (CO_2) concentrations, which has consequences for the climate. In addition, the quantity of microscopic particles (aerosols) has increased in the lowest layer of the atmosphere. This not only has consequences for the climate, but it also affects our health. However, not all changes can be easily expressed as linear increases or decreases. An increase of ozone (O_3) is evident in the troposphere (the lower part of the atmosphere) while a decrease is occurring in the stratosphere (see Box 4). This is most pronounced in the polar regions, where one speaks of the 'hole in the ozone layer'. However, a progressive thinning of the ozone layer is also occurring over Belgium.

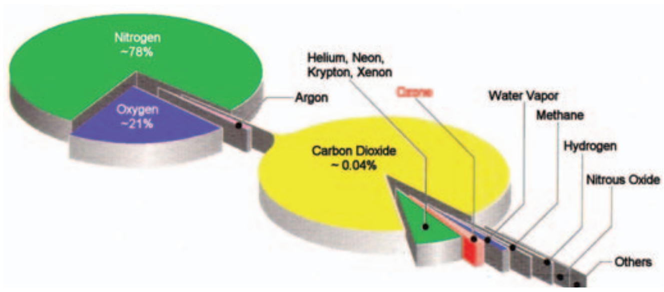
Indications are accumulating that mankind is causing these changes. Via their dwellings, industry, transport and agriculture, humans emit gases and particulate matter into the air that have a direct or indirect effect on the composition of the atmosphere and that lead to a variety of environmental problems. We will restrict ourselves in this chapter to ozone and aerosol issues. Climate change is treated in Chapter 2.

Box 3: The atmosphere, its structure and composition



The atmosphere consists of several layers, each of which is characterised by its own temperature curve as a function of altitude. In the lower layer (the troposphere), the temperature decreases gradually with increasing altitude. At about 10 km, the temperature gradient reverses and the air becomes gradually warmer with increasing altitude. This layer (the stratosphere) extends from about 10 to 50 km. The mesosphere is located at an altitude of 50 to 100 km, where the temperature again lowers, only to finally reverse once more and increase in the thermosphere.

The atmosphere is composed mainly of nitrogen (N_2, 78%) and oxygen (O_2, 21%). It also contains a broad range of less prevalent gases. Although less significant in terms of quantity, they still exercise an important influence on the climate and on the filtering of harmful solar rays. The two gases receiving the most attention today are carbon dioxide (CO_2) and ozone (O_3). The first has a concentration of 0.04% in the atmosphere, while ozone occurs in the stratosphere in a concentration of 0.0003% – three ozone particles per million air particles. In addition to gases, tiny drops of fluid and solid particles are also present. These aerosols have a diameter of 1 nanometer (nm) to over 10 micrometers (µm), i.e. from a millionth of a millimetre to a hundredth of a millimetre.



(R. Zander, ULg-GIRPAS).

Box 4: Ozone, the Janus molecule

Ozone is a gas that consists of three oxygen atoms, represented by the chemical formula O_3. It occurs in two places in the earth's atmosphere: 90% is located in the stratosphere and 10% in the troposphere. Ozone has two faces. In the stratosphere, it forms the 'ozone layer.' The ozone molecules in this layer are the 'shielding face' of this gas, because they absorb most of the solar ultraviolet radiation that is harmful to life on earth. Ozone molecules also have a strong oxidizing action and are, therefore, harmful to living organisms. It is better that they are located far from human beings (in the stratosphere, for example). So, ozone at the earth's surface (in the troposphere) constitutes the 'harmful face' of the gas.

1.1 Ozone in the stratosphere

1.1.1 Ozone and the ozone hole

The ozone hole over the South Pole

In the 1970s, scientists like P. Crutzen, M. Molina and S. Rowland demonstrated in the laboratory that some gases emitted into the atmosphere by humans initiate chemical catalytic cycles that destroy ozone. This primarily concerns many compounds that contain nitrogen (N), chlorine (Cl) and bromine (Br). Even at that time, scientists postulated that these substances could be a threat to the stratospheric ozone layer (see Box 5).

At the beginning of the 1980s, a problem with the ozone present in the stratosphere became clearly noticeable. Measurements using ground-based and satellite instruments showed a decrease in levels of stratospheric ozone. In particular, it was found that a large part of the total amount of ozone in the air (known as the ozone column) was destroyed over the South Pole region during the Antarctic spring (September-November). Initially, this decline extended over an area that was 150 times the size of Belgium. It quickly became clear that the hole in the ozone layer was growing larger and deeper each year. In 2000, it was already five times larger, with 70 - 80% less ozone being measured than in the period before 1980.

The rapid expansion of the ozone hole over the South Pole made it clear that the chemical catalytic cycles of N, Cl and Br compounds alone offered an insufficient explanation. Research showed that the destruction of ozone accelerates when the atmosphere becomes colder and when there are more polar stratospheric clouds. In these clouds, non-active ozone-destroying compounds are converted by so-called heterogeneous chemical reactions into active ozone destroyers. The presence of the so-called polar vortex plays an important role in this process as well (see Box 5).

The northern hemisphere is also threatened

It is very important to also monitor the evolution of the stratospheric ozone layer in the northern hemisphere since most people live in this part of the world. Because a reduction in the ozone layer leads to more ultraviolet radiation from the sun reaching the surface of the earth, a decrease in ozone concentrations as occurred in Antarctica could cause serious health problems for all living organisms. Risks to humans include skin cancer and cataracts.

For this reason, the European Union (EU) organised a number of large-scale programmes to study the evolution of the ozone layer over the northern hemisphere. The purpose was to examine whether ozone-destroying processes were occurring similar to those observed over Antarctica. Also, Belgian researchers participated in these programmes via the following projects: the European Arctic Stratospheric Ozone Experiment (EASOE), the Second European Stratospheric Arctic and Mid-latitude Experiment (SESAME) and the Third European Stratospheric Experiment on Ozone (THESEO). Currently, the VINTERSOL (Validation of International Satellites and Study of Ozone Loss) campaign is also operating in this framework.

Measurements have revealed that an Arctic ozone hole has also been present since the mid-1980s. However, this decrease in ozone is less pronounced than that at the South Pole.

In 1997, for example, the maximum decrease in the ozone column was only 22%. Moreover, the yearly fluctuations of ozone concentrations over the North Pole are larger. Overall, research has shown that the ozone depletion processes in the northern hemisphere are similar to those in the southern hemisphere.

Box 5: Ozone formation and destruction: a complex tangle of reactions

The cycle in balance

The four reactions of the Chapman cycle form the basis for the formation and destruction of stratospheric ozone. In the first reaction, the oxygen molecule (O_2) is split into two oxygen atoms by ultraviolet light (UV) with wavelengths of 185 nm to 220 nm (UV-C). In the second step, the oxygen molecule reacts with an oxygen atom (O) from the previous reaction to form ozone (O_3):

$$O_2 + \text{UV-C light (185 – 220 nm)} \rightarrow 2\,O$$
$$O + O_2 \rightarrow O_3$$

The net effect of these two reactions is the production of ozone. However, under the influence of ultraviolet light with wavelengths between 210 nm to 300 nm (UV-B), the ozone molecules break apart into an oxygen molecule and an oxygen atom. Should the latter come into contact with an ozone molecule, two oxygen molecules are formed:

$$O_3 + \text{UV-B light (210 – 300 nm)} \rightarrow O_2 + O$$
$$O_3 + O \rightarrow 2\,O_2$$

This cycle is responsible for the largest part of the stratospheric ozone formation and destruction, but it alone cannot explain the observed ozone concentrations. For this, the additional catalytic cycles need to be scrutinised.

The catalytic cycle

As an example, the catalytic reactions of chlorine (Cl) compounds with ozone are described, but the destructive reactions with nitrogen (N) and bromide (Br) compounds are similar.

Under the influence of UV radiation, the chlorofluorocarbons (CFCs) are broken apart, releasing chlorine atoms. For example, the photolytic reaction of CCl_2F_2 (one of the most common CFCs, sometimes also called Freon-12 or CFC-12) releases the chlorine atom:

$$CCl_2F_2 + \text{UV light (< 260 nm)} \rightarrow Cl + CClF_2$$

This reaction sets the tone for the rest of the process. Further stratospheric photolysis results in the complete degradation of the CFC with a further release of chlorine atoms. These then initiate the destruction of ozone via the following sequence of reactions:

$$O_3 + Cl \rightarrow ClO + O_2$$
$$O_3 + \text{light} \rightarrow O + O_2$$
$$ClO + O \rightarrow Cl + O_2$$
$$\text{Net} \quad 2\,O_3 \rightarrow 3\,O_2$$

The halogen chlorine (Cl) atom is a catalyst for the ozone destruction: the same atom that is consumed in the first reaction of this sequence is released again in the last reaction.

Because of the regeneration of the chlorine atom in the depletion reaction of ozone, we speak of a catalytic cycle. Thus, a single halogen atom can destroy several hundred ozone molecules before it reacts with another gas molecule, e.g. methane, and is rendered harmless. Reactions of these molecules with a chlorine atom lead to hydrochloric acid (HCl), a stable reservoir for chlorine. Another neutralisation reaction takes place between chlorine oxide (ClO) and nitrogen dioxide (NO_2):

$$ClO + NO_2 \rightarrow ClONO_2$$

Regarding ozone depletion, both molecules, hydrochloric acid (HCl) and chlorine nitrate ($ClONO_2$), are temporarily 'inactive' and are called temporary chlorine reservoirs.

It is for the discovery, at the beginning of the 1970s, of the catalytic reactions involving chlorine, bromine and nitrogen oxides and the analysis of their relative importance in the destruction of the ozone layer, that P. Crutzen, M. Molina and S. Rowland won a Nobel Prize in 1995. It was the first time the Nobel Prize recognised research into man-made impacts on the environment. This discovery led to the 1987 United Nations' Montreal Protocol that bans the production of industrial chemicals that deplete the ozone layer.

The accused

The cycle is put out of balance by a concurrence of circumstances. First, there are the ozone depleting substances that are produced by industrial processes and that do not occur in nature on their own. The most active and well-known source gases that lead to the destruction of ozone are undoubtedly the CFCs, which were produced in massive quantities during the 1970s and 1980s. They served as coolants for refrigerators and cooling installations in industry, propellants in spray cans, as filling gases for insulation foam and fire extinguishers, as de-greasing agents and as cleansing agents for the production of electronic micro-chips and optical devices, etc. But CFCs are not the only ozone destroyers certain bromide compounds (the so-called halons) that are used to fight forest fires, that are incorporated into fire decelerators, or that are used to disinfect greenhouse soil, also deplete stratospheric ozone. Finally, certain nitrogen compounds sent into the air via synthetic fertilisers also have a destructive impact on the ozone layer.

Reservoirs and cold clouds

However, chlorine atoms that intervene in the destruction of ozone also originate in another way: from the chlorine molecule (Cl_2) that is formed at the surface of cold polar stratospheric clouds (PSCs). These clouds consist of water crystals and contain sulphuric acid (H_2SO_4) and nitric acid (HNO_3). They have two negative effects on stratospheric ozone:

- ✓ During the formation of these clouds, nitrogen dioxide (NO_2) is removed from the atmosphere and converted to nitric acid. Since nitrogen dioxide is normally a strong neutraliser of the catalytic cycle of chlorine (through the formation of $ClONO_2$), the rate of ozone depletion will be less slowed down.
- ✓ The polar stratospheric clouds form a surface on which reaction among certain gases can take place during the long polar winter. These are so-called heterogeneous reactions: gases that react with each other on a solid

surface. An important heterogeneous reaction that can occur is the following:

$HCl + ClONO_2$ ---- on ice crystals $\rightarrow$
Cl_2 (gas) + HNO_3 (ice)

The result is the accumulation of chlorine molecules (Cl_2) in the dark polar atmosphere. When the sun reappears over the poles in the spring, these released chlorine molecules will dissociate into chlorine atoms (Cl) under the influence of solar light and further participate in the catalytic cycle that destroys ozone.

This complex chain of reactions immediately explains some striking facts:

- ✓ The reason why the ozone hole over the South Pole always occurs during the local spring: the dark, cold winter period is necessary for the 'inactive' chlorine reservoirs to be converted into 'active' chlorine gas. Only when the sun reappears in the spring above the polar horizon, does the chlorine gas dissociate into chlorine atoms that erode the ozone layer.
- ✓ The reason why injecting nitrogen compounds into the atmosphere has an indirect negative influence, in addition to a possible direct impact on the ozone layer: these compounds are temporarily absorbed into the polar stratospheric clouds (PSCs) and are no longer available to neutralise the reactive chlorine oxide radicals (ClO_x).

Some heterogeneous chemical processes can also take place on aerosols that, for example, have entered the stratosphere through heavy volcanic eruptions.

The polar vortex

In addition, the presence of the so-called polar vortex is important with regard to the ozone destruction processes above the polar stratosphere. This is a particular pattern of wind circulation in the stratosphere that occurs during the local winter over the poles. It is generally stronger over the South Pole than the North Pole. The polar vortex prevents stratospheric air above the polar regions from mixing with air from mid-latitudes, which results in a decrease in the temperature. Consequently, the local stratosphere can be regarded as a sealed reaction chamber in which the entire ozone destruction process takes place in a very efficient manner. Variations in the size and depth of the ozone hole result from inter-annual fluctuations in temperature and the intensity and duration of the polar vortex.

A complex system

The catalytic chlorine cycle presented here is only a small part of the chemistry of stratospheric ozone. This takes place in a complex context of numerous important factors: the sun's activity, the presence of clouds and aerosols, the activity of other gases, and the exchange of air between the stratosphere and the troposphere.
In addition, the impact of atmospheric changes makes itself felt in numerous areas: not only on the ozone layer, but also on climate change. That is why scientists must increasingly study the atmosphere and the changes that take place within it as an integrated, multidisciplinary entity. In short, the atmosphere must be regarded as a holistic system.

Nitrogen, chlorine and bromine compounds play the main role here as well: chlorine monoxide (ClO), bromine monoxide (BrO) and nitrogen dioxide (NO_2) are directly involved in the catalytic cycles that break down ozone. Other compounds, such as chlorine dioxide (OClO), can thus function as indicators for the degree to which largely inactive chlorine reservoirs are converted into reactive ozone destroyers.

A change in policy

In 1985, in response to the concern from the scientific community, the United Nations (UN) established 'The Vienna Convention for the Protection of the Ozone Layer'. This agreement was concretised in 1987 in the Montreal Protocol, which established timely regulations for the full suppression of the production of ozone-depleting gases in a series of steps. All major chemical consortia have upheld the initial decisions contained in the protocol, as well as the amendments and adjustments that were introduced later.

The adaptations to the Montreal Protocol were the consequence of continuous and more global atmospheric measurements, as well as new scientific insights. Belgian researchers have provided important contributions to the updating of this Protocol, among others through their participation in the 'assessments' regularly produced by the World Meteorological Organization (WMO). Furthermore, Belgian researchers also participate in various international technical and scientific panels that prepare decision making.

1.1.2 The importance of measurements

Integrating measurements

Changes in the atmosphere are often divided according to the different layers in which they occur (stratosphere and troposphere) or the different components involved – such as ozone (O_3), aerosols and carbon dioxide (CO_2) – each with its own impact on climate, health, ecosystems, biodiversity, etc. While such a distinction may be logical, these classifications are often too simplistic to do justice to a reality that is much more complex. For example, the stratosphere and troposphere are not strictly separated layers in the atmosphere; there is a continuous exchange between both, through which the chemical and physical processes in one layer have an influence on the other. This adds another dimension of complexity for those who want to fully understand the behaviour of the atmosphere. Moreover, the interaction between the stratosphere and troposphere is not at all constant. It is different at the poles than at the equator and it varies according to season.

The link between the various subsystems of the earth's atmosphere means that the evolution in the composition of the atmosphere must be studied in an integrated way and on a global scale. This worldwide integration of observations entails a combination of measurement techniques carried out from different platforms (e.g., on the ground or in the air, including stratospheric balloons, aeroplanes and satellites) and a whole series of complementary measurement instruments. Sometimes, only in situ measurement data is gathered, but often measurements are made from a distance (remote sensing).

For many years, Belgian researchers from ULg-GIRPAS, BIRA / IASB and IRM / KMI have been actively participating in the gathering of measurement data on the atmosphere. Many of these activities have been performed within international networks of measurement stations on the ground, such as the Network for the

Detection of Stratospheric Change (NDSC). One example of a NDSC station that is used by Belgian researchers is the International Scientific Station of the Jungfraujoch (ISSJ) in Switzerland (see photograph below). However, they also contribute to satellite experiments such as the Atmospheric Trace Molecule Spectroscopy Experiment (ATMOS), the Global Ozone Monitoring Experiment (GOME), the European Environmental Satellite ENVISAT, etc. Furthermore, researchers participate in European and internationally integrated research and measurement campaigns, such as EASOE, SESAME, THESEO, VINTERSOL, and the EUREKA Project on the Transport and Chemical Transformation of Trace Constituents in the Troposphere over Europe (EUROTRAC).

Belgian researchers not only make measurements in Uccle (Brussels, Belgium), but also in Harestua (Norway), Jungfraujoch (Switzerland), Haute Provence (France) and Saint-Denis (Ile de la Réunion). To arrive at a global picture, however, these measurements are combined with those of other scientists throughout the world.

High altitude atmospheric monitoring station at Jungfraujoch in Switzerland (3,580 masl).

Belgian scientists are also involved in the design and building of measurement instruments, calibration and validation campaigns, the production of fundamental spectroscopic and kinetic parameters of atmospheric gases, the processing of measurement data and the development of algorithms to convert satellite observations into useful and understandable quantities, such as concentrations of atmospheric gases and aerosols, etc.

Modelling to learn and predict

Researchers use these measurements to set up numeric models that attempt to describe and understand the behaviour of the atmosphere and the underlying processes. This allows them, for example, to obtain better knowledge of the mechanisms that play a role in the build-up and depletion of stratospheric ozone. Moreover, they achieve better insight into the type and magnitude of anthropogenic influences. They can also predict and quantify the consequences of the depletion of stratospheric ozone. Finally, with the aid of simulations they can examine those policy strategies that are most suited to solving the problems like that of the decrease in stratospheric ozone.

Researchers at various Belgian research institutes (including BIRA / IASB are IRM / KMI are developing numeric models that simulate the behaviour of the atmosphere. For example, a unique model was developed by BIRA / IASB called BASCOE (Belgian Assimilation System of Chemical Observations from Envisat). This model is intended to process the data from ENVISAT (an earth observation satellite that was launched by the European Space Agency ESA in March 2002). There are three instruments on board for the observation of various

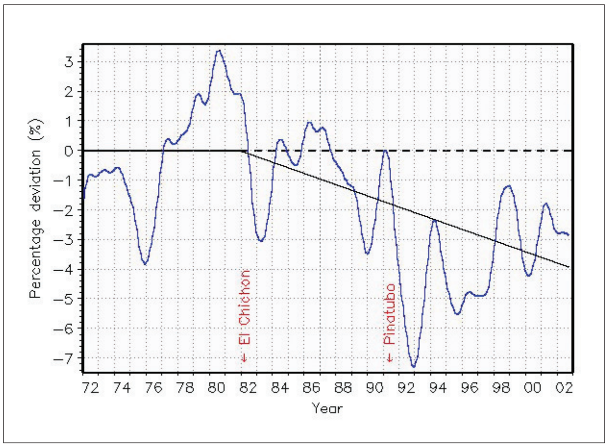
chemical substances in the atmosphere. However, the observations are not continuous, cannot ensure complete geographical coverage in a single day and do not cover all substances.
To improve this situation, BASCOE, which is based on a previous numerical model, makes at the same time use of real ENVISAT measurement data to link the analyses of this numerical model as closely as possible to the reality of the measurements. This model provides uniform information in time and space about the chemical composition of the atmosphere which is consistent with the assimilated observations. Using daily observations, predictions are made regarding the evolution of the chemical composition for the coming eight days. This chemical assimilation and prediction model BASCOE is unique in the world. It is based on one of the most advanced methodologies and is used only by a number of large weather forecasting centres. It also provides indispensable assistance to VINTERSOL (see Section 1.1.1).

1.1.3 The thinning of the ozone layer over Belgium

A negative trend

While stratospheric ozone depletion has been occurring since the early 1980s, mainly over the Antarctic and Arctic areas during the local spring, since the mid 1980s a decrease in stratospheric ozone has also started to occur at middle latitudes. This development needs to be followed closely since there are large populations living in these areas. A decrease in the level of protection against ultraviolet radiation (UV) that stratospheric ozone provides can have considerable consequences for human health.

In the northern hemisphere, the ozone concentration in the stratosphere is continually monitored by, among others, Belgian researchers from BIRA / IASB, ULg-GIRPAS and IRM / KMI (see figure below). They also keep an eye on the concentrations of other gases and other components that influence the depletion of ozone in the stratosphere.



Deviation in percentage of the total ozone column at Brussels-Uccle (Belgium) from the mean between 1972 and 1982. (H. De Backer, IRM / KMI).

Long-term measurements from IRM / KMI indicate that the ozone concentration over Uccle has decreased by an average of 0.27 ± 0.04% per year between 1982 and 2002. This negative trend continues in particular because of strong negative deviations in winter and spring. In addition to a long-term negative trend, strong decreases in the ozone concentration over Uccle were also measured shortly after the heavy eruptions of the volcanoes El Chichón (Mexico, 1982) and Mount Pinatubo (Philippines, 1991). These natural phenomena injected large amounts of aerosols into the atmosphere as far as the stratosphere. Heterogeneous chemical processes take place on these aerosols that are similar to those that take place in the polar stratospheric cloud (PSCs).

'Mini-holes'

Researchers have also found that strong variations in the ozone column can occur from day to day. Over Uccle (Belgium), for example, on certain days the ozone level drops by 30% compared to the long-term average. No anthropogenic factors are involved in the formation of these mini-holes, but they are rather the consequence of dynamic processes. Such mini-holes have also been observed in other places (e.g., in Harestua, Norway, Jungfraujoch, Switzerland, Haute-Provence, France).

1.1.4 Aerosols in the stratosphere

Volcanic eruptions

The atmosphere is not only composed of gases. It also contains aerosols: tiny drops of fluid or solid particles. Their presence in the stratosphere is strongly dependent on the volcanic activity on earth, since heavy volcanic eruptions sometimes send large amounts of these particles into the atmosphere as high as the stratosphere. Stratospheric aerosols consist mainly of a mixture of water and sulphuric acid. Besides the influence that these particles have on the climate (they are a cooling factor – see Chapter 2), they also indirectly augment the depletion of stratospheric ozone.

Belgian researchers have been studying stratospheric aerosols for the past ten years. After the eruption of Mount Pinatubo (Philippines, 1991) in particular, they learned much about the distribution and the behaviour of volcanic aerosols in the stratosphere. They conducted measurements of the earth's atmosphere with the occultation radiometer ORA, which was built by researchers from BIRA / IASB and was on board the EURECA satellite for a period that included 7,000 sunrises and sunsets. One of the most important scientific findings of this experiment was the distribution and evolution of aerosols between altitudes of 12 and 35 km. This important data is also being used to build a model to calculate the average distribution of aerosols in space and time, so-called aerosol climatology. Such models are used to describe atmospheric processes including heterogeneous chemistry. In this way, researchers can obtain more insight into the breakdown of the ozone layer and can develop scenarios to combat this phenomenon.

Impact of aerosols on ozone (O_3) and nitrogen dioxide (NO_2)

As stated above, heterogeneous chemical reactions are of great importance in the depletion of ozone. These are reactions in which gaseous components in the stratosphere (which initially do not themselves break down ozone and are therefore called reservoirs) are converted on a solid surface into ozone destroyers. In the polar areas, these solid surfaces consist mostly of crystals that are present in the polar stratospheric clouds. A lot of these heterogeneous reactions occur at extremely low temperatures (below -78°C). However, laboratory studies show that not all heterogeneous reactions need take place at such low temperatures. Volcanic aerosols are an alternative carrier of heterogeneous chemical reactions. On their surface, nitrogen dioxide (NO_2) can be converted into nitric acid (HNO_3). Active nitrogen monoxide (NO) and nitrogen dioxide are thereby removed from the atmosphere, thus inhibiting the normal conversion of the active chlorine and bromine radicals in their inactive reservoir molecules chlorine nitrate ($ClONO_2$) and bromine nitrate ($BrONO_2$). Measurements after the eruptions of El Chichón (1982) and Mount Pinatubo (1991) showed that volcanic aerosols had indeed depleted ozone in the months thereafter.

1.1.5 The ozone layer and its impact on health and climate

Life on earth would probably be much different without the ozone layer. Stratospheric ozone ensures that all the ultraviolet radiation of the sun is absorbed. This primarily concerns UV-B (280-315 nm) and, to a much lesser extent, UV-A (315-400 nm). With a decrease in stratospheric ozone, more UV-B sunlight reaches the earth's surface, which is extremely harmful to biological life on earth (and thus also to human health). Higher levels of UV-B radiation result, for example, in increased risks of skin cancer, cataract, sunburn, ageing of the skin and changes to the immune system.

Researchers from BIRA / IASB confirmed that a reduction in the stratospheric ozone concentration over Uccle is correlated with an increase in UV-B radiation at the surface of the earth. To point out these dangers to the public, a standard UV index was developed by an international consortium of researchers. This indicates the UV doses that are harmful to human skin. For Belgium, this index is calculated daily by IRM / KMI and communicated to the public over the summer period during the weather forecasts.

Changes in stratospheric ozone also have an impact on the climate. Through its depletion, less heat is reflected from the earth's surface back into space. This means that the hole in the ozone layer produces a cooling effect (impact on the radiation balance of –0.15 ±0.1 W/m²). However, some ozone-depleting gases have a warming effect. Nevertheless, one must take into account the fact that these effects will only be temporary. Scientists expect a significant attenuation of the cooling effect of a lower ozone concentration, as well as the warming effect of the ozone destroyers, by the middle of the 21st century due to the implementation of the Montreal Protocol. This protocol should ultimately lead to a ban of all man-made ozone-depleting gases.

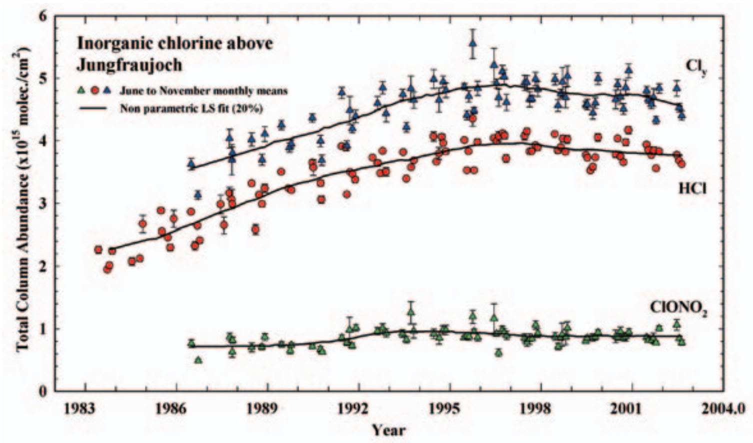
1.1.6 Is the ozone hole under control?

As indicated above, the Montreal Protocol prescribes a progressive elimination of all anthropogenic substances that deplete the ozone layer. First in line were the most destructive substances. Not only their ozone-depleting potential but also the amounts in which they are produced and released into the atmosphere, and their tropospheric and stratospheric lifespan were taken into account. Therefore, the protocol first tackled the chlorofluorocarbons CFC-11 and CFC-12, followed by other CFCs, methyl chloroform (CH_3CCl_3), carbon tetrachloride (CCl_4) and the bromide compounds (halons). The production of these substances was forbidden by the EU and by a majority of the other protocol signatories at the end of 1995. Because of this, the global accumulation of man-made chlorine compounds began to stabilise in the atmosphere. This evolution was first observed in the troposphere and subsequently in the stratosphere.

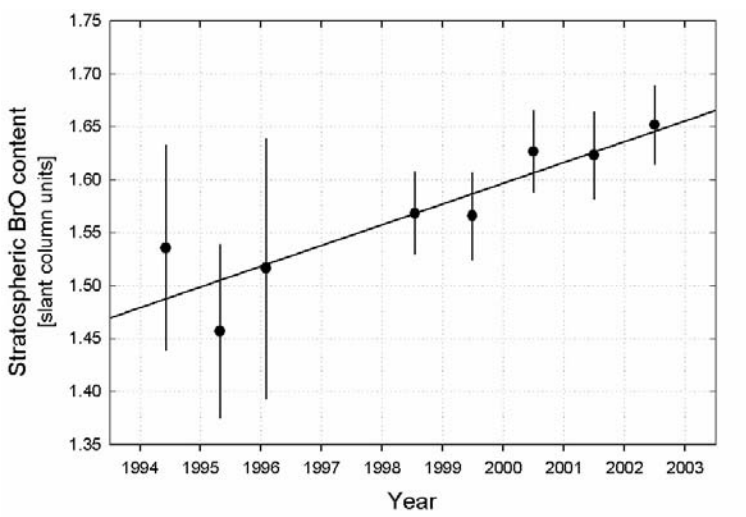
Despite the discontinuation of the production of halons beginning in 1994, the concentration of bromide in the atmosphere continues to increase. This is the consequence of the large stocks of these compounds in the industrialised countries and their continued use as fire-fighting agents. Thus, the problem of halons has not yet been definitely addressed.

Continuous measurements by Belgian researchers from ULg-GIRPAS and BIRA / IASB have made key contributions to the findings that the total concentration of inorganic chlorine in the stratosphere is stabilizing and decreasing slightly, while the amount of inorganic bromine

continues to increase (see figures below).



Evolution of the monthly average amount of hydrochloric acid (HCl) and chlorine nitrate ($ClONO_2$) over Jungfraujoch, Switzerland (inorganic chlorine Cly = HCl + $ClONO_2$). (E. Mahieu, ULg-GIRPAS).



Evolution of the annual average amount of bromine monoxide (BrO) over Harestua, Norway. (M. Van Roozendael, BIRA / IASB).

Assuming full compliance with the restrictions imposed by the Montreal Protocol, model predictions indicate that, by the middle of this century, the atmospheric concentrations of the humanly produced chlorine-containing ozone destroyers will be reduced to levels allowing the ozone layer to return to its pre-1980 state. Therefore, scientists assume that the hole in the ozone layer will slowly repair itself in the coming 50 years. However, the various models do not agree on how quickly this repair will occur. There are too many unknowns present, such as the effects of an additional cooling in the stratosphere as the consequence of increasing carbon dioxide (CO_2) concentrations, changes in atmospheric circulation and in the exchange that occurs between the troposphere and the stratosphere, etc. These uncertain factors mean that vigilance and constant monitoring of the evolution of ozone and the processes that take place in the atmosphere are required.

1.2 Too much ozone near the ground

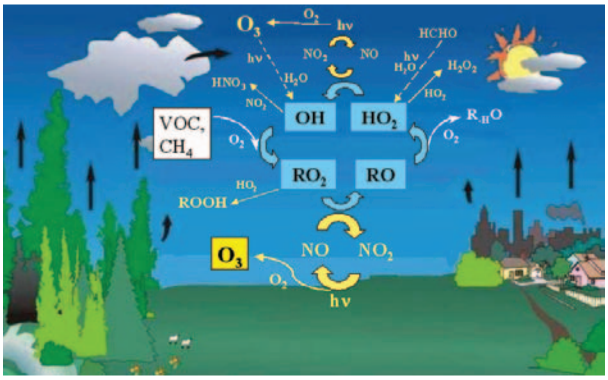
1.2.1 The complex chemistry of tropospheric ozone

A majority (~90%) of the ozone is located in the stratosphere, while the rest is found in the troposphere. This distribution is fortunate, because direct contact with too much ozone is harmful to living creatures. Because of its oxidizing capacity, ozone affects the respiratory system, particularly in children and the elderly, but also in adults who suffer from asthma. Furthermore, ozone causes damage to agricultural crops, forests, ecosystems and even materials like rubber and paint. Moreover, tropospheric ozone is a greenhouse gas: it absorbs the heat emitted by the earth's surface. Thus, tropospheric ozone contributes strongly to the warming of the earth.

There is increasing evidence that the ozone content near the ground is increasing in highly industrialised areas. Yet, ozone is not directly produced by human activity, but by a series of chemical processes in which polluting exhaust gases from transport and industry, as well as substances emitted by natural processes, play a crucial role. This includes nitrogen oxides (NO_x

= NO + NO_2) and volatile organic compounds (also called VOC) such as alkenes, aromatics and terpenes, which are important in the complex chemistry of tropospheric ozone.

The formation of ozone occurs particularly at higher temperatures and with intense sunlight – thus, especially on warm summer days. An overview of the complex tropospheric ozone chemistry is provided in the figure below. The chemistry of tropospheric ozone formation and destruction is not yet understood fully. It is believed, however, that it is comprised of hundreds of constituents, chemical reactions and exchange processes, of which only a few are known. We can, therefore, speak of a real Gordian knot.



General scheme of ozone formation and oxidation of volatile organic compounds (VOCs) in the troposphere. (J. Peeters, KULeuven-PAC; J.F. Muller, BIRA / IASB).

Fundamental insights into the properties of gases and their mutual interactions form the basis of a correct interpretation of more practically oriented atmospheric research. Without this fundamental knowledge, the measurement results regarding the composition of the atmosphere are of little value. During the last decade, Belgian researchers have made important contributions to this fundamental knowledge. Researchers from ULB-SPECAT and BIRA / IASB investigated the absorption and spectroscopic properties of numerous gases present in the atmosphere. Researchers from KULeuven-PAC have mainly studied the chemical reactions of natural VOC in the lower atmosphere, focusing on the reactions through which ozone is formed and destroyed.

Even though the Gordian knot of ozone formation has not yet been completely unravelled, we know the most important driving force behind the phenomenon: natural and anthropogenic emissions of nitrogen oxides (NO_x) and volatile organic compounds (VOC). This knowledge has led to measures being taken at various levels of decision-making and policy to limit the growing danger associated with an increase of ozone in the troposphere. Europe has issued several directives to reduce emissions of the precursor gases by 2010. To reach these objectives, most of the member states will have to considerably cut their releases of VOC and NO_x. These reductions are described in the Gothenburg Protocol (1999) resulting from the 'Convention on Long-Range Transboundary Air Pollution' (CLRTAP) and the EU directive regarding 'National Emissions Ceilings' (NEC, 2001/81/EC). Moreover, with the 'Clean Air for Europe' (CAFE) programme, Europe is seeking to develop an integrated long-term strategy to restrict the effects of air pollution on mankind and the environment.

1.2.2 Future evolution in the background concentration of tropospheric ozone

The initial results of these measures can already be felt. The increase in the background concentration of tropospheric ozone during the 1990s is less pronounced in Europe and the USA when compared to its rapid increase in the 1980s. This is certainly due to decreased emissions of the main precursor gases. However, it is very doubtful that this now guarantees a sustainable decrease in tropospheric ozone over the entire earth. Indeed, the increase in emissions from countries with developing industry and transport will completely offset the decrease from the industrialised countries. Thus, researchers expect that the global background level of tropospheric ozone will increase rather than decrease. If we are not careful, a further increase is quite possible.

The impact of tropospheric ozone on the climate must not be underestimated. Because ozone absorbs heat emitted by the surface of the earth into space, the increase in ozone has a warming effect (0.35 ±0.15 W/m^2). This is a positive contribution to the radiation balance, which corresponds to about 25% of the contribution resulting from the increase in carbon dioxide (CO_2) concentration since the beginning of the industrialised era.

1.2.3 Episodic peak concentrations and Volatile Organic Compounds (VOC)

While the background concentration of tropospheric ozone is still increasing by 0.5 - 1% per year in northwest Europe, a clear trend is evident that episodic peak concentrations are decreasing. This is also confirmed by the mathematical models, which predict the evolution in peak concentrations and evaluate several policy measures. This decrease is primarily due to the reduction in the discharge of VOC as established in the Geneva Protocol (1991) as a consequence of the CLRTAP. Belgium ratified this VOC protocol in 2000 but has not yet reached its targets.

1.2.4 Precursors other than VOC

While reductions in VOC emissions lead to a decrease in tropospheric ozone concentrations, reductions of other precursors are also essential. The EU directive on National Emission Ceilings (2001/81/EC) seeks a drastic reduction of nitrogen oxides (NO_x) emissions. This would not only have an effect on the ozone concentration, but would also help combat the acidification and the eutrophication of the environment. This integrated approach, with the objective of developing a long-term policy strategy for the combined effects of air pollution on human health and the environment, is relatively new. It is actually the core of the recently started CAFE programme.

In this context, it is essential for scientists to provide policymakers with effective tools to evaluate the impact of various policy strategies. Numerical models of the atmosphere are particularly well suited to this task. They describe the atmospheric processes that are responsible for the formation and depletion of ozone such as the emission of precursors, atmospheric diffusion, chemical transformation and deposition.

The IMAGES model (Intermediate Model for the Annual and Global Evolution of Species), developed and used by the researchers from BIRA / IASB, is one of the models that tries to quantify the change in the global composition of the troposphere as a consequence of changes in anthropogenic emissions.

The EUROS (European Operational Smog) model is an atmospheric model that simulates the long-term evolution of tropospheric ozone over Europe. The model was originally developed by RIVM (the Netherlands). In the context of the BELEUROS project (European Operational Smog model adapted to Belgium), VITO and IRCEL coupled a new version of EUROS with a user-friendly interface. The model was installed at IRCEL as a tool for policy support with regard to tropospheric ozone. It enables an evaluation of the impact of possible reductions of various emissions on ozone concentrations and

reveals the non-linear relation between tropospheric ozone concentrations and concentrations of precursor gases. Thus, a reduction in NO_x that is not coupled with a parallel decrease in VOC does not lead to a reduction in ozone concentrations – quite the reverse. On the other hand, each reduction in VOC leads to a decrease in ozone, yet to a lesser extent than would be the case with a simultaneous reduction of VOC and NO_x emissions.

1.2.5 Natural VOC and aerosols

Not all ozone precursor gases are emitted by mankind. On a global scale, the emission of natural non-methane volatile organic compounds (NVOCs) is much larger than those generated by mankind. These natural VOC also have a large impact on the tropospheric ozone concentration and the oxidizing capacity (self-cleaning capacity) of the atmosphere. Indeed, they influence ozone and radicals in various ways. Moreover, their depletion leads to the formation of condensable compounds that are an important source of secondary organic aerosols (SOAs). Numeric models indicate that SOA formation resulting from the release of natural VOC has increased by a factor of 3 or 4 compared to the pre-industrial era. However, a proper quantification of this phenomenon is very difficult because the emission models for natural VOC are very simplistic: the emissions are calculated as simple functions of temperature, light and type of ecosystem. This is in strong contrast to the extremely complex chemistry of these natural VOC. Thousands of organic components and reactions that influence the atmosphere must be taken into account. However, most of these components are not yet being studied in the laboratory. Thus, there is still much work for researchers to do if progress is to be made in understanding the ozone problem in the troposphere.

For example, the influence of monoterpenes (an important class of natural VOC) on the composition of the atmosphere is also insufficiently known. Monoterpenes are mainly emitted by trees. With the aid of modern mass spectrometric techniques, researchers from KULeuven-PAC, and recently BIRA / IASB, are attempting to characterise the chemistry of several monoterpenes. Insight into the oxidative processes of these VOC will enable a better assessment of the contribution of anthropogenic versus natural VOC to the ozone chemistry and the oxidation capacity of the atmosphere.

1.3 Foggy aerosols in the troposphere

1.3.1 From nano to micro

In addition to gases, the atmosphere also contains aerosols. These are tiny drops of fluid or solid particles with diameters ranging from approximately 1 nanometer (nm) to 10 micrometers (µm). These particles enter the air partly via natural processes, but there are also indications that the concentration of aerosols has increased considerably since the beginning of the 20th century as a consequence of human activities. Many of these nano- and micro-particles are directly injected into the air in the form of, for example, soil dust, sea salt, smut, fly ash, industrial dust and biogenic particles. However, aerosols can also be formed in the atmosphere itself from gaseous molecules such as sulphates, nitrates, ammonium and organic compounds. These are sometimes also called secondary aerosols.

1.3.2 The difficulty in generalising

Aerosols play an important role in many chemical reactions in the atmosphere. Moreover, they affect the climate and have a negative influence on the health and well-being of humans and animals. However, not all aerosols influence the environment in the same way: their impact depends on their chemical composition and on the size of the particles. The health risks associated with aerosols are also very dependent on these parameters.

Scientists from UGent-INW have been active in aerosol research for a number of years. They have developed instruments with which to measure the concentrations of aerosols in the troposphere, as well as methods for determining their physicochemical properties. They are gathering and analysing aerosol samples from Belgium, Finland, Norway, Israel and Zimbabwe.

1.3.3 Natural or anthropogenic

By measuring the size and chemical composition of aerosols, it is often possible to determine their (natural or anthropogenic) origin and their subsequent diffusion. This information is important to taking the right policy measures.

For example, with the aid of chemical and physical analyses, researchers from UGent-INW have been able to show that in the summer in Spitsbergen (Norway), 30% of the sulphate particles in the air originate from a natural source: the emission of dimethylsulphide (DMS) by marine phytoplankton. The rest is anthropogenic. In winter and early spring, on the other hand, all fine sulphate originates from human activity in Asia and Europe.
Through their measurements in equatorial and tropical areas, the researchers observed that, in the dry season, almost all fine particulate matter originates from the burning of biomass. In Transvaal (South Africa), only 40% originates from this source; 33% of the fine matter consists of sulphate that originates primarily from energy plants and industrial activities in the 'Transvaal Highveld'.
Several years ago, in collaboration with UA-Phar, a detailed organic analysis of aerosols was initiated, enabling researchers to learn the types of human activities that give rise to aerosols. Chemists and physicists from UA-MiTAC use various microscopic techniques to study aerosol particles from all over the world.

1.3.4 Aerosols and climate

The exact influence of an aerosol particle on the earth's radiation balance depends on its size and composition. Most tropospheric aerosols have a direct negative impact on the radiation balance because they reflect incoming solar radiation back into space. Soot, on the other hand, provides a positive contribution because it absorbs this radiation. Overall, however, it can be said that aerosols provide a net negative contribution to the radiation balance in the troposphere; but this contribution only partially counterbalances the positive impact that emanates from the increase in greenhouse gases.

Finally, aerosols also have an indirect negative effect on climate because they influence cloud formation. This effect could be important, but remains quite difficult to estimate.

1.3.5 Aerosols and health

Aerosols have an impact on health. They cause breathing problems and cardiovascular stress. Some aerosols are also mutagenic or carcinogenic. In addition, the consequences for health again depend on the physicochemical properties of the particles. For instance, particles larger than 10 micrometers (μm) seldom enter the lungs because they are caught by the small filtering hairs in the nose. Particles between 5 and 10 µm settle in the upper airways, those between 1 and 5 µm in the bronchi and particles smaller than 1 micrometer penetrate to the finest alveoli. Furthermore, both the immediate irritating (asthmatic) and the secondary harmful effects (lung fibrosis and reduction in the elasticity of the alveoli) depend on the chemical composition. This is why chemical and physical characterisation of aerosols is necessary.

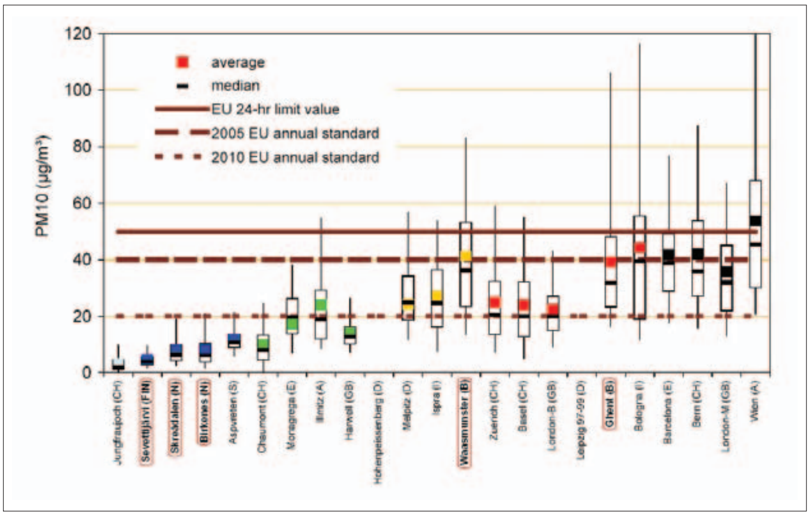
Various epidemiological studies have already been conducted that make a connection between exposure to fine particles in the air and increased mortality and morbidity. However, the presence of aerosols in buildings must also be monitored, because westerners spend an average of 80% of their time indoors. In both residential and workplace rooms, tobacco smoke is the major source of fine particles.

UA-MiTAC is involved in a number of epidemiological studies to quantify the health effects of fine airborne particles in outdoor as well as indoor air. Among other things, researchers have found that asthma is found almost 2.5 more often in young adults in the centre of Antwerp than in the same population group in more rural areas.

1.3.6 European standards and Belgian decision-making

The EU legislation for aerosol concentrations is expressed in terms of guide values for PM10 – 'particulate matter' with a diameter <10 µm. From January 2005, the limit value of 50 µg/m³ PM10 over a time span of 24 hours may be exceeded only 35 times per year and the annual average may amount to only 40 µg/m³ PM10. By 2010, the limit value as well as the annual standard will be reduced; the annual standard will then become 20 µg/m³.

Researchers from UGent-INW performed aerosol measurements in the Belgian municipalities of Gent and Waasmunster (see figure below). They also performed measurements at three locations with 'pure' air in rural Scandinavia. The results were integrated with those of other European research groups in a project that was coordinated by the EC Joint Research Centre of Ispra (Italy). The pooled measurements indicated that the quantity of aerosols with a diameter smaller than 10 micrometers (µm) is up to five times higher in cities than in rural areas. The concentration is especially high close to busy motorways in the cities. Much more effort will be necessary to reach the European guide values for 2005 and especially those for 2010. In particular, automobile traffic stands out in this study as a major villain.



Aerosol concentrations in various locations in Europe. Only aerosols with a diameter <10 µm have been taken into account. (Putaud et al, 2002; W. Maenhaut, UGent-INW).

2. Climate changes

To know whether the present climate changes are an unusual phenomenon, they have to be seen in a context of long-term climate variability. During the last hundred thousand years, the most important global changes are the glacial-interglacial cycles. Many factors influence the climate, of which the most important are the position of the earth in relation to the sun, the solar activity, greenhouse gases, certain atmospheric pollutants and volcanic activity. The study of climate changes linked to these factors contributes to demonstrate the impact of human activity and allows making projections of the future evolution of the climate. Some background information on the climate is presented in Boxes 6 and 7.

2.1 Indications of climate change

Climate changes are currently occuring as shown by a number of observations that demonstrate the increasing average temperature and precipitation over a large part of the earth, the melting of glaciers and the Greenland ice cap, as well as the reduction of the sea ice surface.

2.1.1 Temperature

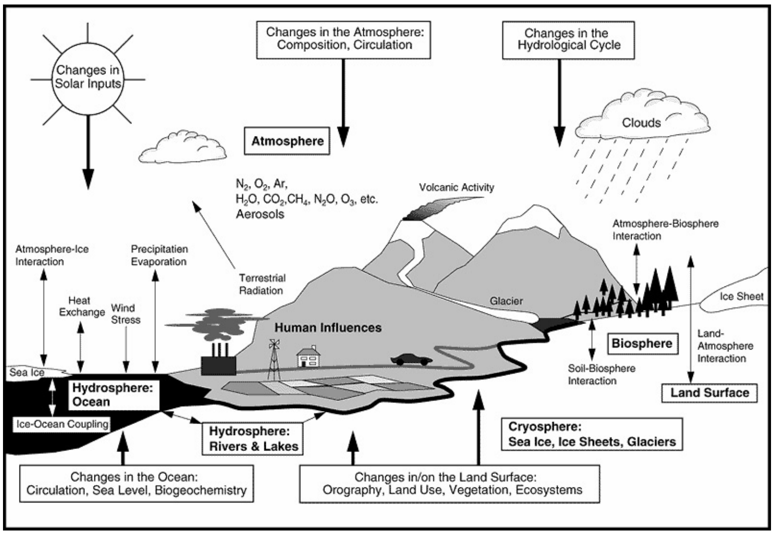
The warming appears in different ways, especially in the following:

✓ An increase in the average temperature of the surface of the earth by 0.6°C during the 20th century. In the northern hemisphere,

Box 6: Definition of climate

A simple definition is that 'climate is the average weather over a long period of time'. Climate can be defined more detailed as a 'statistical description - in terms of average and variability - of a number of relevant parameters such as temperature, precipitation and wind, measured over a given period'. Mostly a period of thirty years is used for this.

Box 7: The climate system



Schematic overview of the components of the climate system, their processes and interactions, and some aspects that can change. (IPCC-TAR - Climate Change 2001: The Scientific Basis).

The climate is determined by external factors such as the energy the earth receives and internal processes such as the atmosphere and ocean circulation and their interaction. It is the internal processes that are part of the climate system. The climate system consists out of five components: the atmosphere, the hydrosphere, the cryosphere, the geosphere, the biosphere and their interactions. The hydrosphere consists out of oceans, seas, rivers, lakes and groundwater. The cryosphere is composed of the whole of snow and ice coverage and permafrost (permanent frozen soil). The biosphere is composed of ecosystems, living matter (including the dead organic matter derived of it).

The climate systems evolves under the influence of its own internal dynamic and as a consequence of external forcing such as eruptions of volcanoes, the variability of the solar activity and the composition of the atmosphere or changes in land use.

the period 1990-2000 was probably the warmest decade of the past millennium. 1998 was possibly the warmest year.

✓ Since the end of the 1960s, the level of ice and snow covering the earth has declined by 10%. In addition, the mountain glaciers in non-polar regions have retreated to a significant extent in the 20th century. There is a strong correlation between the temperature increase at the earth surface and the reduced level of snow and ice cover.

The top figure on the next page shows an overview of the most significant temperature indicators. The speed and the duration of the warming we are undergoing since the 20th century are greater than any other temperature fluctuation that has occurred in the last 1,000 years.

The greatest increase in temperature since the 19th century took place during two periods: between 1910 and 1945 and since 1976. As can be seen in the lower figure on the next page, since 1976 the temperature has increased by 0.15°C per decade. The highest average annual temperature until now was measured in 1997-1998 when El Niño also occurred.

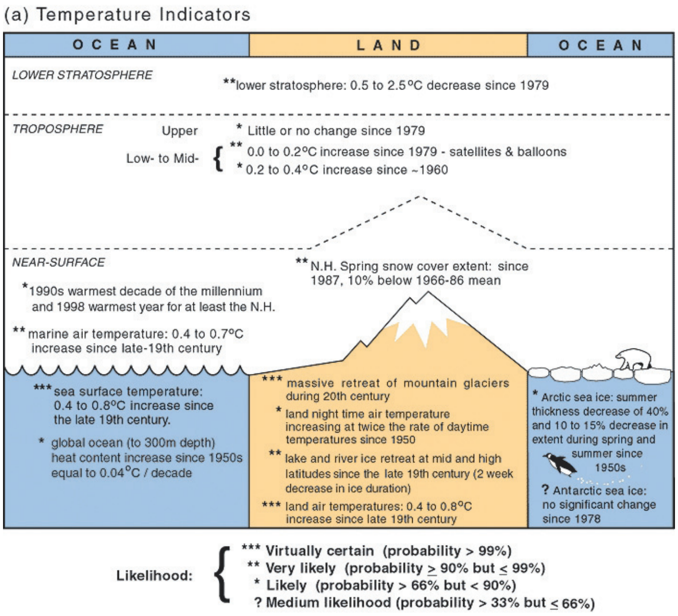
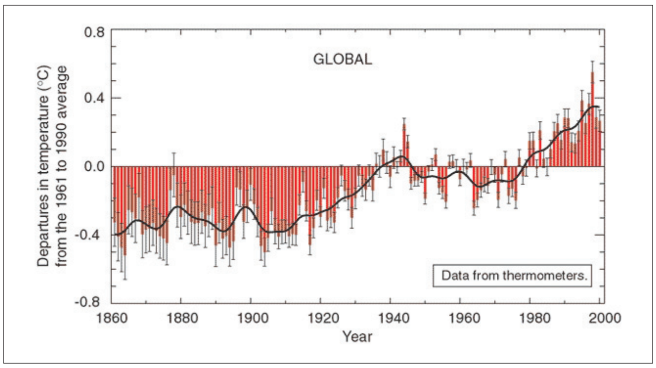


Diagram of variations observed in various temperature indicators. (IPCC-TAR - Climate Change 2001: The Scientific Basis).



Deviations in annual surface temperature between 1861 and 2000 compared to the average between 1961 and 1990. (TAR - Climate Change 2001: The Scientific Basis).

During the last decades, the increase in temperature affected nearly the entire earth but the most remarkable changes occurred in the northern hemisphere in the middle and high latitudes.

This increase in average temperature has also been observed at IRM / KMI in Uccle (Brussels, Belgium): in the last 170 years, an increase of 1 to 2°C has been recorded. The warming in Uccle did not occur gradually, but rather in steps (especially around 1910 and 1985).
Belgian researchers from UGent-PAE, KMMA / MRAC - GEO, UCL-ASTR and FUNDP-URBO were able to demonstrate ongoing warming in the tropical regions. According to their measurements, during the last decades the air temperature in Bujumbura and Mbala – respectively the most northern and southern point of Lake Tanganyika in East Africa – had risen by 0.7 to 0.9°C. In addition to this warming, they were also able to measure the impact on the lake of the El Niño Southern Oscillation. This made it clear that in this region El Niño leads to an increase in temperature, solar radiation and atmospheric pressure and a reduction in wind speed. This data provided the researchers with evidence that in an El Niño year there is less mixing of the nutrient-rich deep-water layers with the surface layers most probably, lowering the biological productivity of Lake Tanganyika so that fishermen catch less fish. This has consequences for the socioeconomic situation of the local peoples (see Box 8).

2.1.2 Precipitation and humidity

It is highly probable that in the last one hundred years in the northern hemisphere between the middle to high latitudes, the level of precipitation over the continents has increased by 5 to 10% This observation appears to be consistent with a higher level of humidity. This way a greater amount of water is available for precipitation. The occurrence of periods with heavy precipitation increased in the second half of the 20th century. Also the degree of cloudiness has likely increased. The increase in precipitation is in any case not systemic:

Box 8: El Niño, a poisoned Christmas gift

El Niño is an abnormal warming of the ocean water in the Pacific Ocean near the equator. El Niño means 'the Christ Child', a name given by Peruvian fishermen because every 3 to 7 years around Christmas this phenomenon would cause all of the fish off the coast of Peru to disappear.

Until the 1960s this phenomenon was seen as a purely regional phenomenon. This oceanic phenomenon is linked to the configuration of the atmospheric pressure in the Indian and Pacific Oceans called Southern Oscillation. The combination of these atmospheric and oceanic phenomena is called El Niño/Southern Oscillation or ENSO. Within an El Niño episode, the trade winds that always blow from the east to the west allow the warmer surface waters from the Indonesian zone to move to the east; where they cover the cold Peruvian water. This phenomenon influences significantly the wind, the temperature of the sea surface and the precipitations in the tropical part of the Pacific. There are climatic effects on the entire pacific basin and in various other regions of the world. This was only discovered in the 1960s.

It causes droughts in Southeast Africa and Northern Brazil, while the west coast of the American continent receives abundant rain and the resulting floods. La Niña usually follows the year after El Niño, a phenomenon in which the ocean water is colder than normal, resulting in the opposite effects.

The climate of East Africa also appears to be influenced by ENSO. Satellite images were used to study whether abnormal fluctuations in rain and vegetation growth occur whenever an ENSO phenomenon takes place. The initial results indicate that an area northwest of Lake Tanganyika, in the Kivu Region of the Democratic Republic of Congo, is strongly influenced by ENSO.

El Niño is not something new, but rather is a phenomenon that has occurred very regularly for centuries. It does appear that this regular pattern has been disrupted since the beginning of the 1970s. This leads to the suspicion that the greenhouse effect has an influence on these disruptions.

The 1991-1992 El Niño events caused the worst droughts of this century in Southern Africa, affecting almost 100 million people. Heavy floods in Kenya, Sudan, Uganda and the surrounding countries could be seen during the 1997-1998 El Niño events.

greater precipitation has been measured especially in Northern Europe but not over East Asia. Less precipitation than before falls around the Mediterranean Sea. For Belgium, there appears to be little change at present (at least what the annual mean concerns). Trends in hydrological and storm-related indicators are shown in the figure on the next page.

Above the subtropics – between 10 °N and 30 °N – the volume of precipitation indicates a downward trend, although a change has been noted in recent years. Near the equator, between 10 °N and 10 °S, there is a slight trend toward an increase.

2.1.3 Sea level, icecaps and glaciers

During the last 3,000 years, the sea level has raised by an average of 1 to 2 cm per century. Recently, however, this increase has occurred quite rapidly:

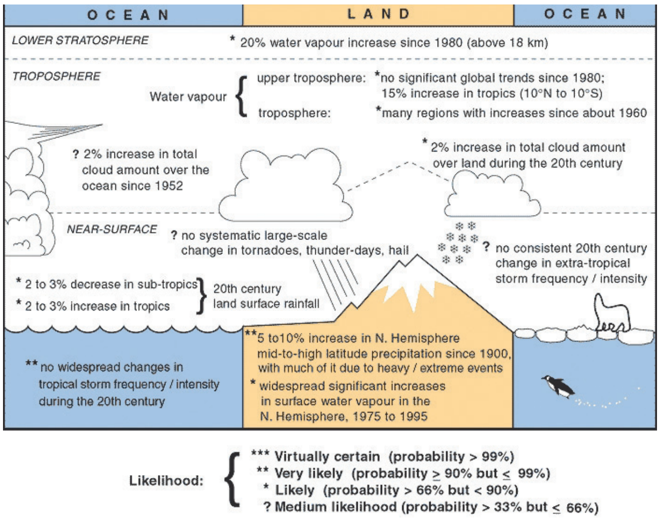


Diagram of observed deviations in the hydrological and storm-related indicators. (IPCC-TAR - Climate Change 2001: The Scientific Basis).

tidal measurements indicate an increase of 10 to 20 cm in only the last 100 years.

There are two major factors that explain this increase. Due to warming, the sea water occupies a larger volume. In addition, the total amount of water in the oceans has increased due to the melting glaciers and ice caps. Should the Greenland and Antarctic icecap fully melt, the sea level would increase by 7 and 60 metres respectively. This is a scenario that is unlikely to occur in the near future, but it does indicate how sensitive the sea level is to even limited melting of these enormous ice caps.

There are also strong indications that alpine and continental glaciers are retreating. There is a consensus among scientists that the global volume of glaciers has decreased compared to the 19th century. However, to understand the contribution of the melting of glaciers to the increase in the sea level, we must have a precise idea of the change in the global volume of glaciers. Unfortunately, volume measurements are available for only a fraction of the 100,000 glaciers on earth.

ULg-URAP and UGent-PAE have studied, in the framework of the LAQUAN project, the history of the changes to the sea level in the Larsemann Hills region (Antarctica). They learned more about regional changes to the thickness of the continental ice sheet and about the timing of the retreat of the ice. This is important to the work of validating models of the dynamics of ice caps.

2.1.4 Sea ice

We find sea ice especially in the Polar Regions. The thickness of the ice in the Arctic oceans averages three metres, and in the seas around Antarctica, one metre. Changes to the thickness of the sea ice can be an important indicator for a changing climate.

Scientists from ULB-GLACIOL have noted a significant decrease in the quantity of sea ice, especially in the oceans around the North Pole. This decrease is discernable regarding both thickness and surface area: the researchers estimate that the ice sheet has become 1.3 metres thinner in the last 30 to 40 years and that annually 25,000 km^2 less sea surface area is covered by Arctic ice. This is an annual reduction equal to the total surface area of Belgium.

However, it remains difficult to estimate whether the reduction in sea ice in the northern hemisphere is due to natural fluctuations or the influence of mankind on the climate.

2.2 Was it different before?

2.2.1 How can we know without measuring?

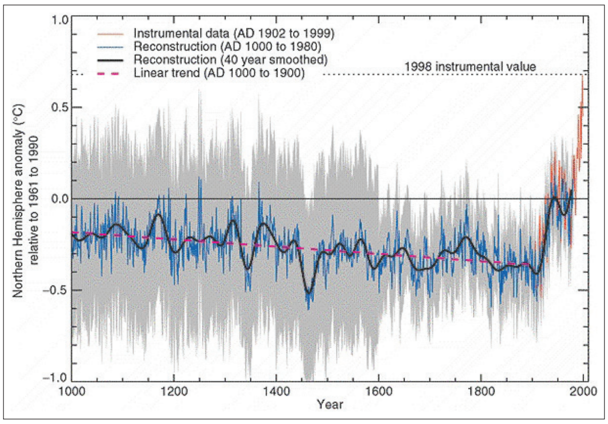
To determine if the warming in the 20th century is exceptional, it is essential to place it in a context of long-term variability. This means that we have to study the past climates. Today we have many instruments at our disposal with which to measure temperature, precipitation, composition of the atmosphere, etc. These instruments were previously unavailable. Systematic data on the climate is only available for the most recent 100 to 150 years; for earlier periods, we must refer to 'natural archives' such as ice cores, marine or lake sediments. These archives allow a reconstruction of temperature, precipitation, etc., thanks to calibration with respect to instrumental observations (see Box 9).

Researchers from ULB-GLACIOL, among others, were involved with the reconstruction of the climate based upon ice cores. Researchers from the CALMARS team (IRSNB / KBIN, KMMA / MRAC, ULB-BIOMAR, VUB-ANCH, UA-EFB) are studying the deposition of marine calcareous skeletons (sclerosponges, bivalves and echinoderms) in the North-east Atlantic Ocean and the Caribbean Islands. These skeletons provide an indication of the evolution in the climate. Researchers from the LAQUAN team (UGent-PAE, ULg-URAP) are also studying the history of the climate using sediments of micro-fossils.

2.2.2 The past 1000 years

The magnitude of present climate change becomes really clear in the light of a reconstruction of the temperatures that dominated the northern hemisphere during the last thousand years (see next figure).

Estimations of the mean surface temperature in the Northern Hemisphere indicate that during the beginning of the second millennium it was relatively warm, while at the end of the 13th century a gradual cooling occurred. This cold period, sometimes also referred to as the 'minor ice age', ends in the 19th century and is followed by the strong increases in temperature of the 20th century. On a planetary scale, this latest temperature increase has probably been the most important over the last 1,000 years.



Reconstruction of the temperatures above the northern hemisphere between 1000 and 1999. (IPCC-TAR - Climate Change 2001: The Scientific Basis).

2.2.3 Past sea levels

Over time scales of 10,000 to 100,000 years, the sea level has also risen and fallen. The factors that have contributed the most to this are the increase and the melting of ice caps through the different cycles of ice ages and warmer intervening periods.

Researchers from VUB-DG among others have established how, in the past, fluctuations in sea level on the order of tens of metres were not exceptional and that increases sometimes occurred very quickly – from 10 mm per year to sometimes even 40 mm per year.

2.2.4 Abrupt climate changes

Reconstruction of the history of the climate teaches us that some climate changes can occur very abruptly.

During the last interglacial period, the Eemian (130,000 – 100,000 years BP), a very rapid and major cooling in temperatures occurred in Greenland (10°C over a period of approximately 70 years).

Box 9: The History of the Climate

Scientists have numerous sources available with which to compile the history of the climate:

- ✓ Weather information: for about the last 150 years, at different places in the world, data on temperature, precipitation, atmospheric pressure and wind have been systematically recorded. The Belgian Royal Meteorological Institute (IRM / KMI) has reasonably reliable data at its disposal starting from 1870.
- ✓ Historical data: since mankind began writing its history, it has also recorded the history of the weather. Historical documents – ship's logs, journals, parish registers, annual reports and accounting for abbeys and estates … – but also paintings and frescos provide us with much information on the climate of the past millennia.
- ✓ Indirect data (reconstructions): nature also maintains a logbook of the history of the weather in various forms. The reconstruction of the palaeoclimate – the climate of former eras – is done using biological and geological archives.

  Snow has been accumulating on the ice caps for many thousands of years. Scientists drill hundreds of meters deep into these ice layers and the analysis of the ice cores obtained this way, allow them to make inferences regarding the climate and composition of the atmosphere that then prevailed.

  They can also learn much from sediment rock. From minerals in the sediments, they can deduct the erosion scheme, the precipitation and the temperature. Biological sediments – pollen, diatoms and fossils reveal much about the vegetation that grew in a specific area. This allows scientists to draw conclusions about the presence or absence of the sea and about various climatic factors – temperature, level of humidity, wind.

  However, much is involved in correctly reading and interpreting the language of the biological and geological archives concerning the climate. One must link the analysed elements such as the isotopic composition and climatic variables such as temperature and date every registration. The methods that are used for this have to be calibrated with indirect sources and historic data.

This observation is based on the analyses of a 3,000-metre long ice core that was drilled in central Greenland (Greenland Ice Core Project, GRIP), a research project to which ULB-GLACIOL has contributed to. However, it is not certain that this cooling has taken place. These results are criticised by other scientists because they suspect that complex transformations occurred in the deepest layers of the Greenland ice sheet. These transformations, which themselves were not caused by climate changes, would have misled the researchers.

This uncertainty shows how important in situ terrain observations are to describe in a pertinent way the physical processes on which models are based.

2.3 Reasons for past climate changes

2.3.1 In search of an equilibrium

Which factors determine our climate? As noted previously, first of all there is the sun. The radiation from the sun is absorbed by the surface of the earth and converted into heat radiation. This energy is than redistributed by atmospheric and ocean currents and reemitted into space under the form of infra-red radiation (see Box 7).

External factors

Throughout the entire year and over all of the earth, the energy of the incoming radiation of the sun is approximately offset by the outgoing radiation of heat. Each factor that affects this incoming or the outgoing radiation has an influence on the climate. Factors that change the distribution of energy within the atmosphere or between the atmosphere, land and oceans, also have an influence on the climate. Each factor that affects this equilibrium brings about a so-called change in the radiation balance (difference between incoming and outgoing radiation) of the earth-atmosphere system. Factors that affect a positive change in the radiation balance, warm the earth; factors that affect a negative change, cool the earth.

There are a number of natural, external factors that have changed the terrestrial climate in the past. Among the most significant of these are the following:

- ✓ The radiation of the sun. The amount of radiation emitted by the sun varies slightly (0.1%) according to an 11-year solar cycle. In addition, variations in the energy output of the sun also occur over longer periods.
- ✓ Small variations in the earth's orbit and the inclination of the earth rotation axe can cause changes in the distribution of the distribution of the radiation of the sun (astronomical theory of the palaeoclimates, first demonstrated by Milankovitch, and confirmed by the work of UCL-ASTR). These variations have played an important role in the climate variations of the past (glacial-interglacial cycles).
- ✓ Greenhouse gases. Certain gases in the atmosphere result in more absorption of outbound heat radiation. Because less of the earth's heat escapes, the surface of the earth and the lower atmosphere will warm up. The positive contribution of these gases is also called the greenhouse effect. The gases work according to the principle of a greenhouse: they allow the radiation of the sun to enter, but prevent the heat radiation from escaping. Greenhouse gases have played a major role in the climate of the earth for billions of years. Without these gases, the average temperature on earth would be -20°C.
- ✓ The most important naturally occurring greenhouse gases are water vapour, carbon dioxide, ozone, methane and nitrogen oxide.
- ✓ Aerosols (see Chapter 1). Volcanoes can spew large quantities of sulphuric gases – especially sulphur dioxide – into the stratosphere. These gases can be converted to sulphuric aerosols. These aerosols absorb and disperse the incoming sunlight at high altitudes. Thus they effect a negative change in the radiation balance.

Internal factors

However, natural climate changes do not always need to be caused by a change in external factors that impact the radiation balance – like changes in the amount of greenhouse gases or volcanic eruptions. Climate change is also possible without any demonstrable external cause. Complex interactions between the components of our terrestrial climate system can result in climate change. An example of this is the El Niño effect and the El Niño Southern Oscillation (see Box 8), which arise as a result of a long-term periodic coupling between the atmosphere and the hydrosphere.

A similar recurring oscillation also occurs in the northern hemisphere: the 'North Atlantic Oscillation' (NAO). This oscillation is attributed to the North Atlantic thermohaline currents. The NAO consists of opposing variations in atmospheric pressure near Iceland and the Azores.

Belgian researchers from ULg-URAP, UGent-RCMG, KMMA / MRAC and UCL-ASTR are studying the interactions between the 'El Niño Southern Oscillation' (ENSO) and the 'North Atlantic Oscillation' (NAO). Some of their findings are presented in the figure below.

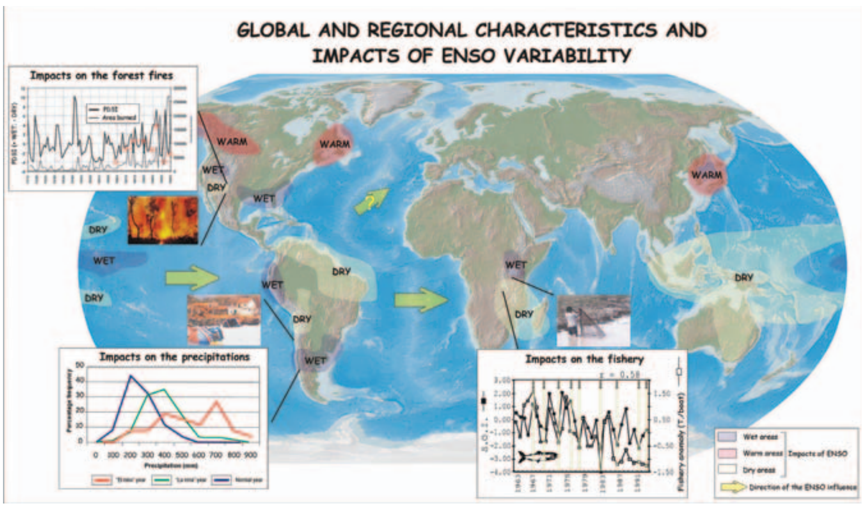
2.3.2 Delayed reaction

When the radiation balance changes, the various components of the climate system do not react with the same speed. Some components like the atmosphere react very quickly; others take time to reach equilibrium. Sometimes they take centuries, sometimes even millennia.

Thus, for example, the oceans have a large capacity to retain heat. This means that they adapt slowly to any warming or cooling of the surface or the atmosphere. In other words, the oceans exert significant delaying effects on global warming.

There are also delaying effects exerted for some increases or decreases in sea level: the growth and melting of ice caps as well as the thermal expansion of water can thousands of years. It can take centuries for the deeper water layers to also warm up. Thus the sea level can continue to change for a very long time in response to a change in the factors that influence the radiation balance.

Researchers from VUB-DG are studying the properties of the ice sheets in Greenland and Antarctica. They are developing three-dimensional models to detail the properties - thermo mechanical, mass/balance and crust – of these ice sheets and to predict how they will react



Global and regional characteristics of the 'El Niño Southern Oscillation' (ENSO) and some effects: forest fires in California, precipitation in Chile and size of the catch in Lake Tanganyika, Africa. (ULg-URAP, UGent-RCMG, UGent-PAE, KMMA / MRAC, UCL-ASTR, UCL-GEOG and FUNDP-URBO).

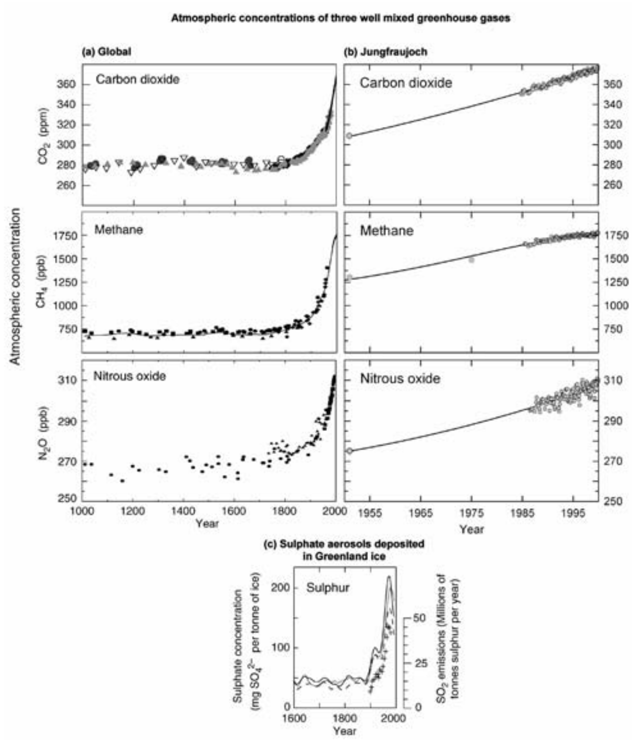
to further warming. Their models were more recently integrated into more general 'General Circulation Models' (GCMs) and 'Earth System Models' in order to investigate the interactions and feedback mechanisms between the continental cryosphere, the atmosphere and the oceans. Furthermore, the VUB research also supports the search for sites for the drilling of ice cores and the interpretation of the cores, as well as the interpretation of satellite data from these regions. These icecap models were integrated in Belgium in earth system models (ocean, atmosphere, ice, vegetation) in the framework of the research projects MILMO and CLIMOD (UCL-ASTR, VUB-DG, ULg-LPAP, IRM / KMI).

2.4 Greenhouse gases and aerosols as chief suspects?

2.4.1 The measurements

Beginning with the pre-industrial era, human activity has caused the atmospheric concentration of greenhouse gases and aerosols to increase considerably. In the last one hundred years, the concentration of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), has increased significantly, principally due to the burning of fossil fuels, agriculture and changes to the land use (see next figure).

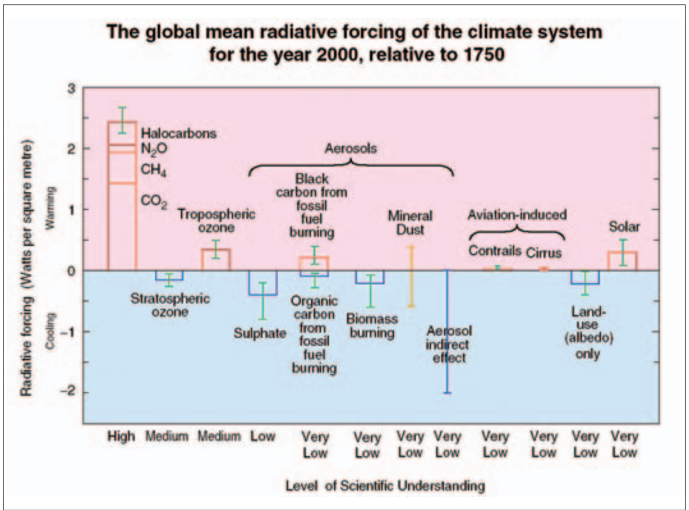
Measurements by Belgian researchers (ULg-GIRPAS) in the Jungfraujoch Station in Switzerland (see photograph on page 20) show that the concentration of greenhouse gases has also continued to increase from year to year over the last five decades. Only in the case of methane does there appear to be a reduction in the rate of increase, a phenomenon that has yet to be explained.



Long-term data on changes to concentrations of gases in the atmosphere demonstrate the influence of anthropogenic emissions. (IPCC-TAR – Climate Change 2001: The Scientific Basis; E. Mahieu, ULg-GIRPAS).

Not all of these gases contribute equally to the greenhouse effect. The impact of 1 kg greenhouse gases depends on their lifetime in the atmosphere and its effect on the radiation balance. The impact is expressed by the indicator 'Global warming Potential' (GWP). For example, the impact of N_2O is 310 times greater than that of CO_2. On the other hand, there are a thousand times more CO_2 molecules in the atmosphere than N_2O molecules. In addition, the relative increase in CO_2 molecules has also been much larger during the most recent 100 years. Because greenhouse gases have a long lifespan and are mixed throughout the various aerial strata, they have a global influence.

This is in contrast to aerosols in the lower aerial strata – the troposphere. Their influence on the climate remains much more local. The exact influence on the radiation balance of an aerosol particle depends upon its dimensions and composition. Tropospheric aerosols have principally a negative influence on the radiation balance because they reflect and absorb incoming solar rays. They also have a positive effect due to their absorption of heat radiation that the earth emits into space. Aerosols also have an indirect negative effect because they influence the formation of clouds. This indirect influence could be quite large, but it continues to be very difficult to estimate this phenomenon. Nevertheless, one can say that the net effect of aerosols on the radiation balance is negative. They only partially compensate for the positive effect due to the increase in greenhouse gases (see figure below).



Present estimates of the effect on the radiation balance of the increased concentration of atmospheric components and other mechanisms. Certain aerosol types (sulphate, aerosols that originate with the burning of biomass) lead to cooling, while other aerosols (soot) lead to warming. There is a significant level of uncertainty concerning the indirect effect of aerosols. (IPCC-TAR – Climate Change 2001: The Scientific Basis).

2.4.2 The models

How can one determine whether the activities of mankind are the root cause of the present climate change and that a convergence of natural changes does not lie at the basis?

To answer this question, scientists construct models that take into account as many factors as possible that influence the climate. Based upon the data entered –, solar radiation position of earth-sun, volcanic eruptions, human activity … - models attempt to reproduce the climates of today, yesterday or tomorrow. These models can be validated based upon their ability to reproduce present and past climates. This reduces the level of uncertainty concerning what is predicted for the future.

In the framework of the network projects CLIMOD and MILMO, researchers from UCL-ASTR have developed various models for the climate system. By using these models they have contributed to a better insight into a number of important mechanisms that control the climate. and thus to the reduction of the level of uncertainty concerning the evolution of the climate. Important research themes were the following:

- ✓ **Reproducing the strong katabatic winds along the polar ice slopes of Antarctica by means of atmospheric models.**
- ✓ **Identifying processes that control the variability of the surface area and the volume of the sea ice in both hemispheres. These models provide better insight into the natural variability of the system and the expected reaction of the sea ice to the warming that has occurred during the last 50 years.**
- ✓ **Simulating the response of the climate system to anthropogenic and natural factors that influenced the radiation balance in the second millennium.**
- ✓ **Analysing the potential changes to the thermohaline circulation in the ocean.**

The models that the scientists use

today allow us to see how especially natural variations are able to explain the climate changes of the past thousand years until just prior to the industrial revolution. However, there is strong evidence that warming over the last 50 years is mainly attributable to human activities, in particular because models can only reproduce the observed climate changes when the anthropogenic emissions are taken into account.

The sea level rise is one of the most difficult aspects for analysing. It is difficult to quantify the different factors contributing to the observed 10 to 20 cm rise during the 20th century (see Section 2.1.3).

One of the most important contributions of researchers from VUB-DG to the Belgian Antarctic and global change research consists in the development of three-dimensional thermo-mechanical models for the evolution of ice caps. These models were successfully applied to the Antarctic ice sheet, the Greenland ice sheet and the Quaternary ice sheet of the northern hemisphere during the ice ages. The researchers were successful in simulating the form, dimensions and the physical properties of these ice sheets beginning with their creation during the Tertiary and Quaternary ice ages, as well as their behaviour in the case of further warming of the earth. These models were also integrated into General Circulation Models and Earth System Models in order to investigate the interaction and feedback mechanisms between the continental cryosphere, the atmosphere and the oceans.

2.5 The 21st century

2.5.1 Worldwide

Basic assumptions

In their predictive models, scientists (IPCC's Special Report on Emissions Scenarios, IPCC-SRES, 2000) assume that mankind will continue to influence the composition of the atmosphere for the entire 21st century. These influences are primarily felt on the concentrations of greenhouse gases and aerosols. The assumptions are the following:

- ✓ CO_2 emissions resulting from the burning of fossil fuels remain the root cause of the increase of CO_2 in the atmosphere in the 21st century.
- ✓ By 2100, an atmospheric CO_2 concentration of 490 to 1,260 ppm – particles CO_2 per million particles of air – is expected. This concentration was 280 ppm in 1750 and reaches 380 ppm in 2004.
- ✓ Changes in land use (in particular deforestation) influence the atmospheric CO_2 concentration. The CO_2 concentration could be 40 to 70 ppm less if there would not have been any carbon loss due to land use change.

The expectations

Based upon the scenarios sketched above, the following is expected:

- ✓ **Temperature**
  - o By 2100, the temperature of the surface of the earth will increase by 1.4 to 5.8°C compared to 1990. With this, the rate of warming will increase significantly in comparison to the 20th century. This is without any precedent over the last 10,000 years.
  - o A much stronger El Niño effect in the tropical regions of the Pacific Ocean.

- **Precipitation**
  - A higher level of mean global atmospheric humidity and more precipitation. During the second half of the 21st century, it will be wetter between the middle to high latitudes and over Antarctica in the winter. At low latitudes, rainfall will increase or decrease depending upon the region.
- **Extreme weather conditions and health risks**
  - The frequency, intensity and the duration of extreme weather conditions will increase – heat waves, number of warm days, periods with heavy precipitation and less cold days in moderate regions. This could lead, however, to an increasing risk of floods and droughts and a negative impact on natural ecosystems, on various socio-economic sectors and on human health.
  - An increasing threat on the human health in particular in tropical and subtropical regions. The health effects can be direct (direct effect of heath waves, casualties due to inundations and storms) or indirect (changes in the geographical distribution of illness vectors such as mosquitoes, water, air and food...)
  - The impact on human health will heavily depend on regional environmental and socio-economic factors, but also on, social, institutional, technological and behavioural adaptation.
- **The thermohaline circulation**
  - The slowing down of the thermohaline circulation in the northern hemisphere leads to a reduction in the transport of the heath towards Europe. This reduction does not compensate the warming due to greenhouse gases. The changes in the radiative balance are as important and long that the thermohaline circulation could stop irreversibly after 2100.
- **Snow and ice**
  - In the northern hemisphere, the surface that is covered by snow and sea ice will decrease
  - Glaciers and ice caps will further melt in the 21st century
  - The Antarctic ice sheet may increase in volume due to more precipitation; the Greenland ice sheet will reduce in mass. If the warming continues beyond 2100, the melting of the ice caps could lead to an increase of the sea level by 60 cm per century.
- **Sea level**
  - Between 1990 and 2100, the global level of the sea could increase by 9 cm to 88 cm as a result of the thermal expansion of water at higher temperatures and the further melting of glaciers and ice caps. This increase could continue during several hundreds of years after the stabilisation of the greenhouse gas concentrations.
  - The melting of all glaciers would increase the sea level by 0,5 m
  - The present contribution of Greenland and Antarctica to the sea level is slightly negative because of an accumulation of snow on Antarctica. Over the next 1000 years, the melting will increase and lead to a 6 m increase of the sea level.
  - Significant regional differences could appear. Moreover, the increase in the number of extreme weather conditions could bring with it more stormy weather, causing extremely high seawater levels to occur more frequently than was previously the case.

2.5.2 Regional level

The scientific community, policy makers and the public continuously demand realistic projections regarding the regional impact of a future climate change. This is not an easy task, because in addition to the large-scale factors (the greenhouse gas concentration) that for example determine the general circulation, model builders must also take account of mesoscale factors that influence local circulation and thus only impact local climatological variables.

The models that scientists use today are 'general circulation models' (GCMs) that simulate and predict the climate over the entire earth. However, their resolution is not fine enough – they use a horizontal resolution of 300 km – to effectively incorporate mesoscale impact factors on the radiation balance and make predictions at regional level. For this, better regional climate models must be developed, with a horizontal resolution of 10 to 50 km, which can also be integrated into the global models.

Nevertheless, scientists now already assume that differences between global and regional changes will be significant:

- ✓ It is possible that the increase in temperature above land will be faster than the global average increase, in particular at high latitudes and in wintertime.
- ✓ At high latitudes, the amount of precipitation will increase significantly, both in the winter and in the summer. The probability of floods occurring will increase throughout all of Europe.
- ✓ There is a whole range of regional variations in see level rise possible in comparison with the global mean projections.
- ✓ The South of Europe will be much dryer.
- ✓ Half of the alpine glaciers and large parts of the permafrost - regions that remain frozen the year round – will disappear by 2100.

A multidisciplinary research team of Belgian researchers (ULg-CEME, FUSAGx-UHAGx, KULeuven-H&EG, IRM / KMI) tested three hydrological models at three Belgian river basins (the Gette / Gete, the Geer / Jeker and the Ourthe that examine the changes that will occur in these river basins due to the influence of various climate changes. A significant impact is projected for almost all tested IPCC scenarios. It always concerns a reduction in the groundwater level, in the river flow rate and in soil humidity, especially in the summer. In the majority of the models, the flow rate in the winter also decreased; in only one model was there an increase.

The conclusion of the researchers is that more precise assessments of the effects of a potential climate change in river basins located in higher areas can be made if the predictive models are further refined.

2.6 Unexpected effects with a major impact

It is possible that in the 21st century the positive perturbation in the radiation balance due to greenhouse gases may have a major impact on physical and biological systems bring about unexpected abrupt changes that. Moreover, these changes could be irreversible. Scientists think in this regard of a collapse of the thermohaline circulation due to the accelerated discharge of ice and ice water into the ocean from the Greenland and West Antarctic ice sheets

A lot of ecosystems can be perturbed very sudden with consequences for their function, biodiversity and productivity. Bleaching of corals due to an increase in seawater temperature is an example. At this moment it is very difficult to predict the likelihood that one of these phenomena would occur. The processes that lie at the basis are insufficiently known.

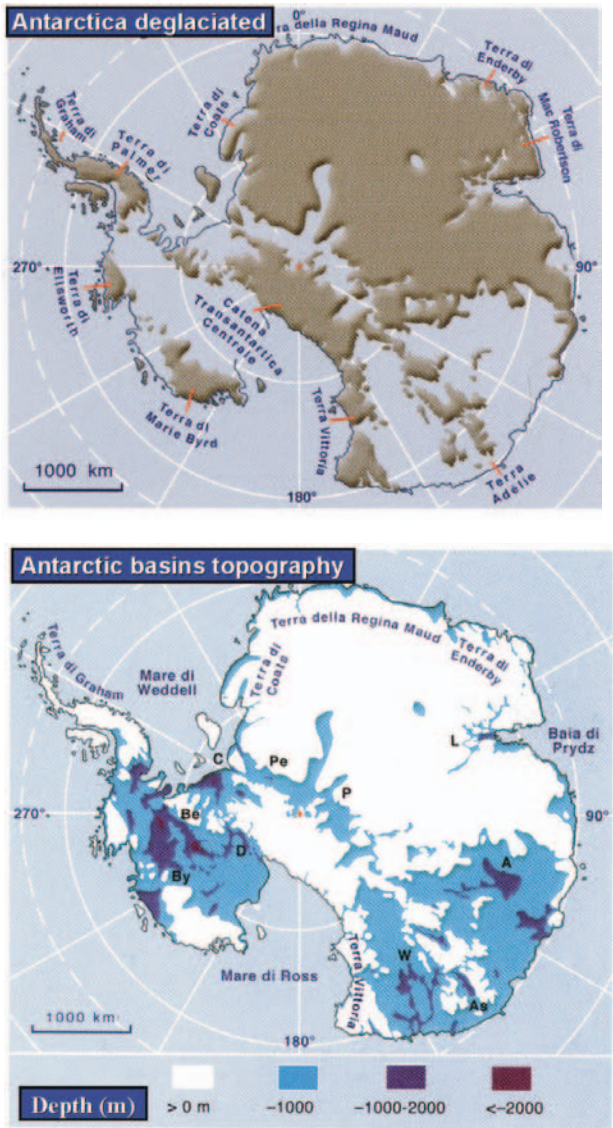
2.6.1 The West Antarctic Ice Sheet

The West Antarctic Ice Sheet (abbreviated WAIS) contains enough ice to increase the sea level by 6 metres. The stability of this ice sheet, which is largely supported by ground that lies under sea level, has been called into question by a number of scientists. It is not entirely inconceivable according to them that the ice located at the edges of the ice sheet would collapse and a large quantity of the WAIS ice would fall into the sea. However, there is a growing consensus on the part of scientists that this phenomenon will probably not occur in the 21st century. In the longer term, however, the danger is real. The WAIS panel of experts estimates that there is a 50% probability that the melting of the WAIS will increase the sea level over a period of 1,000 years by more than 2 mm per year, but also a 50% probability that WAIS will have no significant effect on the increase in the sea level in the coming 1,000 years (see figure alongside).

2.6.2 The thermohaline circulation

A very probable effect of global warming is a partial melting of the Greenland ice sheet. This melting would contribute to the sea level rise over the entire world by 9 cm from now until 2100 the rate of increase could be even quicker after 2100 if the warming trend continues.

Since the Greenland ice sheet lies close to the two North Atlantic deep water formations, the mixing of freshwater with the saltwater will inevitably influence the thermohaline circulation. It is important to include this in models, which was seldom the case until now. According to recent calculations by Belgian scientists among others, the Gulf Stream will abruptly and sharply diminish by the end of the 21st century, resulting in a cooling of Northern and Western Europe.



Potential instability of the WAIS (West Antarctic Ice Sheet). (ULB-GLACIOL).

2.6.3 Biogeochemical surprises.

Another effect that worries scientists is the release, resulting from the climate change, of large quantities of greenhouse gases - carbon and methane - now trapped as gas hydrates in the permafrost and in sediments on the seabed and on the bottom of large lakes. The release of these gases would further increase the greenhouse effect.

Researchers from UGent-RCMG are among those who are investigating the destabilisation of gas hydrates in Lake Baikal and the Black Sea.

2.7 Climate change and the global ozone balance

The problem of ozone was discussed in Chapter 1. There are linking and feedback mechanisms between ozone levels and climate change: not only does ozone - both stratospheric and tropospheric - influence climate change, but climate change also has an impact on the ozone. Its effects remain difficult to quantify due our limited knowledge of climate-related processes that can influence ozone concentrations.

In any case, the holes in the ozone layer and the greenhouse effect have a number of chemical and physical processes in common. This is why the Kyoto Protocol is closely related to the Montreal Protocol. For example, if the concentrations of ozone-destroying CFCs (chlorofluorocarbons) decrease, these will not only have a positive effect on the ozone layer; it will also influence global warming because CFCs are strong greenhouse gases. On the other hand, the replacements for CFCs are also strong greenhouse gases.

Models show that the dilution of the ozone layer together with the increased concentrations of greenhouse gases in the troposphere have contributed to a further cooling of the stratosphere. Thus there is possibly also a feedback mechanism at work because this cooling could in turn increase the formation of polar stratospheric clouds, which in turn would cause more ozone to be destroyed.

All these processes are very complex and mutually coupled. The question remains if climate changes will have an impact on the recovery of the ozone layer.

In many regions, warming leads to dryer vegetation, a higher CO_2 concentration increases moreover the risks of lightning leading to the possibility of more forest fires, which would release the ozone precursors CO, NO_x, CH_4. Climate changes influence the emission of ozone precursors: N_2O and NO from the soil as a result of a greater level of activity on the part of micro-organisms, CH_4 from wetlands and from gas hydrates on the seabed or under permafrost. Emissions of biogenic volatile organic compounds, which lead to the formation of ozone precursors and aerosols, depend upon meteorological conditions.

An increase in atmospheric humidity increases the concentration of OH radicals, which decreases the life of ozone precursors in the atmosphere. Climate changes also influence the transport of ozone in the troposphere and between the stratosphere and the troposphere.

2.8 Can Kyoto save the climate?

2.8.1 Why must the climate be saved?

According to projections of the IPCC predicts that the climate will change drastically in the coming centuries. This holds both disadvantages and advantages for mankind. Among the advantages it can be cited that:

- ✓ regions where it is now too cold could become suitable for farming;
- ✓ new sea routes could become available due to the dilution and reduction in size of the Arctic sea ice;
- ✓ the increase in temperatures would lead to less severe winters and a resulting decrease in the mortality rate.

However, there are also many negative consequences:

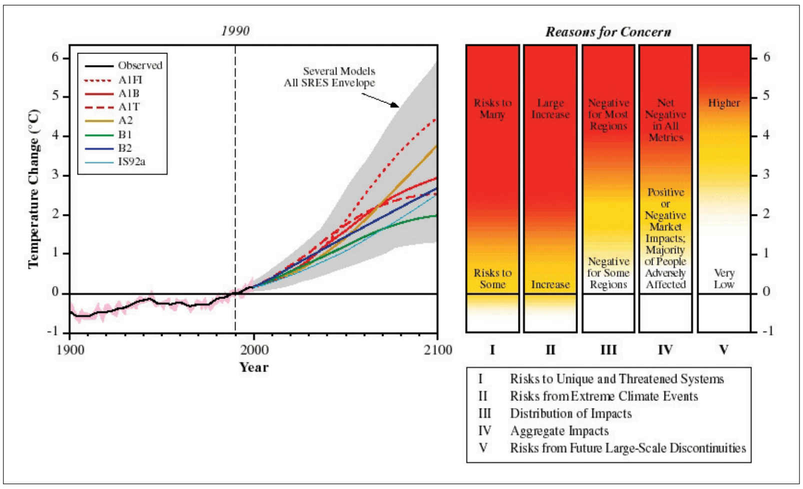
- ✓ lowered harvest yields in most tropical and subtropical regions but also in the mid latitudes with a temperature increase of 2-3°C;
- ✓ less drinking water in particular in subtropical regions;

- ✓ an increase of casualties due to heat waves;
- ✓ more people with vector born diseases like malaria, and
- ✓ an increase of flood risk.

These negative consequences would have a much greater impact than the few positive consequences. This is indeed recognised by the international community, among others in the Climate Convention (UN Framework Convention on Climate Change, UNFCCC, 1992) that has as ultimate goal *"stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner."* (UNFCCC article 2). The Climate Convention does not address what this level should be in absolute, quantitative terms. The technical, social and natural sciences contribute to determining this level by increasing our knowledge and reducing the level of uncertainty. The final decision concerning what is dangerous is also a value judgement that is determined by socio-political processes in which consideration is taken of development, equality and sustainability, as well as of uncertainties and risks (see Box 10).

To facilitate possible decisions regarding where the 'danger level' lays, the impact of possible future climate changes was summarised by the IPCC into five risk categories. The figure below clearly shows that the risk of negative consequences increases as the changes become greater. Each risk category is perceived by the different actors and countries in a different way. That is why there is presently no international consensus regarding what level of climate change or greenhouse gas concentrations are to be considered dangerous. However, in 1996 the Council of Ministers of the European Union adopted an official position: *"Given the serious risk of such an increase and particularly the very high rate of change, the Council believes that global average temperatures should not exceed 2 degrees above pre-industrial level (…).".*

To answer the question whether the Kyoto Protocol will save the climate, we will thus assume that 'saving the climate' implies the implementation of the objectives of the European Union.



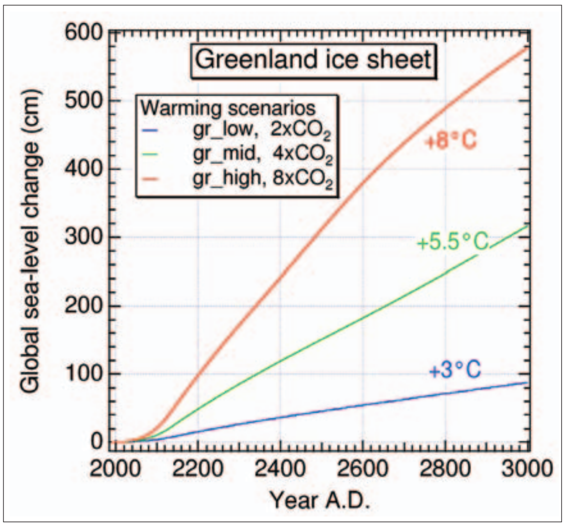
Reasons for concern about the consequences of the projected climate changes.
The risk of harmful consequences due to climate change increases as the size of these changes increase. The left part of the figure shows the observed, relative increase in temperatures after 1990, as estimated by Working Group 1 for scenarios contained in the Special Report on Emission Scenarios of the IPCC (IPCC-SRES, 2000). The right part shows the five reasons for concern with respect to the risks associated with climate change from now until 2100. White represents the neutral and minor negative or positive consequences of the risks, yellow indicates the negative consequences for specific systems or low level of risk, and red indicates the negative consequences or risks that are more common and/or greater.

Box 10: A number of examples of vulnerable physical systems that were investigated by Belgian researchers

The Greenland ice sheet

Even after the climate has stabilised, the Greenland ice sheet will continue to react to a climate change for the coming thousands of years. Using models assuming an expected local 'annual average' temperature increase of 3 °C, the researchers expect that the ice sheet will finally disappear over a few millennia, except for glaciers at high altitudes, and that consequently the sea level will increase by 7 metres worldwide.

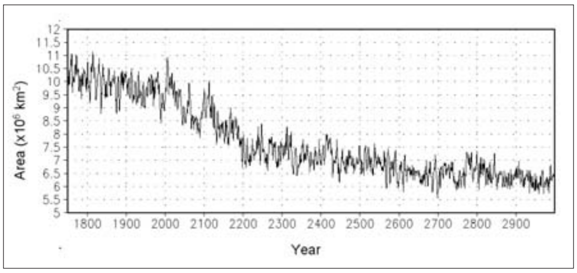
The warming of Greenland should be more important than the global mean. In that case, a warming of 5.5 °C in Greenland will cause the sea level to increase by 3 metres after thousand years.



Reaction of the Greenland ice sheet to three climatological warming scenarios in the third millennium. The figures next to the graph refer to the annual average temperature increase above Greenland until the year 3000. The projected temperature increases in Greenland are higher than the global average (by a factor of 1.2 to 3.1). (VUB-DG).

Marine ice in the South Pole Region

According to a simulation in a global atmosphere-ocean-sea-ice model, the reaction of the Southern Ocean to an increase in greenhouse gas concentrations in the atmosphere can be divided into two phases. Initially the ocean, due to its ability to absorb a lot of heat, will mitigate the warming of the earth surface. However, a century after the most significant increase in greenhouse gases, the warming will be reinforced as a result of positive feedback connected with a stronger transport of heat via the oceans from the north to the Southern Ocean. This reinforcing phase, responsible for a significant reduction in the ice surface in the Southern Ocean, will take place one or more centuries after the significant increase in greenhouse gas concentrations. Its effect must be taken into account in the predictions and the models.



Evolution over time (in years) of the annual average ice surface (in millions of km²) in the South Pole Region as simulated by a climate model that incorporated the observed increase in greenhouse gases in the period 1750-2000. During the third millennium, the concentration of greenhouse gases was held at the levels noted in 2000. Even in this optimistic, but perhaps unrealistic, scenario, the simulation shows an enormous decrease in the ice during the third millennium. (UCL-ASTR).

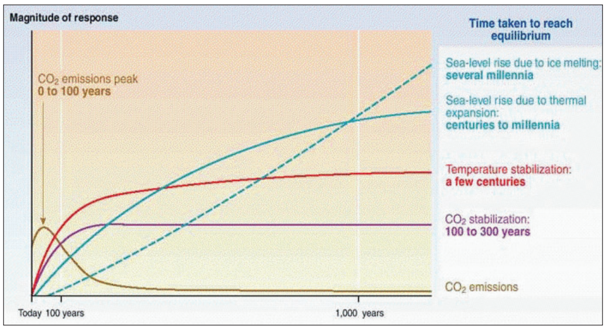
2.8.2 Nature is slow

To assess the changes in emission rates required to stabilise the climate and prevent the global average temperature from rising by more than 2°C above the pre-industrial level, it is necessary to understand the chain of causes and effects that exists between emissions, concentrations in the atmosphere and the global temperature, and to identify the sources of inertia of the climate system. Inertia is in fact a feature that is inherent to the climate, ecological and socio-economic systems. The combined effects of the inertia of the different systems is so that the stabilisation of the climate and the depending systems will only be reached long time after the reduction of emissions.

Atmospheric and oceanic perturbations due to anthropogenic emissions of CO_2 since 1750 will continue during centuries because of the slow redistribution of carbon in the terrestrial and oceanic reservoirs.

The disruption to the CO_2 concentrations in the atmosphere and the oceans will persist for centuries, long after the anthropogenic emission of greenhouse gases has decreased. It will take time for the excess carbon to again be sequestered in carbon reservoirs on land and in the sea. The concentration of CO_2 (a gas with a long lifespan) in the atmosphere will remain at its highest attained level for centuries. Natural processes can reduce the concentration of CO_2 to pre-industrial levels only over geological time spans. However, greenhouse gases, like methane, with a shorter lifespan can be reduced to pre-industrial levels over a number of decennia.

As previously stated, the climate always reacts with some delay to a disruption in the radiation balance. The principal delays of the climate system on a millennium timescale are connected with the oceans and the cryosphere (ice caps, glaciers and permafrost) because of their mass, thinness, thermal capacity and slow heat transport. The increase in the sea level will stretch across millennia for various reasons. The penetration of the heat of the atmosphere to the top mixed layers of the ocean lasts only a few decades, but it can take centuries for this heat to penetrate to the deeper layers of the sea. Because of this, an increase in the sea level resulting from thermal expansion of the seawater will stretch across centuries, even if the atmosphere has already stabilised. In addition, the melting away of the ice caps will extend across even longer periods (see figure below).



CO_2 concentration, temperature and sea level continue to increase long after emissions have decreased. (IPCC-TAR – Climate Change 2001: The Scientific Basis).

2.8.3 Kyoto, a first important step

The climate changes that will occur in the future will be determined by emissions of greenhouse gases from the past, the present and the future. The projected warming and associated increase in the sea level becomes smaller and slower as the decrease of emissions becomes larger and is initiated sooner.

The Kyoto Protocol (1997) has as goal a reduction of greenhouse gas emissions by an average of 5% in the industrialised world in the period 1990 to 2008-2012. This goal is in fact much too far away from what is necessary to be able to 'save' the climate and to keep the temperature increase less than 2°C above the pre-industrial level. It has been shown that if the Kyoto Protocol is fully implemented by all industrialised countries, the CO_2 concentration in 2010 would only be 1 to 1.5 ppm less than had it not been implemented.

Yet Kyoto is important. As Bert Bolin, the former Chairman of the IPCC states: *"Because of the long residence time of CO_2 in the atmosphere, even a modest reduction in the rate of increase of atmospheric CO_2 would be of a long-term significance."* Nevertheless, many other steps will need to be taken.

2.9 Key uncertainties to address in further research

Significant progress has been made in many aspects of the knowledge required to understand climate change and the human response to it. Still the third assessment report of the IPCC (IPCC-TAR - Climate Change 2001) has identified the following important areas where further work is required:

- ✓ Detection and the search for causes of climate change.
- ✓ Increasing our expertise and improving the ability to predict regional climate changes and climate extremes.
- ✓ The quantification of the impact of climate changes at world, regional and local level.
- ✓ Further analysis of adaptations and mitigation the activities.
- ✓ Integration of all aspects of climate change into strategies for sustainable development.
- ✓ Carrying out integrated and detailed research to support the assessments of what 'a dangerous anthropogenic disruption of the climate system' really encompasses.

3. The role of the oceans in global change

3.1 From a CO_2 source to a CO_2 sink

Until recently, the oceans were a source of carbon dioxide (CO_2) for the atmosphere. Each year they emitted 520 million tons (Mt) of CO_2 into the atmosphere. These emissions had their source in chemical and biological reactions that were a part of the marine carbon cycle. However, the situation has now been completely reversed: concentrations of CO_2 in the atmosphere have increased so strongly (see Chapters 1 and 2) that the oceans are now absorbing enormous quantities of CO_2. A brief look at the figures: according to the 'IPCC Second Assessment Report: Climate Change 1995' (IPCC, 1995a), mankind emits 7,100 ± 1,100 Mt of carbon (in the form of carbon dioxide) into the atmosphere annually. Of this, 3,800 ± 200 Mt is absorbed: most by the oceans (2,000 ± 800 Mt) and the rest by a string of recipients (carbon sinks) which has yet to be identified. Despite the importance of the oceans in tempering climate change, we are still far from knowing all the parameters involved in the complex processes of the marine carbon cycle. Moreover, the measurements and models used to describe the interchange of CO_2 between the atmosphere and the ocean contain many gaps. The global models, for example, take into consideration only the open seas and oceans while ignoring the importance of the coastal zones, the continental shelf and the continental slopes. However, it is precisely in these zones that the most active biological processes take place.

3.2 The physical, chemical and biological pumps

3.2.1 Forms of carbon in the ocean

Carbon (C) is present in the hydrosphere in inorganic (mineral) and organic forms. In the rest of this chapter we will often be referring to dissolved CO_2 or CO_2 in water. When dissolved in water, carbon dioxide (CO_2) will primarily take the form of bicarbonate ions (HCO_3^-) and to a lesser extent take the form of carbonate ions (CO_3^{2-}). By this we implicitly mean that the following equilibrium reactions take place:

$$CO_2 + H_2O \leftrightarrow H^+ + HCO_3^-$$
$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

These reactions (where the H^+ ion intervenes) demonstrate that inorganic carbon plays an important role in regulating the level of acidity (pH) of seawater. Inorganic carbon is also present as solid particles of calcium carbonate ($CaCO_3$). A variety of living organisms (extending from microscopic algae to molluscs and coral) use $CaCO_3$ to produce their internal or external skeletons.

3.2.2 From shallow to deep water

Carbon dioxide (CO_2) is a gas that dissolves easily in water. Thus, there is a constant exchange of this gas between the atmosphere in seas and oceans. When the concentrations of CO_2 in the atmosphere increase, the concentrations in the surface layers water layers (that are in contact with the atmosphere) increase too. The total amount of CO_2 exchanged between the ocean and the atmosphere primarily depends upon the size of the contact surface and the thickness of the water layer that is in contact with the atmosphere. The thickness of this 'mixing layer' is usually limited to a few hundreds metres. A second important factor is temperature. The solubility of CO_2 is inversely proportional to the temperature of the water: the lower the temperature, the greater the number of gas molecules that will dissolve.

The deeper ocean water layers do not come into direct contact with the atmosphere. Other mechanisms play a role in the accumulation of CO_2 into these layers. The three most important processes responsible for a transfer of CO_2 from the upper to the lower water layers are the physical, biological and chemical (or carbonate) pumps (see figure alongside).

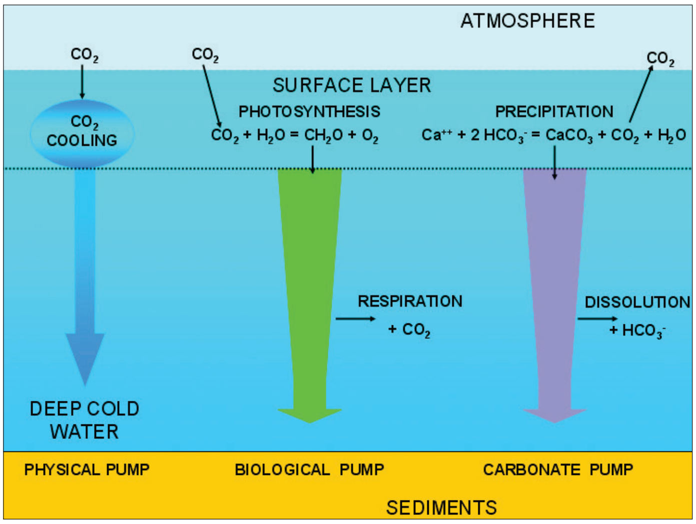


Diagram of the most important carbon pumps at work in the ocean.

3.2.3 The physical pump

Differences in density in the ocean water (caused by variations in temperature and salinity) generate currents over the entire oceans. This is what we call the thermohaline current. Cold and heavy water (rich in dissolved CO_2) sink to the depths of the North Atlantic Ocean. This brings about a transfer of carbon from the surface water to the deeper water layers. This process (also referred to as the physical pump), forms a carbon sink for thousands of years. This means that, on average, the carbon absorbed in this way by the deep water layers of the ocean is only released back into the atmosphere after thousands of years.

3.2.4 The biological pump

Another important mechanism used to transfer carbon from the atmosphere is photosynthesis. Photosynthesising organisms, under the influence of light, are able to convert CO_2 into hydrocarbons. Oxygen (O_2) is also released in this process. A simplified reaction equation of the process is the following:

$$CO_2 + H_2O \xrightarrow{\text{Photosynthesis}} CH_2O + O_2$$

where formaldehyde (CH_2O) is a simplified representation of the synthesised organic material.

Only in the upper zone of the oceans (the euphotic zone) light is sufficiently present to allow photosynthesis to occur. Hence algae are primarily responsible for photosynthesis in the oceans. Living or dead algae can be utilised as food by other organisms (zooplankton, fish and bacteria). They in turn reconvert a part of the organically bound carbon back to CO_2 in a process called respiration. Respiration is exactly the opposite of photosynthesis:

$$CH_2O + O_2 \xrightarrow{\text{Respiration}} CO_2 + H_2O$$

When the respiration takes place in the upper water layers, the CO_2 released in the photosynthesis can be recycled or emitted into the atmosphere. However, a part of the organically bound carbon sinks to deeper water layers in the form of dead organisms or faecal waste. In the intermediate water layers (above 1,000 metres), this organic carbon is also broken down into CO_2 (usually by bacteria), but the released CO_2 can never be exchanged with the atmosphere and remains dissolved. These intermediate water masses constitute a carbon sink on a time scale of a few decades.

Only a small fraction of the carbon that is organically bound in the upper water layers finally reaches the floor of the ocean. These molecules, after deposition by organisms that live on the seabed (benthic organisms), are further broken down. Finally, a still smaller fraction of the settled organic matter is buried and preserved in marine sediments for millions of years.

3.2.5 The chemical pump

The chemical pump or carbonate pump has only recently been recognised as an important mechanism in the transfer of carbon from the higher water layers to the deeper ones. Many living marine organisms are able to build a calcium carbonate ($CaCO_3$) skeleton from dissolved bicarbonate and calcium ions. The reaction is as follows:

$$2\ HCO_3^- + Ca^{2+} \rightarrow CaCO_3 + CO_2 + H_2O$$

It is thus a process that produces CO_2, but it also allows the sedimentation of skeletons of dead organisms. In the deeper water layers, a part of the $CaCO_3$ can, under the influence of lower temperatures and higher pressure, again disintegrate into bicarbonate (HCO_3^-) and calcium (Ca^{2+}) ions. Nevertheless, a significant fraction of the $CaCO_3$ remains buried for millions of years in marine sediments.

3.3 How efficient is the ocean as carbon sink?

3.3.1 Study of coasts and the Southern Ocean

We know that currently the oceans absorb a considerable portion of the anthropogenic CO_2 emissions present in the atmosphere. However, predicting how the concentrations of CO_2 in the atmosphere will evolve and how the climate will further change remains a difficult task. One of the biggest problems is that models describing the global carbon cycle focus almost exclusively on the open oceans and thus almost entirely miss the effects of the continental slopes, coastal zones and estuaries. The heterogeneity and the complex processes in these regions make it difficult to integrate these processes into global models of the carbon cycle. Yet these areas (which cover only 7% of the total ocean surface) are enormously important: they are characterised by very active physical, chemical and biological processes that strongly influence the carbon cycle of the oceans and are responsible for a significant part of the world's carbon exchange.

Another very important region is that of the Southern Ocean around Antarctica. It is estimated that this ocean contributes 30% to the global ocean carbon sink while only accounting for 10% of the total ocean surface area. But, the carbon cycle processes at work in this ocean are largely unquantified.

Various Belgian researchers have contributed on filling in this gap. A part of their answers is synthesised in the paragraphs that follow.

3.3.2 CO_2 in surface water close to coastal areas

Perhaps the best method of assessing the exchange of gases between atmosphere and ocean at world level is the worldwide measuring of the CO_2.concentration in the surface waters in as many different places as possible. Belgian researchers also contribute to this to an important extent. It is striking how poor the information continues to be on coastal areas, the continental margins and the Southern Ocean.

Rivers and estuaries

River water contains high concentrations of dissolved CO_2 due to the breakdown of organic material from wastewater discharged by mankind and from organic material due to soil erosion in which mankind also plays a role.

The distribution of dissolved carbon dioxide (CO_2) and the exchange with the atmosphere in estuaries are being studied intensely by ULg-OCEANCHEM. The researchers developed a large part of the measurement equipment themselves. This has allowed them not only to measure the concentrations of dissolved CO_2, but also to directly measure the gas exchange between the atmosphere and the water surface. Their first measurements were taken in the Scheldt estuary (Belgium) where the concentrations of CO_2 exceed equilibrium values by more than a factor of 25, making the Scheldt an important net source of CO_2 for the atmosphere. Amounts of up to 790 tons of carbon per day were observed.

In the meantime, the ULg researchers have expanded considerably the number of areas measured. They monitored ten estuaries of several European rivers (EU project BIOGEST, 'Biogas Transfer in Estuaries'). This research indicated that the European rivers emit 30 to 60 Mt of carbon into the atmosphere annually, which is approximately 5 to 10% of the total level of European anthropogenic emissions.

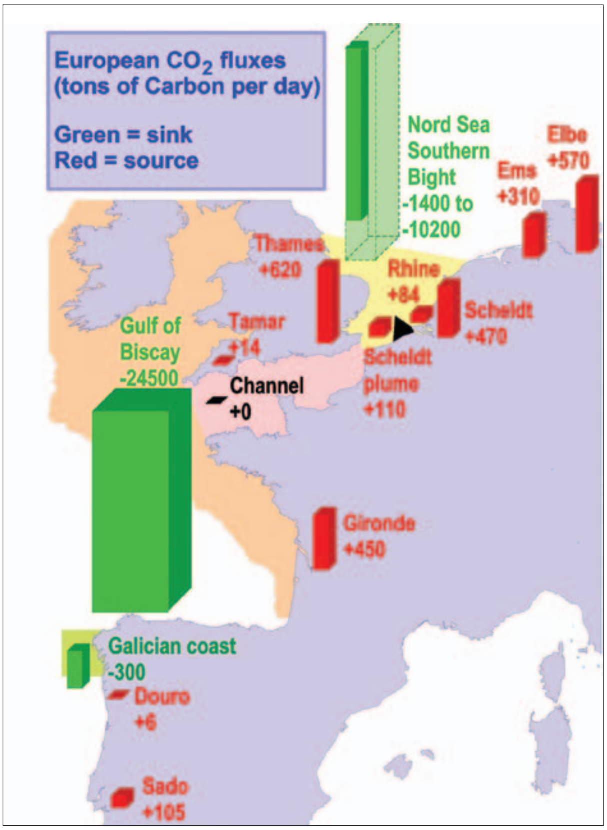
Researchers from ULg-OCEANCHEM and VUB-ANCH are now also performing their measurements outside Europe, among others in a number of mangrove estuaries in Southeast Asia and East Africa.

Coastal areas

In the water of the coastal areas, the concentrations of dissolved CO_2 depend upon various processes: there is the inflow of CO_2-rich water from the rivers, but also the upwelling of water from deeper water layers. This upwelling at the margins of the continental shelf is influenced by the wind. The water from the deeper water layers is not only cold but also rich in CO_2 due to the breakdown of settling organic material. This water is also rich in nutrients stimulating the growth of algae and bringing about an increased uptake of CO_2 over time.

With their experiments in the Bay of Biscay, Belgian researchers (ULB-GMMA, ULB-OCEAN, ULg-OCEANBIO, ULg-OCEANCHEM, ULg-LPAP, VUB-ANCH) were among the first to study this upwelling

from deeper water layers at the margins of the continental shelf. As a result of this pioneering work, the European project OMEX ('Ocean Margin Exchange') was started under the coordination of the ULB-OCEAN team. The coastal areas being monitored by the Belgian researchers (the Bay of Biscay, the costal region of Galicia and the North Sea) function as carbon sinks on a yearly basis (see figure below). However, the contribution at world level made by the coastal areas remains a point of discussion. Hence there is a need for research into other coastal areas.



CO_2-exchange between the atmosphere and the sea for various European coastal areas. (ULg-OCEANCHEM).

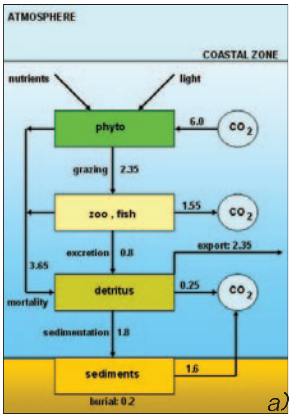
3.3.3 The biological pump in coastal areas

The biological pump at the continental shelf is influenced by a large number of parameters that differ from those present in the open oceans. For example, in a coastal zone, the particles containing organic material will sink to the floor more quickly and will be buried more easily. In addition, the coastal areas are also the zones where the organic material from the rivers and estuaries is deposited. This rapid accumulation of organic sediments is responsible for a more intense level of biological activity (molluscs, fish, worms, bacteria, etc.) than is present in the open oceans.

A number of Belgian research teams are engaged in multidisciplinary collaboration that is attempting to unravel the most important processes and parameters at work in the carbon cycle in the Southern Bight of the North Sea. Their research has provided a better understanding of the vertical distribution of organic material, benthic organisms (in and on the seabed living organisms), oxidants and metabolites in marine sediments.
In addition they developed various models: hydrodynamic (IRSNB / KBIN - MUMM), chemical (ULB-GMMA, ULB-OCEAN, ULg-OCEANCHEM, VUB-ANCH) and biological (UGent-MARBIOL, ULB-GMMA, ULB-ESA, ULB-OCEAN, ULg-OCEANBIO, VUB-ECOL). This allows a better integration of the data over a long period, which also allows the prediction of the effects on the environment of changing environmental conditions (e.g., dredging)
To summarize, the researchers demonstrated that photosynthetic production in the Southern Bight of the North Sea amounted to approximately 230 g of carbon per m^2 per year, approximately three times more than that in the open ocean. However, the vast majority of this production is again broken down and converted to CO_2 or exported to

the northern part of the North Sea. Approximately 4% of the total production is deposited and buried in the sediments.

The Belgian results agree strongly with those obtained by other researchers in coastal areas of the North Atlantic Ocean or the northern part of the Pacific Ocean. Compiling all of this data made possible the drawing up of a tentative balance of the carbon flux for all the coastal areas of the world as shown in the next figure.



Carbon (C) cycle for all coastal areas of the entire world (in billions of tons of carbon -C- per year). (ULB-OCEAN).

3.3.4 The biological pump in the deep ocean

The importance of the biological pump in the seas around Antarctica had been insufficiently assessed until recently. Long-term research (by Belgian scientists among others) has revealed that these oceans constitute a carbon sink on an annual basis. Thus, the Indian sector of the Southern Ocean alone absorbs 250 Mt of carbon annually. This CO_2 remains sequestered in the deeper water layers of this ocean for a period extending from several decades to a few centuries. The biological pump is not only active in the deep ocean but also on the continental margins, as has been demonstrated by a number of Belgian research groups in the Bay of Biscay.

VUB-ANCH and ULB-OCEAN focus on improving the techniques for measuring the concentrations of organically bound carbon in deeper water layers. Ten years of oceanographic measurements and the construction of models (VUB-ANCH, ULB-ESA, ULg-OCEANCHEM, UCL-ASTR, KMMA / MRAC) has also yielded much information about the role of the oceans around Antarctica as a carbon sink.

3.3.5 The importance of the chemical pump

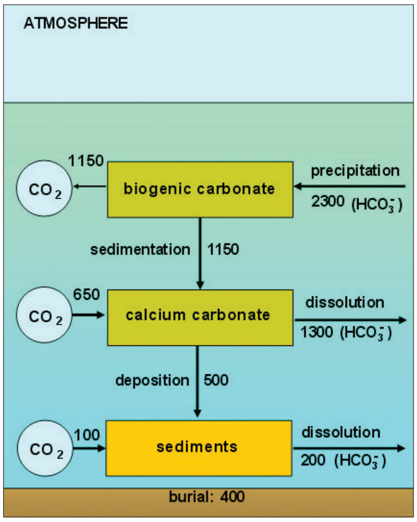
Until now, research into the carbon cycle has focused too little on the inorganic carbon cycle. By far the most attention has gone to the organic carbon cycle. Yet, the carbon that is bound in calcium carbonate ($CaCO_3$) is an important player in the global carbon cycle. Carbonate rocks on land are sensitive to erosion and when exposed to rainwater dissolve into bicarbonate (HCO_3^-) and calcium (Ca^{2+}) ions. These ultimately end up in the seas and the oceans at a worldwide rate of at most 390 Mt of carbon per year. Maintaining the chemical composition of the ocean requires that one half of this carbon be precipitated as $CaCO_3$ and the other half be released into the atmosphere as CO_2.

Coccolithophorids are an important group of algae that produce a calcite skeleton. They are, for example, the dominant species present in the Bay of Biscay. They can convert 100 g carbon per year to $CaCO_3$ per m^2 of water surface area. Yet, only a small part of this calcium-bound carbon is deposited on the seabed and buried. A large part is possibly dissolved again into calcium and bicarbonate ions.

Coral reefs are the main producers of calcium carbonate. It is estimated that they fix 100 million tons of carbon per year worldwide. However, because they

are composed of algae with a relatively active carbon metabolism, it is often difficult to calculate their net effect on the CO_2 balance. According to research carried out by ULg-OCEANCHEM, coral reefs are more likely a source of CO_2. This phenomenon is reinforced by increasing concentrations of atmospheric CO_2. Only in a eutrophic (nutrient-rich) environment would coral reefs function as a carbon sink.

A tentative budget of fluxes linked to the chemical pump, is represented in the figure below It indicates that the precipitation of carbonates (CO_3^{2-}) in surface waters, its dissolution in deeper waters and its sedimentation constitutes an efficient carbon pump responsible for vertical fluxes similar to those of the biological pump



Tentative global cycle of calcium carbonate ($CaCO_3$) in the marine system (all fluxes are indicated in millions of tons of carbon -C- per year). (R. Wollast, ULB-OCEAN).

This figure makes it clear that the ocean system is presently not in a steady state. There is an excess of precipitated carbonate with respect to the river input. However, this does not represent an additional sink for CO_2, since the precipitation of one unit of carbonate generates one unit of CO_2. Many parameters of the oceanic carbonate cycle remain unknown and efforts are still underway in the Belgian research community to resolve these uncertainties.

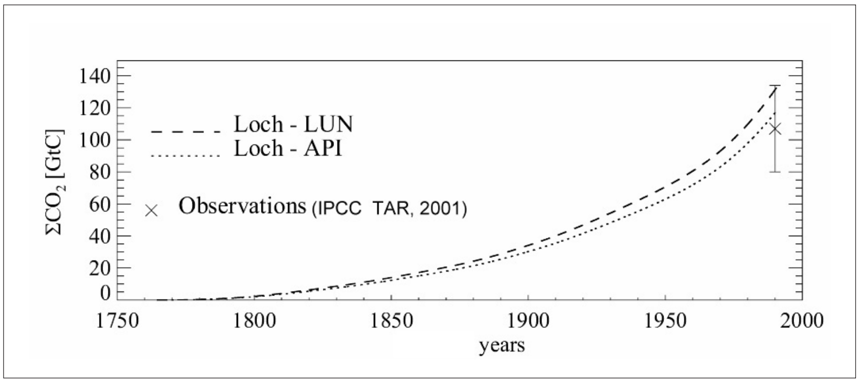
3.3.6 Use of models

As mentioned above, it appears that the oceans at present absorb much carbon. Researchers develop models to assess human impact on this phenomenon and to make predictions.

Belgian researchers have been involved for some time with measurements and the development of models that describe the exchange of carbon between atmosphere and hydrosphere. This work is not only important to calculating the flux but also to predicting the future evolution of the entire carbon cycle.

An example of such a model is LOCH, developed ULg-LPAP. It concerns a three-dimensional reaction-transport model that can calculate the evolution of numerous carbon parameters in the oceans: the total amount of organic and inorganic carbon, the alkalinity, the content of phosphate (PO_4^{3-}), silica (SiO_2) and also oxygen (O_2). The most important processes included in the model are the exchange of gas at the surface between hydrosphere and atmosphere, as well as the physical, biological and chemical processes through which carbon migrates to the deeper water layers.

LOCH functions within the ‘Oceanic General Circulation Scale’ models, describing the general ocean circulation and, among other things, allows to estimate how much carbon has been absorbed by the oceans since 1765 (see figure below). Moreover, it appears that the total exchange of carbon between the oceans and the atmosphere is in reality many times more than the 2,000 Mt that the oceans absorb annually.



The amount of carbon (C) stored in the oceans since 1765 according to different numeric models. These take account of the increase in the carbon dioxide (CO_2) concentrations in the atmosphere. (ULg-LPAP).

3.4 The importance of nutrients

3.4.1 More than light

Photosynthesising organisms need more than just light. They must also have access to nutrients. The most important of these are nitrogen (N) and phosphorus (P), but trace elements such as iron (Fe) and zinc (Zn) must also be present. Moreover, some organisms like diatoms also require dissolved silica (SiO_2) for the construction of their skeletons. If these nutrients are not available in sufficient quantities, primary production will cease. Thus, the availability of these elements in the ocean environment plays an important role in the functioning of oceans as a carbon sink.

3.4.2 Nitrogen

Polluted rivers

Nitrogen (N), in the form of nitrate (NO_3^-) or ammonium (NH_4^+), is often considered the most important limiting nutrient in most marine systems. Hence it receives more attention than other nutrients.

The nitrogen cycle is relatively complex (see figure below). Nitrogen is present in water mostly as dissolved nitrogen gas (N_2). However, in this form it is very difficult for the phytoplankton to use as source of nitrogen. In the form of nitrates, phytoplankton is able to absorb and use the nitrogen to produce biomass. When this biomass is broken down, the nitrogen is again released in the water in the form of ammonium. In this form, it is easily absorbed by the phytoplankton. In addition, it can be converted by bacteria into nitrate (nitrification). In the absence of oxygen (O_2), bacteria can also convert nitrate back into nitrogen gas (denitrification).

The activities of mankind interfere significantly in the nitrogen cycle. Massive amounts of nitrogen compounds arrive in rivers due, among others, to over-fertilisation and the discharge of wastewater (both industrial and domestic), leading to excessive algae growth. Yet, rivers are by no means the only source of nitrogen available to the seawater of the coastal areas.

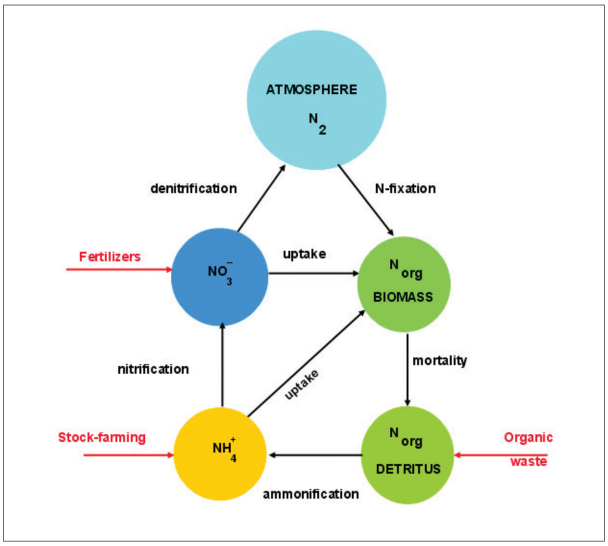
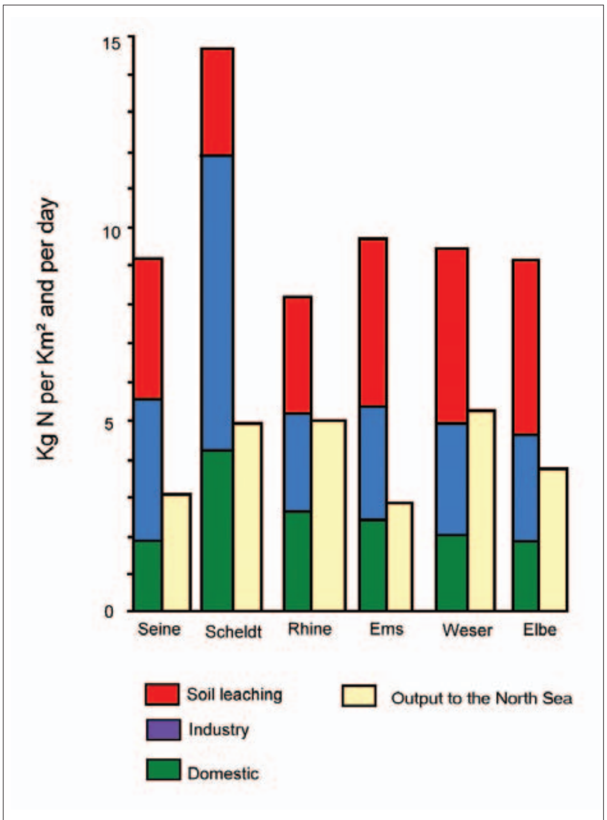


Diagram of the nitrogen (N) cycle in rivers and marine environments.

The nitrogen cycle in the hydrosphere has been studied by UA-MiTAC, ULB-GMMA, ULB-ESA, ULB-OCEAN and VUB-ANCH. Their research indicates that the concentrations of nitrogen compounds in European rivers are from ten to one hundred times greater than those in unpolluted rivers. This is a cause of excessive algae growth, a process also referred to as eutrophication.
However, it is surprising that only half of this excess nitrogen ultimately arrives in the North Sea. This means that a part is ‘processed’ along the way, on the one hand by anaerobic bacteria that convert the nitrogen compounds into nitrogen gas, and on the other hand due to precipitation of the nitrogen compounds on the river bottoms (see figure below).



Estimate of the quantities of nitrogen (N) that arrive via agriculture, industry and domestic activities in the rivers that empty into the North Sea. (ULB-GMMA).

According to a study by ULB-GMMA, conventional purification of wastewater would be responsible for a reduction in the denitrification that occurs in the rivers. The purification process indeed provides for a decrease in the total organic load, causing the water column and the sediments to remain more aerobic. This phenomenon is enhanced by present river policy that provides for a higher rate of flow and better aeration of the water column. The high levels of investment in conventional water treatment and river policy thus paradoxically result in more nitrogen arriving in the sea.
In another study, ULB-ESA showed that the use of tertiary water treatment (the removal of nitrogen and phosphorus from waste water) is inadequate to the task of addressing the increasing eutrophication of the coastal areas in the Southern Bight of the North Sea and the North Sea if the input of nitrogen from agriculture is not also dealt with at the same time.
ULB-GMMA and ULB-OCEAN are also studying the processes that influence the nitrogen cycle in sediments. They have developed models to describe the recycling of organic nitrogen and to predict the flows of various nitrogen compounds (NO_3^-, NH_4^+, N_2). It appears from these that the rapid recycling of nitrogen in the sediments is an important cause of the high productivity of the continental shelf.

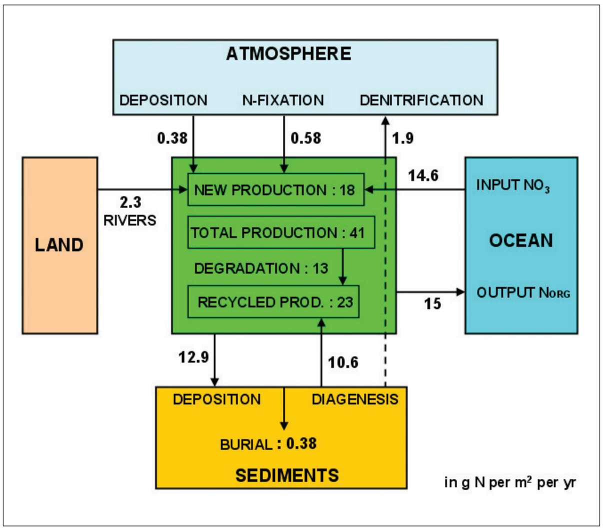
Deep water layers

In the 1960s, researchers were convinced that the most important source of nutrients for the coastal areas was the influx of rivers. Yet, more recent research shows that the upwelling of nutrient-rich deep water layers along the continental shelf is also important. Just how important this was, was not clear until recently.

Belgian researchers were among the first to perform experiments in this regard.

ULB-OCEAN, ULg-OCEANCHEM and VUB-ANCH investigated the upwelling of deep water layers and its influence on the nitrogen cycle in the Bay of Biscay. They found that the vertical mixing of intermediate water layers was responsible for an annual production of up to 200 g of organically bound carbon per m². This level of production is more than twice that found in nearby measuring stations in the open ocean where this upwelling does not take place. Furthermore, the researchers showed that the effects of the nutrient-rich upwelling water are not limited to the Bay of Biscay. The current carries it into the Channel, as far as the Southern Bight of the North Sea. The deep water layers of the Atlantic Ocean are the most important source of nitrogen nutrients for this entire region, much more important than the rivers that empty into the North Sea.

A tentative estimate of the levels of nitrogen flux in coastal areas over the entire world is provided in the next figure. This estimate was made based upon measurement data and models developed by UA-MiTAC, ULB-GMMA, ULB-ESA, ULB-OCEAN and VUB-ANCH. The role of nitrogen recycling is striking here, as is the flux of nitrogen from the deeper water layers. The exported nutrients must be replaced in the surface water through vertical mixing of the water column or by input from rivers and the atmosphere. The production associated with these non-recycled nutrients is also sometimes referred to as 'new production'. The contribution of the rivers is relatively small: 15% of the new production.



Average global flux of nitrogen (N) in the coastal zones. (UA-MiTAC, ULB-GMMA, ULB-ESA, ULB-OCEAN en VUB-ANCH).

3.4.3 Phosphorus

Phosphorus (P) in the form of Phosphates (PO_4^{3-}) is a second important nutrient for the phytoplankton. In most natural marine systems, there is an adequate supply of phosphorus present and this element is rarely completely depleted in the water column.

The input of anthropogenic phosphorus into the hydrosphere is proportionally lower than that of nitrogen. Since the appearance of washing powders without phosphates, the discharge of phosphates into the surface water has even decreased considerably. Thus in some river basins, phosphorus can become the limiting factor for growth. In these environments, phosphorus recycling is a significant factor in the primary production of organically bound carbon.

ULB-OCEAN, ULB-ESA and VUB-ANCH are some of the research institutes that are studying the phosphorus dynamics of the Southern Bight of the North Sea. They are attempting to determine which organisms are involved in the assimilation and recycling of phosphorus. Preliminary

results indicate that in coastal areas it is primarily bacteria that are the important consumers of dissolved phosphates.

3.4.4 Silica

Anthropogenic activities contribute significantly to the increase in the nutrients (mainly nitrogen and phosphorus) that are transported by the rivers to the North Sea, leading to the eutrophication of the Belgian coastal waters.

For some micro-organisms such as diatoms, dissolved silica (SiO_2) is also an important nutrient: diatoms require this substance to develop their skeletons.

In building dams and locks and via other interventions in the hydrological cycle, mankind has brought about an increased retention and collection of silicates in lakes, reservoirs and rivers. Because of this, there is a relative shortage in the coastal waters of silica when compared to the excess of nitrate and phosphate present. This causes a change in the composition of the phytoplankton, bringing about a change in the entire food chain of the marine coastal areas.

ULB-OCEAN and UGent-PAE are attempting in the project SISCO ('Silica Retention in the Scheldt continuum and its Impact on Coastal Eutrophication') to detail the silica flux in the Scheldt (Belgium) and to calculate its impact on the eutrophication of the seawater for the coastal areas.

Because of the high fertilisation levels of nitrogen and phosphorus in the rivers, each year in the spring there is an explosive growth of algae (Phaeocystis colonies) in the water of the Southern Bight of the North Sea. Researchers from ULB-ESA have found that these colonies are highly resistant to the traditional phytoplankton grazers and that they have a negative effect on the marine ecosystem and the environment. In an undisturbed marine environment, where no nitrogen and phosphorus fertilisation occurs and sufficient silica is present, the Phaeocystis colonies are held in check by an early flourishing of diatoms in the spring. ULB-ESA has developed a complex biological model (MIRO&CO) capable of calculating the timing, size and geographical distribution of the diatom and Phaeocystis growth, based upon the synergy between climate and anthropogenic activity.

3.4.5 Iron

It was recently shown that iron (Fe) can be a limiting factor in the production of organic material by phytoplankton. This is, among others, the case in the Southern Ocean around Antarctica. This has led to a few large-scale experiments in which the ocean was 'fertilised' with iron. Belgian researchers were involved in one of these experiments, which will be covered in more detail in the following section.

3.5 Giving the ocean a hand

3.5.1 To fertilise or inject?

Carbon dioxide (CO_2) is the most significant greenhouse gas (see Chapters 2 and 3). It is estimated that it is responsible for two thirds of the process of climate change. The most important reason why concentrations of CO_2 are increasing in the atmosphere is the burning of fossil fuels by mankind. One way to reduce these emissions lies in switching to alternative sources of energy that do not generate greenhouse gases. Another alternative lies in absorbing the greenhouse gas emissions in so-called carbon sinks or reservoirs.

It is estimated that the oceans already contain 40,000 billion tons of carbon: this is approximately 50 times the level stored in the atmosphere. These figures alone make it clear that the hydrosphere appears by far to be the most suitable potential reservoir for excess CO_2.

Scientists are investigating how this uptake of carbon by the oceans can be accelerated. Two techniques are under consideration: fertilising the upper layers of the ocean with nutrients or injecting CO_2 directly into the deeper water layers.

The study of these processes has been strongly encouraged by a number of countries such as the US, Japan and Norway. They are supporting large-scale experiments and even patents have already been applied for. This is a clear indication that there are enormous economic interests at stake in the development and utilisation of these technologies.

However, other researchers are less happy with these experiments. They believe that the potential risks have not been sufficiently weighed against the advantages and that there is a lack of dialogue on establishing thorough, scientific criteria evaluation.

3.5.2 The efficiency of fertilisation

The theory

An increase in the primary production of organic material at the sea surface would lead to an increased uptake in carbon from the atmosphere. The idea is that the organic material sinks and is broken down in the deeper water layers, with the released CO_2 remaining in solution for dozens or even thousands of years. According to proponents of this process, an additional benefit to a higher concentration of organically bound carbon is that it stimulates the food chain, ultimately benefiting fish production.

The experiment

In both the Southern Ocean and the Pacific Ocean near the equator, the production of phytoplankton is hindered by a lack of iron. Nitrogen and phosphorus are present in sufficient amounts in these areas. Thus, researchers were attracted to these two areas as sites at which to perform four large-scale iron fertilisation experiments.

The results

Experiments indicate that the production of phytoplankton increases significantly after the fertilisation with iron. Yet not all scientists are convinced. According to some, this increase is only temporary: the predators of phytoplankton have not yet adapted to the new situation. They also note that very little of the carbon sinks to intermediate water layers. Thus, the increased uptake of carbon just after fertilisation with iron would represent a carbon sink that would only last a few years.

Even if more carbon were to sink to deep water layers, there is a risk of undesirable side effects. The increased sedimentation of organic carbon would lead to a higher level of respiration, quickly bringing about a lack of oxygen in the deeper water layers. This would cause the formation of the toxic gas hydrogen sulphide (H_2S), as well as methane (CH_4) and nitrogen oxides (NO_X). The two latter are stronger greenhouse gases than carbon dioxide (CO_2)!

Given the great number of uncertainties associated with the large-scale fertilisation of oceans, many scientists would like to see a consensus reached on the criteria applied to the scientific evaluation. Unfortunately, they find that at present there is a lack of substantial discussion on the matter.

3.5.3 The efficiency of injection

This technique involves introducing an almost pure form of carbon dioxide (CO_2) into the ocean. To prevent the gas from quickly returning to the atmosphere, it would be injected into the ocean, in one go, at a great depth (> 1,000 metres) where it would remain for thousands of years. The technique would in fact mean an acceleration of the natural mechanisms by which carbon in the upper layers is taken up and only very slowly migrates to the lower layers.

Various techniques have been proposed for injecting CO_2 into deeper water layers. However, the possible risks to the ecosystem are still largely unknown. Scientists principally fear a local acidification of the water. The local levels of acidity in the water could decrease to a pH of 4, meaning a certain threat to the local ecosystems. However, account must be taken of the fact that the biomass of the living material in the oceans deeper than 1,000 metres is relatively limited.

Whether or not the massive injection of CO_2 into the deeper water layers is a viable option for tempering climate change appears in the first place to depend upon social and political arguments. Taking into consideration the precautionary principle with respect to the ecosystems of the ocean, the implementation of this strategy should only be possible if all parties (public and private) have the opportunity to participate in the debate.

4. Global change in ecosystems

4.1 The loss of biodiversity

From its very beginning some 3.8 billion years ago, life on earth has been subject to numerous changes. Periods in which biological life was strongly diversified have alternated with periods of extinction. Biologists estimate that a massive extinction of species has occurred five times in the past. We currently find ourselves again in an era in which species are dying off in large quantities: it is estimated that 137 animal species disappear daily. At this rate, in 100 years around half of the present species will have disappeared. The present era thus is sometimes labelled the sixth wave of extinction. The difference with the past lies in the fact that the present loss of species is occurring at a rate that is many times greater than that of the previous waves of extinction and that the causes are not always natural.

4.1.1 The effects of diversity on the functioning of the ecosystem

To halt the loss in biological diversity, efforts are increasingly being made to protect biotic systems against the loss of species, habitat and ecosystems. One result of the growing interest in this issue is the Convention on Biological Diversity (CBD). This has given new impetus for research projects focused on the disappearance of species, its implications for biodiversity and its effects on the functioning of the ecosystem. Since its entering into force, field research and especially modelling research has concentrated on the relation between the loss of diversity and the stability of the functioning of the ecosystem. The results have not always been unambiguous and sometimes have even been contradictory. However, they do demonstrate the general fact that a reduction in biodiversity has direct consequences for the functioning of the ecosystem (see Box 11).

In addition, the loss of biodiversity would also have indirect effects on the way in which ecosystems react to other global (climatological) changes. In experiments using simulations of natural heat waves, it was established that the stability of the functioning of the ecosystem

Box 11: Biodiversity and Stability

Biodiversity = species richness + species evenness

Species richness is often wrongly used as a synonym for diversity; however, biodiversity also depends upon the evenness of the species. All species occur within their natural habitat in specific numbers. This is called the abundance of a species. Within a habitat, the number of species and the maximum abundances are limited by the resources available. If several species occur within the same natural area or habitat, each with their own abundance, we speak of a 'hierarchy of dominance'. Within this hierarchy, the abundances of the various species are in proportion to each other. For this reason we speak of dominant and subdominant species which occur in limited numbers.

An example:

- ✓ If the abundance of the various species is approximately equal and the maximum number of species is thus evenly distributed over the number of available locations within a habitat (so-called niches), diversity will be high.
- ✓ However, if the abundance of the different species is not equal and only one species is abundantly present, this species will occupy a large number of niches that cannot be occupied by other species. Because of this, the number of species in the habitat will be more limited and diversity will be lower. When one species occupies almost all habitat niches and other species are only present to a very limited degree, we speak of a 'monoculture', of which examples are many of our present agrarian systems.

Stability = resistance + resilience

The extent to which an ecosystem or community is able to handle stress situations and disruptions is referred to as its stability. Stress includes all anthropogenic and natural factors that negatively influence growth, such as lack of nutrients or light, and suboptimal temperatures. Disruption refers to all (non-)mechanical processes and factors that reduce the biomass. For plants, these can be herbivores and pathogens. The stability of an ecosystem is determined by the extent to which the starting situation is deviated from (resistance) and the time necessary to return to the starting situation (resilience).

Diversity ≈ Stability

The relationship between the diversity and stability of an ecosystem is reflected in the 'diversity-stability' hypothesis. Though not purely a 'cause-effect' relationship, the two are heavily dependent on each other. Communities and ecosystems with a high level of diversity are capable of spreading the effect of disruptions and stress situations across several species, thus buffering the forces destructive to the community. However, vulnerable species also receive a chance in a stable system. So, the number of species (and with this also the diversity of the ecosystem) will increase. In other words, there is also a link between stable systems and biodiversity. Complete clarity concerning the 'cause-effect' character of diversity and stability is not yet available, but it is certain that the two components influence each other in different areas.

depends on the diversity of species present. According to predictions using 'General Circulation Models' (GCMs), more heat waves will occur in the future, as will other extreme weather conditions like floods, tropical storms, etc. (see Chapter 3).

Researchers from UA-PLECO and UGent-PP used artificial model ecosystems (grassland cultures) to measure the effects of species richness on the ability to survive extreme temperatures. Climate models predict an increase of such climatological extremes. Surprisingly, the experiments show that less diverse systems are not necessarily less able to cope with extreme events. They do imply, however, that measures that slow climate change will especially protect diverse systems, precisely by limiting the loss of biodiversity.
Other experiments that investigated the effects of diversity in a plant community support the hypothesis of the 'complementarity of resources'. According to this generally accepted hypothesis, interspecific differences and preferences of species lead to a more efficient exploitation of the various resources within an ecosystem. The large number of species prevents the disappearance of resources from the system. A decrease in the diversity of species will thus lead to an impoverishment of the entire ecosystem.

4.1.2 The effects of management practices on diversity

In Belgium, grasslands quantitatively constitute the most important (managed) ecosystems: they cover 50% of the agriculture surface area and 30% of the total surface area. For the sake of comparison, woods and fallow cover only 12% of Belgian territory. The dominant position held by grasslands is due to their economic advantages. Nevertheless, they also have ecological value. Their permanent character means that they constitute a habitat for a large number of plant species. Furthermore, their management does not require the use of herbicides. Only fertilisation can present an ecological problem when the level of nutrients added is too high.

Grasslands are thus a dominant and permanent feature of the Belgian landscape and constitute a major source of vegetative diversity. Correct management can maintain or maximise this diversity of species.

An experiment was carried out to study the effect of various grassland management methods (3, 4, 5 or 6 mowings per year and fertilisation with 100, 250 or 400 kg nitrogen –N- per ha per year) on diversity. It was shown that a high frequency of mowings (6 mowings per year) in combination with a low level of nitrogen fertilisation (100 kg N per ha per year) leads to the greatest level of species diversity in grasslands. The low levels of added nutrients and the continuous removal of nutrients via mowings mean that both highly competitive and less competitive species can occur. For this reason, the total number of species in the Belgian grassland ecosystems could increase if a change was made from an intensive to an extensive (concerning the input of nutrients) exploitation policy.

4.1.3 Predicting the demise of a species and taking preventative measures

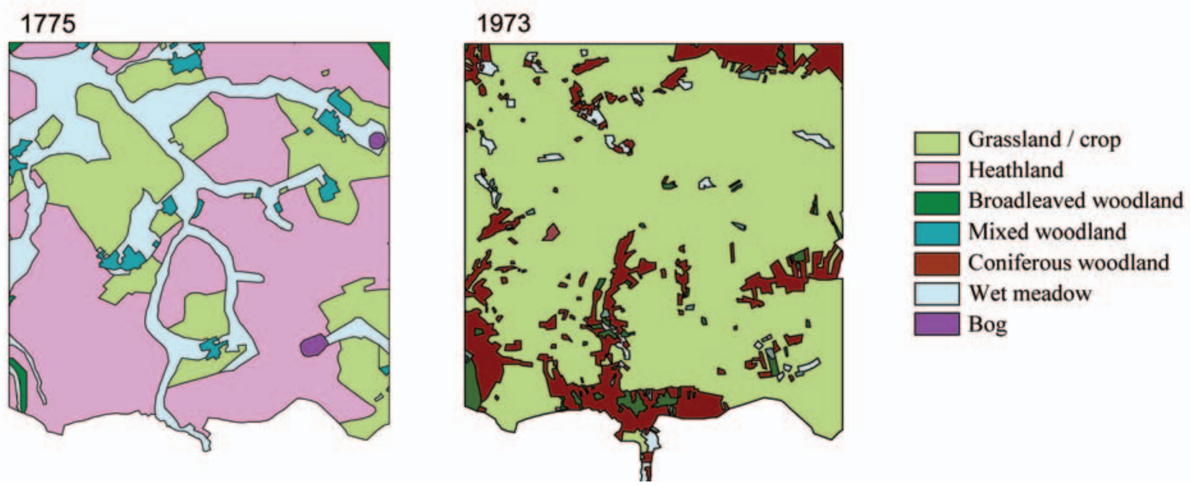
The term 'global change' covers not only all global physical and biological natural changes, but also those induced by mankind. Natural changes usually occur gradually and are quite constant over time. In addition, they are not easily influenced. Anthropogenically induced changes usually occur very quickly and are local in scope. However, their general occurrence over the entire earth can give them a worldwide character. In contrast to natural changes, this anthropogenic impact on biological systems can be reduced (certainly at the local level).

The development of analytical models that simulate the functioning of the ecosystem or population make it possible to take account of this anthropogenic impact and thus to predict long-term effects.

Habitat fragmentation is an example of a local anthropogenic component of global change. The destruction and fragmentation of remaining habitats are radical processes with far-reaching consequences for populations and species. The effects of this anthropogenic component can be predicted using models, and developments can easily be fine-tuned at the local level.

In this context, UCL-ECOL has developed the 'Population Viability Analysis'. This is capable of predicting the reactions of marsh fritillary butterfly populations based on different scenarios. This butterfly lives principally in (peat) bogs such as those in the Lienne valley (Lierneux, Belgium). The aim was to introduce cattle into this region as a management measure. Based upon predictions made by the 'Population Viability Analysis', their introduction into certain areas was limited in order to prevent all of the bistort vegetation from being consumed. Bistort is an elementary link in the life cycle of the marsh fritillary butterfly and its disappearance would have disastrous consequences for the butterfly population (see figure below).

Models and analyses like the 'Population Viability Analysis' provide researchers and environmental managers with the opportunity to react before it is too late. The next step in the process is the development of models adapted to different forms of landscape, regions and collections of species. As such, environmental managers are provided with an instrument that allows them to evaluate the effects of various



Approximately 99% of the wetland vegetation area in the Lienne valley (Lierneux, Belgium) was lost or fragmented in the period 1775 to 1973. Bistort, which belongs to this type of vegetation, is an indispensable part of the habitat of the marsh fritillary butterfly. Despite its small area, the Lienne valley is an important region for the survival of the marsh fritillary butterfly in Belgium. (Le Boulangé, UCL-ECOL).

management methods before they are actually implemented.

4.2 Ecosystems and the increase in greenhouse gases

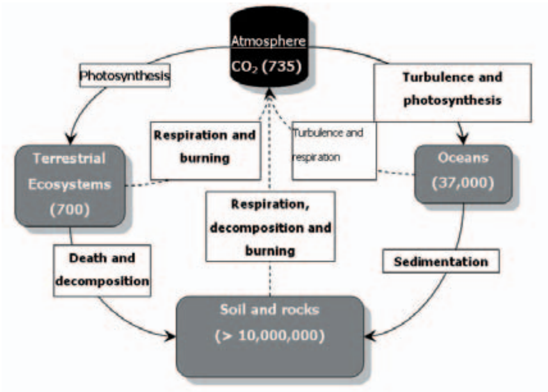
4.2.1 Carbon sinks on the Belgian mainland

Carbon exchanges between the atmosphere, terrestrial systems and the soil are controlled by the photosynthesis and respiration of the vegetation on land and the respiration of organisms living in the soil. Nevertheless, not all carbon molecules are involved in this circulation: a part is accumulated, among other places, in terrestrial ecosystems. The amount of carbon accumulated depends on the 'Net Ecosystem Productivity' (NEP). While various factors influence the circulation and accumulation of carbon, temperature and precipitation are by far the most important global factors (see Box 12).

Models

As a result of the quantifiable relationships

Box 12: Carbon Sinks



The amount of carbon (C) in the compartments is expressed in 10^9 tons (Gt) of carbon. (modified after IPCC, 1995b).

The sequestration of carbon comprises all processes in which carbon is bound in an almost permanent way. It concerns the uptake of carbon in terrestrial ecosystems, in the soil and rocks, as well as in the oceans. Carbon occurs in different forms in these carbon sinks: in all terrestrial ecosystems as living matter, dissolved in the oceans or as calcium carbonates, and in the soil as humus and rock. The ocean and soil sinks are by far the largest. The carbon present in the atmosphere and in living organisms is quantitatively less important, but does belong to the circulating carbon pool. This carbon is continuously exchanged between the terrestrial and the atmospheric systems via photosynthesis and respiration. The quantity of carbon that is assimilated in vegetation, minus the part that is lost in the process of respiration, is referred to as the Net Primary Productivity (NPP). This is not actually the 'yield' of vegetation, since an additional part is always used by heterotrophic organisms. The NPP minus this part is then the Net Ecosystem Productivity (NEP).
While rocks and minerals have a very static character as carbon sink, there has been a change since the beginning of the industrial revolution. The burning of fossil fuels (and terrestrial systems) has led to a major transfer of the carbon molecules to the atmosphere. Since this carbon is released as carbon dioxide (CO_2) and this molecule is a greenhouse gas, it has consequences for the climate.

between the carbon stocks (living biomass, timber production and soil) and the carbon flows (heterotrophic respiration, logging), forest types can be described using models based upon the surface area, the volume and the annual increase per age category. The 'European Forest Information Scenario Model' (EFISCEN) describes 2,689 European forest types in this way. Based upon these models and on the data collected in the field, predictions concerning the capacity of the European forests can be made (see figure below). These are extremely relevant within the framework of the Kyoto Protocol (articles 3.3 and 3.4) and the associated 'Conferences of the Parties' (COPs).

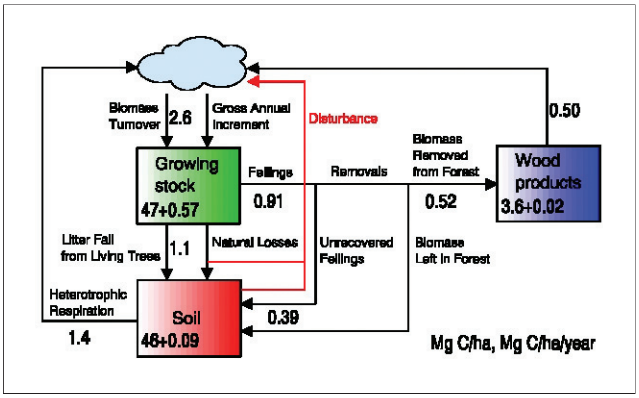


Diagram of the interconnections between carbon stocks (living biomass, timber and the soil) and carbon flows (logging and heterotrophic respiration) according to the European Forest Information Scenario Model - EFISCEN. (Pussinen et al, 2000).

With respect to the carbon flows and sinks, management practices include logging and timber production. In the EFISCEN model, forest management practices are divided into two levels: basic management (including thinning and logging) and the total harvest volume (specified by country and tree species). Management practices were viewed at national level in this model, with 'the country' as the basic spatial unit.

The amount of carbon in the soil depends on the rate of decomposition, which in turn is determined by the biomass aboveground and underground, the proportion of woody to non-woody components and the concentration of lignin in the leaves. Thus, the difference in the amount of carbon (C) in the soil between deciduous forests (120 kton C per ha) and coniferous forests (150 kton C per ha) is explained by the influence of litter quality on the rate of decomposition.

Studies made by VITO-TAP and UCL-GEOG on the Belgian terrestrial carbon sinks and flows showed that the carbon pool in the forest floor is in equilibrium with that in the living biomass (see table on the next page).

These figures were compiled from Flemish and Walloon regional forest inventory data. The information on carbon in the soil comes from 13,000 descriptions of soil profiles made between 1950 and 1970. Use was also made of the data from the BELSPO projects 'Carbon Sequestration in Terrestrial Ecosystems' (CASTEC) and 'Modelling Ecosystem Trace Gas Emissions' (METAGE).

The results are in line with those of most European forests. The amount of (circulating) carbon per surface area is indeed higher in Belgium than the European average. This is due to the favourable temperature and precipitation conditions in our country.

Since in our country the total amount of carbon in the soil (276,000 kton C) greatly exceeds that which is present in the forest biomass (53,800 kton C), it is clear that changes in the soil can have radical consequences for the national balance of greenhouse gases. Thus, further research is required to quantify possible changes in this pool (resulting from changes in land use, land management and climate).

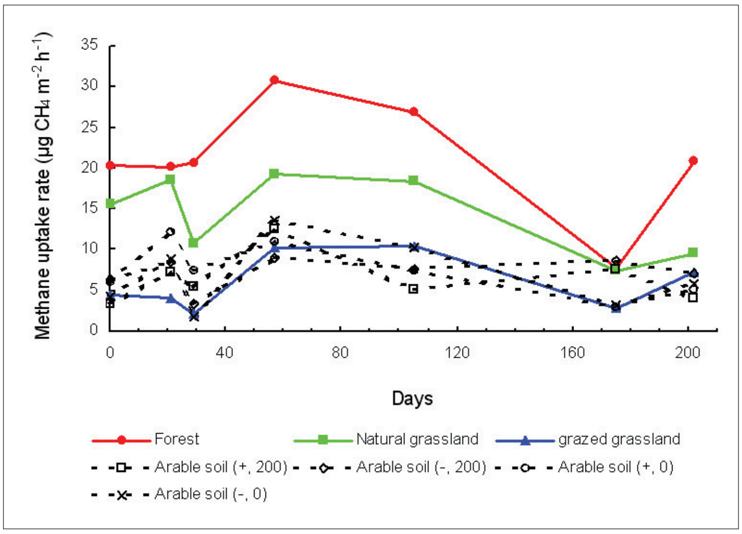
Carbon stocks and flows of Belgian terrestrial ecosystems and soils. (F. Veroustraete, VITO-TAP and B. Van Wesemael, UCL-GEOG).

Stocks	Per unit area (ton C/ha)	Totals for Belgium (kton C)
Forest biomass	94.4	53,800
Soil (from national soil survey 1950-1970)		
Humus layer in forests	61.5	35,000
Soil (0-30 cm)	58 (10-190)	144,000
Soil (0-100 cm)	98 (18-986)	241,000
Fluxes	**Per unit area (ton C/ha/yr)**	**Totals for Belgium (kton C/yr)**
All vegetation NEP	4.8	14,600
Forest biomass accretion (NEP)	5.0	2,800
Forest felling	2.1	1,200
Soil as a result of management	?	500-800

4.2.2 Other gases that affect climate and ozone

Several biochemical and geochemical reactions that take place in terrestrial ecosystems contribute to the formation or uptake from the atmosphere of gases such as methane (CH_4), nitrous oxide (N_2O) and other nitrogen oxides (NO_x). Some are greenhouse gases (see Chapter 2), while others affect the concentration of ozone in the atmosphere (see Chapter 1). Thus, it is important to thoroughly study the exchange of these gases between the terrestrial systems and the atmosphere. Aerobic soils can absorb up to 29,000 kton CH_4 per year. They constitute the most important means of conveying methane to the terrestrial carbon sink. Agricultural soils, on the other hand, are the most important source of NO_2 for the atmosphere, accounting for 60% of global NO_2 emissions.

Research at, among others, UGent-ISOFYS indicates that the uptake and production function with respect to CH_4 and N_20 from aerobic soil is strongly dependent on the climate and soil management. Nevertheless, it can generally be stated that the uptake capacity for CH_4 decreases and the production of N_2O increases in the conversion from natural soil to agricultural soil (see figure below).



The effect of land use on the uptake capacity of methane (CH_4) in terrestrial ecosystems. The '+' sign indicates secondary fertilisation with 175 kg ammonium nitrate (NH_4NO_3) per ha and '200' indicates fertilisation with 200 kg nitrogen (N) per ha in the form of semi-liquid manure. (P. Boeckx, UGent-ISOFYS).

Emission factors (EF) for nitrogen dioxide (N_2O) and nitrogen monoxide (NO) were developed that can be applied to Belgian agricultural land. The results of these studies illustrate (i) the major uncertainty that exists with respect to the emission of N_2O and (ii) the fact that the N_2O EF is greater for intensive agricultural systems than that included in 1996 in the guidelines for inventorying greenhouse gas emissions of the 'Intergovernmental Panel on Climate Change' (IPCC).

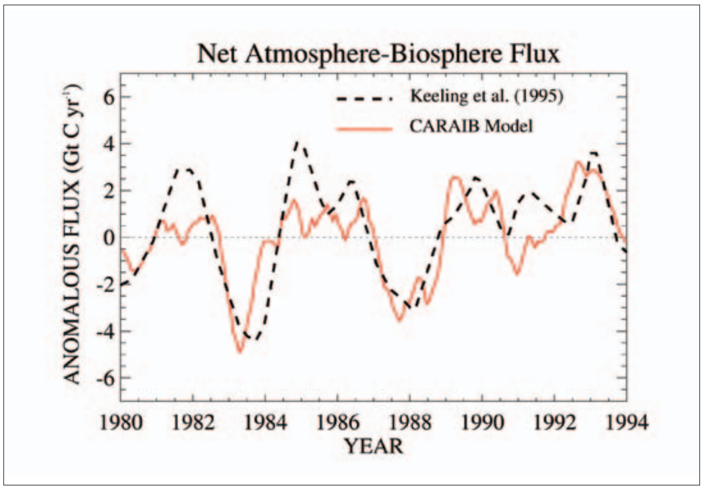
4.2.3 Annual changes

Carbon sequestration in natural environments exhibits annual fluctuations both globally and locally. These variations in the uptake of carbon are attributable to weather patterns. Some of these weather patterns, such as the effects of 'El Niño', also have a global scope (see Chapter 2). It is extremely important to understand these variations given the need to determine the contribution of an ecosystem to carbon sequestration over longer periods (at least 10 years). In addition, due to their small time interval, they represent a unique opportunity to verify the predictions of models with the actual response of ecosystems.

The variations in the net flow of carbon dioxide (CO_2) from the atmosphere to the biosphere can be calculated in two ways: by directly measuring the quantity of CO_2 in the atmosphere at various points or by making use of biospheric models. Such measurements were made by ULg-LPAP and used in a comparative analysis with the CARAIB model ('Carbon Assimilation In the Biosphere'). This comparison, presented in the next figure, which covers the period 1980 to 1993, shows that the uptake of CO_2 by terrestrial ecosystems is reduced during El Niño periods.

4.2.4 Emissions of carbon and uptake in forests

The most important anthropogenic source of atmospheric carbon is the burning of fossil fuels.



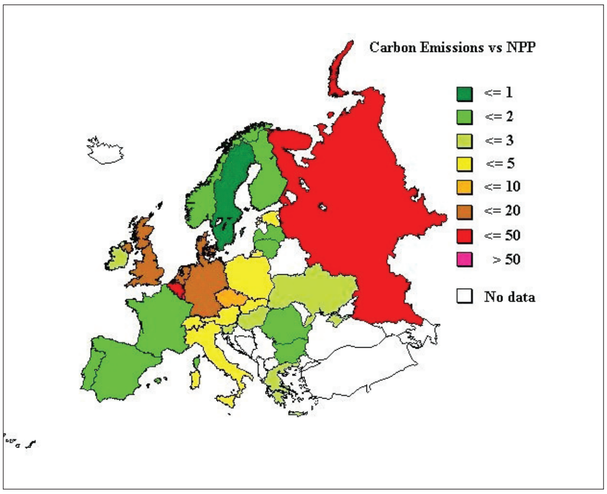
The net carbon dioxide (CO_2) exchange between the atmosphere and the biosphere between 1980 and 1993 calculated using the CARAIB ('Carbon Assimilation In the Biosphere') model (ULg-LPAP) and reconstructed by Keeling et al. (1995) from measurements of atmospheric CO_2 concentrations and the isotope composition. The values indicated are the differences compared to the average amount throughout the period 1980-1993. (L. François, ULg-LPAP).

The production of cement is also a significant source of CO_2 emissions. Despite increasing awareness of the problem of greenhouse gases, these emissions of CO_2 continue to increase. Thus, for the 'Special Report on Radiative Forcing' (IPCC, 1995b), average emissions of 5,500 million tons (Mt) carbon (C) per year for the 1980s and 6,300 Mt C per year for the 1990s were calculated.

Natural systems and forests can play a major role in compensating for above-average CO_2 emission levels. Forests are indeed an important means of channelling carbon away from the atmosphere: they can fix large quantities of carbon for several centuries in the form of standing biomass and litter, both on and in the soil.

The various forest types in Belgium also have this ability to fix carbon. Thus, they can be used to promote carbon fixation in order to combat the increase in greenhouse gases. The uptake of CO_2 in the sequestration cycle of a given forest type by correctly fine-tuning the management practices, the reforestation of logged areas and the preservation of existing forest types is being increased and accelerated. Computer models of the initial and predicted sequestration rates made it possible to evaluate beforehand the possible measures to be taken.

The 'C-Fix model', developed by VITO-TAP, allows the carbon fixing properties of a forest or ecosystem to be identified. According to this model, the carbon fixation capacity of present European vegetation is 111,000 Mt per year. This is only 7 to 12% of the total amount of anthropogenically-emitted carbon in Europe. At this moment, nowhere in Europe are carbon emissions in equilibrium with the fixation capacity of the forests. In the Benelux, the emissions uptake balance is completely out of equilibrium: the level of CO_2 emitted is 50 times higher than that absorbed (see figure below).



The ratio of the Net Primary Production (NPP, in carbon -C- units) to the total anthropogenic carbon emission per country for Europe in 1997. (VITO-TAP).

4.2.5 Land use and land management practices

The sequestration of carbon in the vegetation and the soil are possible ways to reduce the quantity of CO_2 in the atmosphere. It is then of crucial importance to understand the actions that can be taken to promote the process of sequestration. Suitable management practices and the responsible use of land indeed influence the rate of sequestration. They constitute a possible method, in addition to reducing emissions, to attain the norms with respect to CO_2 emissions imposed by the Kyoto Protocol (article 3.3). The transition from forest to agricultural land is generally accompanied by a decrease in the quantity of organic carbon in the soil. This is the result of a decrease in the litter input, the differences in decomposition rates of leaves and harvest residues, and the effects of tillage (increased aeration and decreased physical protection of the organic matter in the soil). Management practices to increase the levels of carbon in the soil include the use of bio-energy crops, limiting fertilisation to agricultural land, the regeneration of forests, etc.

Based upon two Belgian studies, it can be demonstrated that carbon sequestration in the soil can be influenced by changes in land use and land management, and that the potential carbon uptake of the soil increases. Between 1775 and 1973, the sequestration of carbon in the Ardennes underwent radical changes in the form of 'Soil Organic Carbon' (SOC). Using soil profiles (the geological database) and a time series of topographical maps, changes in land use were reconstructed. In a period of 200 years, the quantity of SOC has increased by 10.2 ton C per ha. Yet, this is rather small when compared to the increase in the total annual uptake of carbon by Belgian ecosystems (5 kton C per ha). Unfortunately, existing and planned management practices in Belgium are only applied to a very limited

area. These spatial limitations imply a very small potential uptake of 180 to 320 kton C per year, which represents only 0.5 to 0.8% of Belgian greenhouse gas emissions for the year 1990.

4.2.6 Soil acidification and nitrogen deposits

The enrichment of the environment with nutrients (especially nitrogen) as a result of human activity constitutes a serious problem in several Belgian regions. This 'fertilisation' disrupts ecological processes (such as biogeochemical cycles). In an unpolluted environment, the limited availability of the important nutrient nitrogen (N) regulates the competition between plant species. Thus, the release of nitrogen into a natural environment has a serious impact on the dominant hierarchy among the vegetation.

The supply of nutrients can come from the deposits of nitrogen and sulphur compounds in the atmosphere. Gaseous compounds like sulphur dioxide (SO_2) and nitrogen oxides (NO_x) can be transported over very long distances, while other gases (like ammonia, NH_3) tend to spread only locally. Moreover, when these compounds enter the soil, they initiate processes of acidification such as nitrification. The end and intermediate products of these processes can leach and enter the groundwater.

To limit these effects, so-called 'Critical Loads' were developed by the 'United Nations Economic Commission for Europe' (UNECE). These can be defined as follows: 'the maximum deposition of a given component that causes no protracted, harmful effects to the structure and function of the ecosystem'.

'Critical Loads' were also established for deciduous and coniferous forests in Belgium. The BELFOR ('Belgian Forest ecosystems') project determined the level of nitrogen deposition in five experimental forest ecosystems in Flanders and Wallonia. It indicated that the Flemish deciduous and coniferous forests exceeded the long-term 'Critical Loads'. In addition to monitoring the atmospheric deposition, this study also demonstrated that 'Critical Loads' must be specified as locally as possible and must be different for deciduous and coniferous forests. In addition, the high level of nitrogen deposits in northern Belgium lead to a decrease in the number of micro organisms in the soil, an increasing dominance in ecosystems of vegetation that thrives on nitrogen and probable pollution of the groundwater.

4.2.7 Belgian forests in the 21st century

Scientists expect that the concentration of atmospheric CO_2 will increase to between 550 and 1,000 ppmv (i.e., the number of CO_2 molecules in a compartment of 1 million molecules of air) by the end of the 21st century, a doubling of the present concentration of approximately 370 ppmv. It is assumed that as a result the temperature will increase globally by 1.4 to 5.8°C. In Belgium, the temperature will increase by between 2 and 4°C, a phenomenon that will increase, accompanied by a seasonal and local redistribution of precipitation. For our region, scientists expect a trend towards more precipitation in the winter and no change to less precipitation in the summer.

Ecosystems such as forests will be heavily influenced by these changes in carbon dioxide (CO_2) concentration, temperature and precipitation patterns. The size of this impact is difficult to predict and can only be estimated using growth models that take into account the management of the energy, water, carbon and nutrients of these ecosystems and the impact on them from outside.

Within the BELFOR project, researchers from ULg-LPAP have developed the

ASPECTS model (Atmosphere-Soil-Plant Exchange of Carbon in Temperate Sylvae). This was tested in several forested areas in Belgium. Researchers from UA-PLECO and FUSAGx-ECOPHYS collaborated in this project from their experimental measurement stations in Brasschaat and Vielsalm. According to their research and the predictions of ASPECTS, the net carbon uptake by Belgian forests in the 21st century will increase due to accelerated photosynthesis (as a result of the higher carbon dioxide concentration in the atmosphere) and a lengthening of the growing season. However, the increase depends upon the age of the forest, with maximum sequestration occurring in forests between 20 and 40 years old. Moreover, management practices and annual weather conditions will also play a role here.

4.3 Influence on structure, function and distribution of ecosystems

4.3.1 The productivity of Belgian grasslands

Increasing concentrations of atmospheric carbon dioxide (CO_2) and the associated global increase in temperature have a clear influence on the processes of photosynthesis and the respiration rate of the vegetation. A large part of Belgian vegetation consists of grasslands and these will also change as a result of these effects of global change. Due to their economic importance and dominant position, grasslands were chosen as model system by several research groups.

Experiments by UA-PLECO and UGent-PP demonstrate that protracted exposure to increased levels of CO_2 have an influence on the various species of grass. Various ecosystem processes change: the rate of photosynthesis increases, but the water consumption of the vegetation decreases. The latter is caused by the stomata in the leaf closing more due to the higher concentration of CO_2. The higher levels of carbon also cause thicker leaves and denser foliage. Temperature plays a role, principally in biogeochemical processes that influence nutrient uptake and growth. The effect of temperature is more difficult to determine because the optimum temperature differs according to plant species. Thus, an increase in temperature in the spring can have a beneficial effect, while the same increase in the summer can cause drought stress. Thus, the productivity of grasslands can change considerably due to higher temperatures, and these changes can be both positive and negative.

The influence of increasing temperatures on the productivity of grasslands also has an impact on Belgian agriculture. It is positively influenced in the spring (more and faster production), but this effect is overshadowed by the negative influence in the middle of summer. This is a problem, because in the summer season, the grasslands already fall short of being able to provide sufficient feed for livestock. This effect will become more pronounced in the future if CO_2 concentrations continue to increase. Even though grassland production increases due to this phenomenon, the biomass produced is of a lower quality because the protein content decreases.

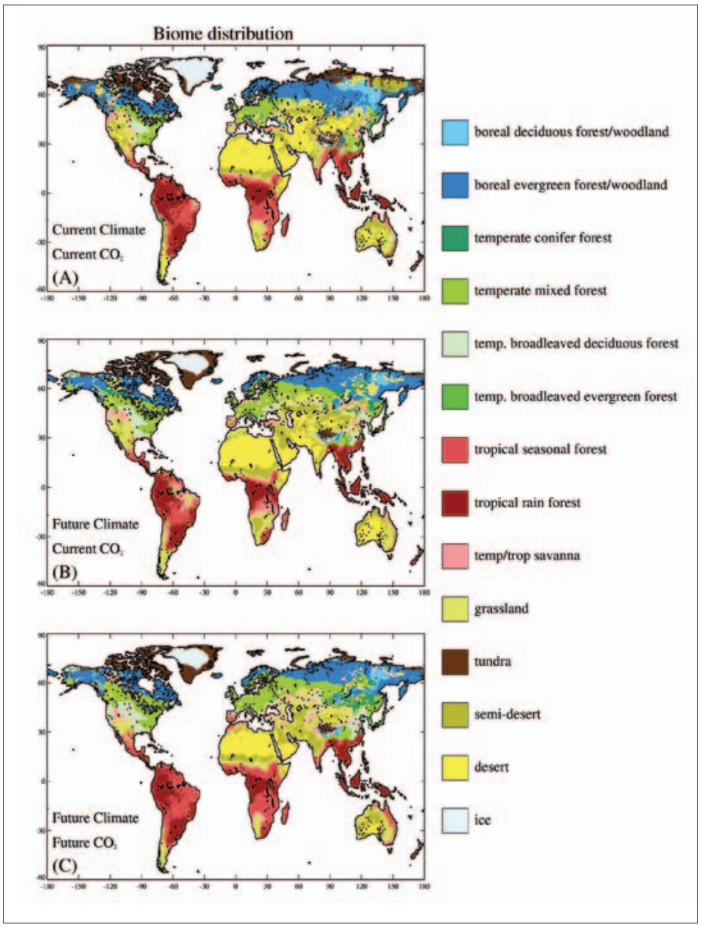
4.3.2 Management practices

Few measures are helpful as a response to increasing temperatures. Some researchers believe that restricting the nutrient supply would help. This would decrease the rate of photosynthesis and thus also the degree of opening of the stomata. This would decrease the rate of transpiration and thus also the level of dehydration, making the vegetation less sensitive to temperature. However, this measure will not limit the loss in production (resulting from increased temperatures) since a restriction of the supply of nutrients brings with it a drop in production in its own right. Only the radical measure of a transition to plant species that thrive in a warmer climate could provide a solution.

4.3.3 World vegetation patterns

Increasing temperatures and CO_2 concentrations will influence not only the functioning but also the global distribution of vegetation. Models predict that major shifts in the distribution of the various biomes on earth will occur.

A decrease in tundra and an increase in desertification are two of the predictions made by the CARAIB ('Carbon Assimilation In the Biosphere') model that was developed by ULg-LPAP (see figure below). This model makes a distinction between CO_2-induced and temperature-induced changes. However, these predictions vary according to whether one or both effects are incorporated into the calculations. Nevertheless, it is expected that species with a narrow tolerance range will disappear due to the quickly changing climatological conditions. If no substitute species are available, the carbon stock will decrease and the greenhouse effect will increase as a result of CO_2 emissions. In short, we are in a vicious circle.



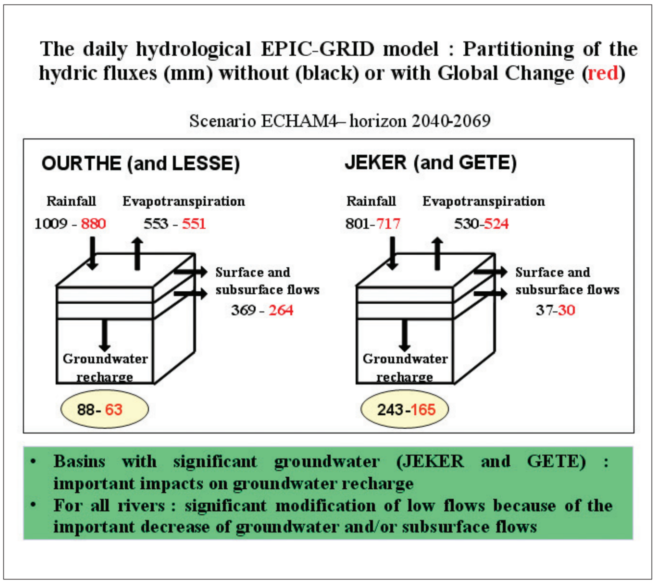
Geographic distribution of the various biomes, calculated using the CARAIB ('Carbon Assimilation In the Biosphere') vegetation model developed by ULg-LPAP. The model shows the separate impact on vegetation of future climate changes (temperature and precipitation) and changes in concentrations of atmospheric CO_2: (A) a standard simulation using the present climatological conditions and CO_2 concentrations, (B) a simulation using future climatological conditions and present CO_2 concentrations and (C) a simulation using future climatological conditions and future CO_2 concentrations. 'Present' refers to the period 1990-1999 and 'future' to 2090-2099. (L. François, ULg-LPAP).

4.4 Global change and impact on the water balance

4.4.1 Impact on Belgian hydrological basins

Fresh water is valuable, both qualitatively and quantitatively. This is clearly emphasised in European (Water Framework Directive 2000/60/EC) and international (AGENDA 21, Chapter 18 on water resources) legislation. Global change scenarios predict an increase in temperatures and changes in the patterns of precipitation. These change the hydrological cycle by affecting the amount of water that enters an ecosystem, which in turn changes, among others, the relationship between the soil and vegetation. What are the consequences for Belgium?

Researchers from FUSAGx-UHAGx made simulations of Belgian river basins using the 'EPIC-GRID' hydrological model. They distinguished two major components: the lateral flows (surface flows) and the supplements to the groundwater. Depending upon the permeability of the soil, one of the two components will dominate. In soil with low permeability, the surface flows will dominate (as is the case for the basins of the Lesse and the Ourthe). In soils with higher permeability, the role of groundwater flows will be more pronounced. Examples (see diagram below) of this are the basins of the Gette / Gete and the Geer / Jeker. The predictions indicate that for all river basins (regardless of whether the water flows are dominated by groundwater or surface flows), the flow rates will decrease significantly.



Distribution of water flows within Belgian river basins and the influence of climate change on this (EPIC-GRID simulations, ECHAM4 scenario, horizon 2040-2069). (C. Sohier and S. Dautrebande, FUSAGx-UHAGx).

4.4.2 Changes in the groundwater regime

Climate changes influence the hydrological cycle, which affects, among other things, soil moisture, supplements to the groundwater table, water quality and groundwater flows. Using the results of three General Circulation Models (GCMs), the Belgian Royal Meteorological Institute (IRM / KMI) developed three climate change scenarios for Belgium in which the temperature increases.

Two of the three scenarios indicated that global change would lead to a decrease in the annual quantity of precipitation in Belgium; the third predicted little change. All scenarios indicated a decrease in the quantity of precipitation during the summer months. FUSAGx-UHAGx applied these three scenarios to the hydrological EPIC-GRID model that allows calculating the impact of potential climate changes on the hydrological cycle. Two of the three scenarios indicate a considerable annual reduction in the lateral flows and the supplements to the groundwater table. Simulations on a monthly basis indicate an increase in these flows during the winter (depending upon the precipitation). The shortage with respect to the supplements to the groundwater table varies according to the scenario used from 1 to 34% and will have major implications for the water supply (principally negative effects on crops during the summer months).

4.4.3 Changes to agriculture

The increase in temperature, a reduction in the availability of water and an increase in concentrations of CO_2 in the atmosphere lead to changes in evapotranspiration (i.e., transpiration of water from plant and soil), which has consequences for vegetation and agricultural production.

Simulations with the EPIC-GRID model show that with increasing temperatures, the evapotranspiration in the spring will increase due to the earlier growth of the crops. However, it will decrease in the summer due to water stress and the earlier ripening of the crops. Increases in the level of CO_2 will generally increase agricultural production, depending on the crop and the availability of groundwater. A reduction in precipitation in the summer means that vulnerable crops must be irrigated. The water shortage, in combination with a decrease in soil moisture, influences the productivity of grasslands and thus brings about a reduction in the food supply for livestock. The accessibility of the land is also affected by higher soil moisture in the spring.

4.4.4 Changes in wetland areas

The almost permanent presence of water above ground level means that hydrology plays a central role in wetland areas. In the fully saturated soil, the biogeochemical processes are dominated by the presence of water. Nevertheless, this soil chemistry is more dynamic than was first thought. The water table drops in the dry summer months, exposing a part of the soil surface to air. The chemical processes that then occur cause an acidification of the soil. Global change reinforces this phenomenon.

Researchers from UA-ECOBE participated in an international research project in the Belgian provinces of Brabant (Torfbroek) and Luxembourg (Marais de Vance), as well as in Great Britain (Buxton Heath). This clarified the changes that take place in the wetland soil. The experiments showed that with a decrease in the quantity of ground water, the pH decreases and the concentrations of sulphate (SO_4^{2-}), magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions increase. Since the quantity of iron (Fe), aluminium (Al) and chlorine (Cl) remained almost constant, the increase in SO_4^{2-}, Mg^{2+} and Ca^{2+} ions was not due to a pure concentration effect resulting from evaporation of the water molecules. These higher concentrations are rather the result of the increased level of acidity, which among other things increases the solubility of cations. This process leads to an impoverishment of nutrients over time (see Box 13).

4.5 Driving forces behind changes to the ecosystem

4.5.1 Initial conditions, driving forces and feedback

The changes in terrestrial ecosystems are brought about by a complex combination of socioeconomic and biophysical factors. In the last decades, changes in land use have constituted the most significant threat to habitats and the species that occur there, as well as to the soil, water flows and the vulnerability of ecosystems and population groups. These factors affect not only the resilience of terrestrial ecosystems, but they also constitute a medium in which various anthropogenic reactions take place.

In this chain of ecosystem changes, three groups of factors can always be distinguished. To detect changes, the interactions between these groups must be known. First, there are the initial conditions (environmental characteristics and history), second, all the driving forces (immediate causes and underlying forces) and third, there are all the feedback mechanisms. An example summarising the approach to and

Box 13: Degree of acidity (pH) and Solubility

Nutrients in the soil are located for 98% in humus (decomposed organic material) and clay. They cannot be directly absorbed by plants and therefore are inaccessible. Nevertheless, processes of decomposition and disintegration cause a very small part (0.2%) of these nutrients to be dissolved in the groundwater, making them accessible.
These dissolved and available nutrients are predominantly absorbed by soil particles: small negatively charged particles (0.1 to 10 µm) such as clay and humus. In clay particles, the basic cation (i.e., positively charged ion) is silicium (Si^{4+}), often replaced by the inferior cations aluminium (Al^{3+}) or calcium (Ca^{2+}), causing these clay particles to carry one or more net negative charges.

Humus is composed of amino acids. With a neutral degree of acidity (pH), amino acids occur in the form of a 'zwitterion' (a negative and positive charge is present in the molecule causing the particle to be globally neutral). Because of their negative charge, both clay and humus particles can bind cations, thus preventing their leaching. With acidification of the soil naturally occurring or influenced by mankind), these negatively charged locations will be occupied by hydrogen (H^+) ions (which are then present in high concentrations). In doing so, they displace the other cations present, which are washed away with the groundwater. Because cationic nutrients gradually disappear, this leads to a process of impoverishment of the soil.

the analysis of the factors that influence the change in ecosystems is provided in the figure (see figure on the next page).

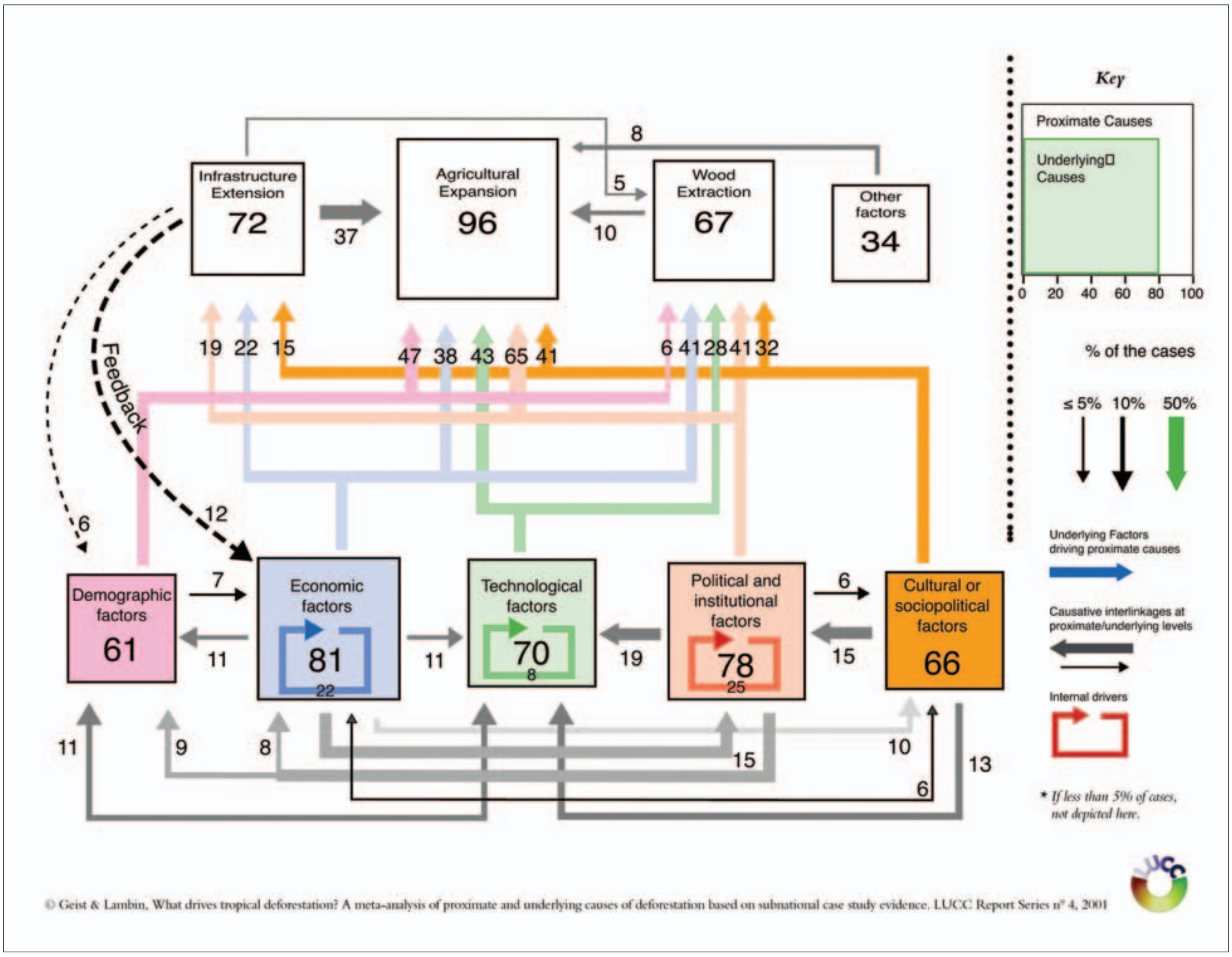
4.5.2 The key factor

Research reveals that usually there is no single key factor that determines the changes in land use as driving force within ecosystems. Rather, it is a combination of different factors that vary according to time and place and that depend heavily on anthropogenic conditions. Some contradictory synergistic reactions can lead to a neutralisation of their effect, which means that no change whatsoever is initiated. However, it can also happen that the interaction of various factors works as an autocatalytic process that, once begun, inexorably continues. Moreover, whether the change within an ecosystem is in the direction of degradation or restoration depends upon associated feedback mechanisms. Predicting a result is then only possible when as many factors as possible are known and taken into account.

In an analysis of 300 sites in both tropical and moderate ecosystems, researchers from UCL-GEOG looked for the proportion of systems in which the changes that occurred were explained by a single factor, a so-called 'key factor'. It was possible to indicate such a factor in only 10% of the cases. The proportion of purely 'causal forces' was just as small (5 to 8%). In most of the cases (70 to 90%), combinations of interactions dominated.

4.5.3 Socioeconomic forces

In addition to the biophysical forces that drive changes to ecosystems, there are also socioeconomic forces. While often a distinction is made between the biophysical and the socioeconomic forces, this is a rather artificial division because ecosystem changes always occur within a connected anthropogenic-natural system.



Example of a systematic and generalising analysis of the patterns that lead to deforestation of tropical rain forests. It is seldom the case that a single key variable (like population growth or changes in cultivation methods) unambiguously explains the phenomenon. A combination of direct causes and underlying (social) forces usually best explain the loss of tropical forests. A continually recurring combination of economic, political and institutional forces supports the pattern of direct factors (like agricultural development, infrastructural expansions and logging) that lead to deforestation. While some researchers claim that the interactions within these patterns are irreducibly complex, it nevertheless must be possible to discover and explain undeniable regional patterns. (H. Geist and E. Lambin, UCL-GEOG).

4.6 Conclusions and prospects

The impact of global change is diverse and complex. Today, a number of simultaneous global changes influence a series of related processes across a divergent series of ecosystems. Some cause global change, but at the same time are also a part of the consequences of this change. Thus, the loss of biodiversity is a result of these global changes, but in turn influences the functioning of the ecosystem and the use of land.

Not only are effects sometimes also causes and vice versa, but often the effects are related via feedback to their causal factors. Soil respiration is an example of this. Because the organic material in the soil contains twice as much carbon as the atmosphere and 10% of the carbon in the soil is released annually, small changes in the carbon stock in the soil can have major consequences for the CO_2 concentration in the atmosphere. Temperature influences soil respiration in a positive way: the higher the temperature, the higher the level of respiration. This respiration binds carbon (C) from the soil with oxygen (O_2), causing it to be released in the atmosphere as carbon dioxide (CO_2). This enhances the greenhouse effect, causing a further increase in temperatures, possibly ending in a vicious circle.

Climate changes mean that we will more frequently be faced with extreme weather conditions. Because they pave the way for the loss of plant species (which are already highly sensitive to the extremes of the present climate), these weather conditions could induce the destruction of the ecosystems. Thus, future research must make a priority of making ecosystems robust. New instruments have been developed that are capable of better managing ecosystems based upon the population dynamic, thus limiting the loss of species.

Calculations using models, and atmospheric observations of CO_2 emissions and uptake, teach us that approximately 1/3 of annual atmospheric CO_2 emissions (from the burning of fossil fuels and from deforestation) are reabsorbed by the terrestrial biosphere. This phenomenon takes place principally in the forests of the mid-latitudes of the northern hemisphere. In other words, the management and use of these ecosystems has a major impact on the concentrations of greenhouse gases in the atmosphere. This also makes it possible to compensate for global change and its effects.

Invasive species constitute an additional threat to ecosystem biodiversity. Many of the natural barriers to spreading have been destroyed as a result of human activities, and less mobile species are also able to penetrate a new and favourable habitat. The economic damage resulting from invasive species is enormous (crop loss, costs of control and eradication), but their impact on the (little) remaining nature in our cultural landscape is also significant.

Whether it concerns the loss of biodiversity or increased concentrations of greenhouse gases, the cause is a combination of both anthropogenic and natural factors. These usually depend on each other and there are numerous feedback mechanisms.

Annex 1 - Belgian research institutions

Institution		Contact	Website
Federal Scientific Institutions			
BIRA / IASB	**Belgisch Instituut voor Ruimte-Aëronomie / Institut d'Aéronomie Spatiale de Belgique (Belgian Institute for Space Aeronomy)**	De Mazière M., Muller J.-F.	**http://www.bira.be**
IRM / KMI	**Institut Royal Météorologique / Koninklijk Meteorologisch Instituut (Royal Meteorological Institute)**	De Backer H., Tricot C.	**http://www.meteo.be/IRM-KMI**
IRSNB / KBIN	**Institut Royal des Sciences Naturelles de Belgique / Koninklijk Belgisch Instituut voor Natuurwetenschappen (Royal Belgian Institute of Natural Sciences)**		**http://www.naturalsciences.be**
Invertebrates	Invertebrates	Grootaert P., Willenz Ph.	http://www.naturalsciences.be/science/organigram/invertebres
MUMM	Management Unit of the North Sea Mathematical Models	Pichot G.	http://www.mumm.ac.be/EN/index.php
KMMA / MRAC	**Koninklijk Museum voor Midden-Afrika / Musée Royal d'Afrique Centrale (Royal Museum for Central Africa)**		**http://www.africamuseum.be**
GEO	Geology and Mineralogy	André L.	http://www.africamuseum.be/research/geology
Universities			
FPMS	**Faculté Polytechnique de Mons**		**http://www.fpms.ac.be**
FLUIDMACH	Groupe Mécanique	Passelecq Ch., Hanton J.	http://www.fpms.ac.be/fr/teaching_units/tu_meca_fluides.html
FUNDP	**Facultés Universitaires Notre-Dame de la Paix**		**http://www.fundp.ac.be**
URBO	Unité de Recherches en Biologie des Organismes	Descy J.-P.	http://www.fundp.ac.be/urbo/index.html
FUSAGx	**Faculté Universitaire des Sciences Agronomiques de Gembloux**		**http://www.fsagx.ac.be**
ECOPHYS	Unité de Biologie végétale - Ecophysiology des arbres forestiers	Laitat E.	http://www.fsagx.ac.be/ecophys/index.htm
UHAGx	Unité de Hydrologie et Hydraulique agricole	Dautrebande S., Sohier C.	http://www.cref.be/Recherche/UnitDesc.asp?IdUnit=FUSAGx021300
KULeuven	**Katholieke Universiteit Leuven**		**http://www.kuleuven.ac.be**
H&EG	Hydrogeology & Engineering Geology	Dassargues A.	http://www.kuleuven.ac.be/geology/hsg/H&EG/H&EG-intro.html
PAC	Division for Physical and Analytical Chemistry	Peeters J., Vinckier C.	http://arrhenius.chem.kuleuven.ac.be/fysanal/fysanal_en.html
LFNL	Laboratory fo Forest, Nature and Landscape Research	Van Orshoven J.	http://www.agr.kuleuven.ac.be/lbh/lbnl/index-eng.htm
LSWM	Laboratory for Soil en Water Management	Feyen J.	http://www.agr.kuleuven.ac.be/lbh/lbwb
UA	**Universiteit Antwerpen**		**http://www.uia.ac.be**
DECO	Laboratory of Animal Ecology	Mathyssen E.	http://www.uia.ac.be/bio/deco
ECOBE	Ecosystem Management Research Group	Meire P., Verheyen R.	http://www.ua.ac.be/main.asp?c=*ECOBE
EFB	Ecofysiologie en Biochemie	Blust R.	http://143.129.203.3/nl/onderzoek/dept/bio/efb.htm
MiTAC	Micro and Trace Analysis Centre	Van Grieken R.	http://www.uia.ac.be/chem/en/index.html
Phar	Laboratory of Biomolecular Mass Spectrometry	Claeys M.	http://www.ua.ac.be/main.asp?c=*MASSS
PLECO	Research Group of Plant and Vegetation Ecology	Ceulemans R., Nijs I.	http://www.uia.ac.be/bio/pleco
UCL	**Université catholique de Louvain**		**http://www.ucl.ac.be**
ASTR	Institut d'Astronomie et de Géophysique G. Lemaître	Berger A., Deleersnijder E., Fichefet Th., Schayes G., van Ypersele J.-P.	http://www.astr.ucl.ac.be
ECOL	Unité d'Ecologie et de Biogéographie	Le Boulangé E., Baguette M.	http://www.ecol.ucl.ac.be
EFOR	Unité des Eaux et des Forêts	André P.	http://www.efor.ucl.ac.be
GEOG	Unité de Géographie	Geist H., Lambin E., Van Wesemael B.	http://www.geo.ucl.ac.be/UNITES/GEOG/index.html
GEOL	Unité de Géologie	Seret G.	http://www.geo.ucl.ac.be/UNITES/GEOL/index.html
UGent	**Universiteit Gent**		**http://www.ugent.be**
INW	Institute for Nuclear Sciences	Maenhaut W.	http://aivwww.ugent.be/Onderzoeksbeleid/techno2002/EN/WE/I-WE08V04.htm
ISOFYS	Department of Applied Analytical and Physical Chemistry,Laboratory of Applied Physical Chemistry	Boeckx P,, Van Cleemput O.	http://fltbwww.UGent.be/isofys
MARBIOL	Marine Biology Section	Vincx M.	http://www.marinebiology.ugent.be
OC	Department of Organic Chemistry	Van Langenhove H.	http://fltbwww.ugent.be/departments/index.php?department=LA11
PAE	Protistologie en Aquatische Ecologie	Vyverman W., Cocquyt Ch.	http://aivwww.rug.ac.be/Onderzoeksbeleid/techno2002/NL/WE/I-WE11V10.htm0
PLANTECO	Laboratory of Plant Ecology	Lemeur R., Vandewalle I.	http://allserv.rug.ac.be/planteco
PP	Department of Plant Production	Reheul D., Behaeghe T.	http://fltbwww.UGent.be/vakgroepen/index.php?vakgroep=LA02
RCMG	Renard Centre of Marine Geology	De Batist M.	http://allserv.rug.ac.be/~jphenrie
SOILMAN	Department of Soil Management and Soil Care	Hofman G.	http://www.soilman.ugent.be
ULB	**Université Libre de Bruxelles**		**http://www.ulb.ac.be**
BIOMAR	Centre Interuniversitaire de Biologie Marine	Dubois Ph.	http://www.ulb.ac.be/sciences/biomar/index.html
ESA	Ecologie des Systèmes Aquatiques	Lancelot C.	http://www.ulb.ac.be/rech/inventaire/unites/ULB115.html
GLACIOL	Glaciologie Polaire	Lorrain R., Souchez R.	http://www.ulb.ac.be/rech/inventaire/unites/ULB182.html
GMMA	Groupe de Microbiologie des Milieux Aquatiques	Billen G.	http://www.ulb.ac.be/rech/inventaire/unites/ULB115.html
OCEAN	Laboratoire d'Océanographie Chimique et Géochimie des Eaux	Chou L., Wollast R,	http://www.ulb.ac.be/sciences/dste/ocean
SPECAT	Unité de Spectroscopie de l'Atmosphère	Colin R., Carleer M.	http://www.ulb.ac.be/rech/inventaire/unites/ULB587.html

Institution		Contact	Website
Universities			
ULg	**Université de Liège**		**http://www.ulg.ac.be**
BOT	Institut de Botanique	Demoulin V.	http://www.ulg.ac.be/facsc
CEME	Centre d'Etude et de Modélisation de l'Environnement	Smitz, J.	
CIP	Centre d'Ingénierie des Protéines	Wilmotte A.	http://www.ulg.ac.be/cingprot
ECOHYD	Unité d'Ecohydrodynamique	Hecq J.-H.	http://modb.oce.ulg.ac.be/ECOHYD./welcome.htm
GIRPAS	Groupe Infrarouge de Physique Atmosphérique et Solaire	Mahieu E., Zander R.	http://sunset.astro.ulg.ac.be/girpas/girpasf.html#CONT
LGIH	Laboratory of Engineering Geology, Hydrogeology and Geophysical Prospecting	Monjoie A	http://www.lgih.ulg.ac.be
LPAP	Laboratoire de Physique Atmosphérique et Planétaire	François L., Gérard J.-C, Munhoven G.	http://www.astro.ulg.ac.be/GRech/lpap_f.html
OCEANBIO	Laboratoire d'Océanologie	Bouquegnau J.-M.	www.ulg.ac.be/oceanbio
OCEANCHEM	Chemical Oceanography Unit	Frankignoulle M.	http://www.ulg.ac.be/oceanbio/co2
URAP	Unité de Recherche Argiles et Paléoclimats	Fagel N.	http://www.ulg.ac.be/urap
UMH	**Université de Mons-Hainaut**		**http://www.umh.ac.be**
FS	Service d'Informatique Générale	Dufour P.	http://sinfo.umh.ac.be/equipes.htm
VUB	**Vrije Universiteit Brussel**		**http://www.vub.ac.be**
ANCH	Laboratorium voor Analytische Scheikunde	Bayens W., Dehairs F.	http://we.vub.ac.be/dsch
DG	Department of Geography	Decleir H., Huybrechts Ph., Pattyn F.	http://www.vub.ac.be/DGGF
ECOL	Laboratorium voor Ecologie en Systematiek	Daro M.H.	http://we.vub.ac.be/~ecol
Regional Institutes			
CELINE / IRCEL	**Cellule Interrégionale de l'Environnement / Intergewestelijke Cel voor het Leefmilieu (Interregional Cell for the Environment)**		**http://www.irceline.be**
CLO	**Centrum voor Landbouwkundig Onderzoek (Agricultural Research Centre)**		**http://www.clo.fgov.be**
DFE	Departement voor Fytotechnie en Ecofysiologie (Department of Crop Husbandry and Ecophysiology)	Carlier L.	http://www.clo.fgov.be/dfe
IBW	**Instituut voor Bosbouw en Wildbeheer (Belgian Institute for Forestry and Game Management)**	Van Slycken J.	**http://www.ibw.vlaanderen.be**
VITO	**Vlaamse Instelling voor Technologisch Onderzoek (Flemish Institute for Technological Research)**		**http://www.vito.be/english**
TAP	Remote Sensing and Atmospheric Processes	Mensink C., Veroustraete F.	http://www.vito.be/milieu/teledetectie.htm

Note: The institutions listed here are those which are mentioned in this report

Annex 2 - Acronyms and abbreviations

Name	Description	Website
6EAP	Sixth Environment Action Programme (EU)	http://europa.eu.int/comm/environment/newprg/
AD	Anno Dominus	
AGENDA 21	Comprehensive plan of action to be taken globally, nationally and locally by organizations of the United Nations System, Governments, and Major Groups in every area in which human impacts on the environment	http://www.un.org/ga/special/sids/agenda21/
ASPECTS	Atmosphere-Soil-Plant Exchange of Carbon in Temperate Sylvae	
ATMOS	Atmospheric Trace Molecule Spectroscopy	http://atmos.jpl.nasa.gov/atmos
BASCOE	Belgian Assimilation System of Chemical Observations from ENVISAT	http://www.bascoe.oma.be/index.html
BELEUROS	European Operational Smog Model adapted to Belgium	http://www.beleuros.be/
BELFOR	Belgian Forest ecosystems	http://www.vito.be/belfor/
BELSPO	Belgian Federal Science Policy Office	http://www.belspo.be
BIOGEST	Biogas Transfer in Estuaries	http://www.ulg.ac.be/oceanbio/biogest/
CAFE	Clean Air For Europe	http://europa.eu.int/comm/environment/air/cafe/
CALMARS	Calcareous Marine Skeletons	http://www.vub.ac.be/calmar/
CARAIB	Carbon Assimilation In the Biosphere	http://gaim.unh.edu/Structure/Intercomparison/EMDI/models/caraib.html
CASTEC	Carbon Sequestration in Terrestrial Ecosystems	http://allserv.rug.ac.be/~ovcleemp/
CBD	Convention on Biological Diversity	http://www.biodiv.org/
CFC	Chlorofluorocarbon	
C-Fix	A Satellite Based Carbon Budgeting Tool	
CLIMOD	Climate Modelling	http://www.climate.be/popwork/introclim.html
CLRTAP	Convention on Long-Range Transboundary Air Pollution	http://www.unece.org/env/lrtap
COPs	Conference of the Parties	http://unfccc.int/cop3/
DIVERSITAS	an international research programme of biodiversity science	http://www.diversitas-international.org/
DMS	Dimethyl Sulphide	
EASOE	European Arctic Stratospheric Ozone Experiment	http://badc.nerc.ac.uk/data/easoe/
EC	European Commission	http://europa.eu.int/comm/index_en.htm
ECHAM4	Current version of the climate model developed from the ECMWF atmospheric model and a comprehensive parameterisation package developed at Hamburg	http://ipcc-ddc.cru.uea.ac.uk/cru_data/examine/echam4_info.html
ECMWF	European Centre for Medium range Weather Forecasts	http://www.ecmwf.int
EF	Emission Factor	
EFISCEN	European Forest Information Scenario model	http://agrifor.ac.uk/hb/4c3701607bfdc93fcc662fc89bf3bdb2.html
ENSO	El Niño Southern Oscillation	
ENVISAT	Environmental Satellite	http://envisat.esa.int/
EPIC-GRID	a catchment hydrological model	http://styx.esrin.esa.it/cliff/Partners/UnivGemb.html
ESA	European Space Agency	http://www.esa.int
ESF	European Science Foundation	http://www.esf.org
ESSP	Earth System Science Partnership	http://www.ess-p.org/
EU	European Union	http://europa.eu.int/
EURECA	European Retrievable Carrier	http://www.esa.int
EUREKA	pan-European network for market-oriented, industrial R&D	http://www.eureka.be
EUROCORES	ESF Collaborative Research Programmes	http://www.esf.org/esf_activity_home.php?language=0&domain=0&activity=7
EUROS	European Operational Smog model	
EUROTRAC	The EUREKA project on the transport and chemical transformation of trace constituents in the troposphere over Europe	http://www.gsf.de/eurotrac/
FP6	Sixth Framework Programme (EU)	http://fp6.cordis.lu/fp6/home.cfm
GCM	General Circulation Model	
GOME	Global Ozone Monitoring Experiment	http://earth.esa.int/services/esa_doc/doc_gom.html
GRIP	Greenland Ice Core Project	http://nsidc.org/data/gisp_grip/index.html
GWP	Global Warming Potential	
HadCM	Hadley Centre Coupled Model	http://www.met-office.gov.uk/research/hadleycentre/models/modeltypes.html
HCFC	Hydrochlorofluorocarbon	
HFC	Hydrofluorocarbon	
IGBP	International Geosphere-Biosphere Programme	http://www.igbp.kva.se
IGFA	International Group of Funding Agencies for Global Change Research	http://www.geo.ucl.ac.be/LUCC/outreach/funding/world/IGFA.HTML
IHDP	International Human Dimensions Programme on Global Environmental Change	http://www.ihdp.uni-bonn.de/
IMAGES	Intermediate Model for the Annual and Global Evolution of Species	http://www.ucar.edu/communications/acronyms/I.html

Name	Description	Website
IPCC	Intergovernmental Panel on Climate Change	http://www.ipcc.ch
IPCC-SAR	IPCC Second Assessment Report	http://www.ipcc.ch/
IPCC-SRES	IPCC Special Report on Emission Scenarios	http://www.ipcc.ch/
IPCC-SYR	IPCC Climate Change 2001: Synthesis Report	http://www.ipcc.ch/
IPCC-TAR	IPCC Third Assessment Report - Climate Change 2001	http://www.ipcc.ch/
ISSJ	International Scientific Station of the Jungfraujoch	http://www.ifjungo.ch/
JRC	Joint Research Centre (EC)	http://www.jrc.it/
LAQUAN	Late Quarternary climate history of coastal Antarctic environments: a multi-proxy approach	http://www.laquan.ugent.be
LOCH	an off-line three-dimensional (3-D) reaction-transport model of the marine carbon cycle	
LS fit	least squares fit	
masl	metres above sea level	
METAGE	Modelling Ecosystem Trace Gas Emissions	http://www.geo.ucl.ac.be/metage/
MILMO	Modelling the evolution of climate and sea level over the Third Millennium	http://www.climate.be/research/MILMO/
MIRO&CO	3-Dimensional coupled physical-biological model	http://www.igbp.kva.se/obe/OBE_PS10.pdf
NAO	North Atlantic Oscillation	
NDSC	Network for the Detection of Stratospheric Change	http://www.ndsc.ncep.noaa.gov/
NEC	National Emissions Ceilings	http://europa.eu.int/comm/environment/air/ceilings.htm
NEP	Net Ecosystem Production	
NGO	Non-Governmental Organisation	
NPP	Net Primary Production	
NVOC	Non-methane Volatile Organic Compounds	
OMEX	Ocean Margin Exchange	http://www.pol.ac.uk/bodc/omex/omex.html
ORA	Occultation Radiometer	
PDSI	Palmer Drought Severity Index	
PM	Particulate Matter	
ppbv	parts per billion (volume)	
ppm	parts per million	
ppmv	parts per million (volume)	
PSC	Polar Stratospheric Clouds	
RIVM	National Institute for Public Health and the Environment (Rijksinstituut voor Volksgezondheid en Milieu - the Netherlands)	http://www.rivm.nl/
R&D	Research and Development	
SESAME	Second European Stratospheric Arctic and Mid-latitude Experiment	
SISCO	Silica Retention in the Scheldt continuum and its Impact on Coastal Eutrophication	http://www.ulb.ac.be/sciences/dste/ocean/SISCO/frame.html
SOA	Secondary Organic Aerosols	
SOC	Soil Organic Carbon	
SPSD	Scientific Support Plan for a Sustainable Development Policy (Belgium)	http://www.belspo.be/belspo/home/port_en.stm
THESEO	Third European Stratospheric Experiment on Ozone	
UN	United Nations	http://www.un.org/
UNECE	United Nations Economic Commission for Europe	http://www.unece.org/env/lrtap/
UNEP	United Nations Environment Programme	
UNFCCC	United Nations Framework Convention on Climate Change	http://www.unfccc.de/
UV	Ultraviolet	
UV-A	Ultraviolet with wavelengths 315-400 nm	
UV-B	Ultraviolet with wavelengths 280-315 nm	
UV-C	Ultraviolet with wavelengths less than 280 nm	
UVI	Ultra-Violet Index	
VINTERSOL	Validation of International Satellites and Study of Ozone Loss	
VOC	Volatile Organic Compound	
WAIS	West Antarctic Ice Sheet	http://igloo.gsfc.nasa.gov/wais/
WCRP	World Climate Research Programme	http://www.wmo.ch/web/wcrp/wcrp-home.html
WMO	World Meteorological Organization	http://www.wmo.ch/

Annex 3 - Abbreviations for chemical compounds and chemical formulae

Abbreviations

Name	Description	Name	Description
CFC	Chlorofluorocarbon	HFC	Hydrofluorocarbon
CFC-11	CCl_3F, chlorofluorocarbon 11	NVOC	Non-methane Volatile Organic Compounds
CFC-12	CCl_2F_2, chlorofluorocarbon 12	SOA	Secondary Organic Aerosols
DMS	Dimethyl Sulphide	SOC	Soil Organic Carbon
HCFC	Hydrochlorofluorocarbon	VOC	Volatile Organic Compound

Formulae

Symbol	Name	Symbol	Name
Al, Al^{3+}	aluminium, aluminium ion	HF	hydrogen fluoride (hydrofluoric acid)
As	arsenic	HNO_3	nitric acid
Br	bromine	HOBr	hypobromous acid
BrO	bromine monoxide	HOCl	hypochlorous acid
$BrONO_2$	bromine nitrate	HO_x	radical peroxyl (HO) or hydroperoxyl (HO_2)
C	carbon	Hg, Hg^{2+}	mercury, mercuric ion
Corg	organic carbon	Mg, Mg^{2+}	magnesium, magnesium ion
^{12}C	carbon radioisotope 12	Mn, Mn^{2+}	manganese, manganese ion
^{13}C	carbon radioisotope 13	N	nitrogen
^{14}C	carbon radioisotope 14	Norg	organic nitrogen
$\delta^{13}C$	abundance of the carbon isotope 13	N_2	molecular nitrogen
CCl_2F_2	dichlorodifluoromethane (CFC-12)	N_2O	nitrous oxide
CCl_3F	trichlororfluormethane (CFC-11)	N_2O_4	dinitrogen tetroxide
$CHClF_2$	chlorodifluoromethane (HCFC-22)	NH_3	ammonia
CH_3CCl_3	methyl chloroform	NH_4^+	ammonium ion
CCl_4	carbon tetrachloride	NH_4NO_3	ammonium nitrate
CH_4	methane	NO	nitric oxide
C_2H_2	acetylene	NO_2	nitrogen dioxide
C_2H_6	ethane	NO_x	total nitrogen oxides
CH_2O (HCHO)	formaldehyde	NO_3^-	nitrate ion
CO	carbon monoxide	Ni	nickel
CO_2	carbon dioxide	O	atomic oxygen
CO_3^{2-}	carbonate ion	$\delta^{18}O$	abundance of the oxygen isotope 18
COF_2	carbonyl fluoride	O_2	molecular oxygen
COS	carbonyl sulphide	O_3	ozone
Ca, Ca^{2+}	calcium, calcium ion	OClO	chlorine dioxide
$CaCO_3$	calcium carbonate	OH^-	hydroxyl radical
Cd	cadmium	P	phosphorus
Cl, Cl^-	chlorine atom, chlorine ion	Porg	organic phosphorus
ClO	chlorine monoxide radical	PO_4^{3-}	phosphate ion
ClO_x	chlorine oxide	Pb	lead
$ClONO_2$	chlorine nitrate	^{210}Pb	lead radioisotope 210
Cl_2	chlorine	ROOH	alkyl hydroperoxides
Cl_y	total inorganic chlorine	RO_2	peroxyl radical
Fe	iron	S	sulphur
H, H^+	hydrogen, hydrogen ion	SF_6	sulphur hexafluoride
H_2O	water	SO_2	sulphur dioxide
H_2O_2	hydrogen peroxide	SO_4^{2-}	sulphate ion
H_2S	hydrogen sulphide	Si, Si^{4+}	silicium, silicium ion
H_2SO_4	sulphuric acid	SiO_2	silica or silicium dioxide (opal)
HCl	hydrogen chloride (hydrochloric acid)	Th	thorium
HCN	hydrogen cyanide	^{234}Th	thorium radioisotope 234
HCO_3^-	bicarbonate ion	Zn	zinc
HDO	deuterated water vapour		

SI (Système Internationale) Units		
Physical quantity	**Name**	**Symbol**
amount of substance	mole	mol
length	meter	m
mass	kilogram	kg
time	second	s

Prefixes, fractions and multiplication factors of the international system SI		
Fraction	**Prefix**	**Symbol**
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	t
Multiple	**Prefix**	**Symbol**
10	deca	da
10^{2}	hecto	h
10^{3}	kilo	k
10^{6}	mega	M
10^{9}	giga	G
10^{12}	tera	T
10^{15}	peta	P

SI-derived and other units			
Physical quantity	**Name**	**Symbol**	**Definition**
area	square metre	m^2	
area	hectare	ha	10,000 m^2
column density	Dobson Unit	DU	$2.687*10^{16}$ ozone molecules per cm^2
content	cubic metre	m^3	
content	liter	l	
content	parts per billion (10^9) by volume	ppbv	
content	parts per million (10^6) by volume	ppmv	
degree of acidity	potential of Hydrogen	pH	
length	micron	µm	
mass	gram	g	
mass	ton, tonne	t	
power/radiant flux	watt	W	$m^2.kg.s^{-3}$ (energy per unit time)
pressure	bar	b or bar	
quantity	parts per million (10^6)	ppm	
temperature	degree Celcius	°C	
time	year	yr	

Special symbols		
Physical quantity	**Name**	**Symbol**
length	diameter	Ø

Intergovernmental Panel on Climate Change (IPCC):

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