What we know What we do not know and How we try to better understand global change

Introduction to research questions, challenges and methods for CarboSchools projects

CarboSchools

EUROPEAN COMMISSION
DIRECTORATE-GENERAL
Joint Research Centre

What **we know**
What **we do not know**
And **how we try** to better understand **global change**

An introduction to research questions, challenges and methods for Carboschools projects

CarboSchools

This publication is supported by the Sixth EU Framework Programme for Research and Technological Development

CarboEurope IP (contract GOCE-CT-2003-505572) and CarboOcean IP (contract 511176-2)
Directorate General Joint Research Center

CarboSchools: Teacher-Scientist Partnerships on Global Change

CarboEurope and CarboOcean are major research projects that study the impacts of human activity on the state and future of our common habitat. As such, they not only have a contractual but also a moral obligation to contribute the results of this research to the public discussion on global change.

As the citizens and decision-makers of tomorrow, young people are particularly affected by and concerned about the changes in the environment. They should be equipped with a basic understanding of the processes at work and the state of current research in order to make informed choices about future action.

In order to achieve this, CarboEurope and CarboOcean have joined forces with the Joint Research Center of the European Commission to promote the CarboSchools initiative and to foster partnerships between scientists, secondary school teachers and their students. Through common projects, these partnerships are intended to encourage

- scientific learning based on hands-on experience and up-to-date research,
- innovative interdisciplinary approaches,
- discussion of global change issues based on first-hand knowledge,
- the search for solutions both from an individual perspective and also within the European context.

As a step towards the establishment of lasting partnerships between schools and research, CarboEurope and CarboOcean will

- contribute to initiating pilot projects,
- explicitly acknowledge the involvement of fellow scientists in school projects as a valuable part of their professional work,
- encourage PhD students to participate in joint projects with schools as an integral part of their training as future scientists,
- contribute to the development and provision of resources for school projects through the www.carboschools.org website.

Ernst-Detlef Schulze
CarboEurope Coordinator

Annette Freibauer
CarboEurope scientific officer

Christoph Heinze
CarboOcean Coordinator

Andrea Volbers
CarboOcean scientific officer

Manfred Grasserbauer, Director, JRC Institute for Environment and Sustainability

What will you find in this booklet?

Many high-quality materials present *what we know* about climate change. This one invites you to discover *what we do not know* and *how researchers are working towards a better understanding of climate change*, in general and within the framework of two large-scale European programmes.

Anyone interested in climate research will, therefore, find useful information here, but above all this booklet is provided as a tool for secondary school teachers planning *interdisciplinary projects* on this topic. Consequently, the stakes are no longer only to inform or transfer knowledge, but *to encourage questioning* among young people, to increase *their desire for understanding* and *the will to build a future* that will enable us to manage the challenge of global change.

For this reason, we focus here *on the way new knowledge is built through scientific* research rather than on the knowledge itself. Project-based teaching has the strength of bringing together knowledge from different disciplines, and for the pupils, adding meaning to them and enhancing their understanding of the problem being addressed.

Global change deeply challenges our way of thinking and making decisions. We must learn how to think and act with the complexity, globality, and interdependence of systems in mind. Therefore, this booklet also aims to illustrate:

- the *interdisciplinary character of research* (as opposed to the traditional division of science into specialities);
- the *need to strive for an overall picture* (as opposed to the tendency to be satisfied with a piecemeal approach);
- the *various degrees of uncertainty* (as opposed to the view of science as synonymous with truth);
- the *often disorderly way in which knowledge is gained*, that is not necessarily linear, but creative and spontaneous
- the *close link* between global issues, collective decisions and everyday individual choices.

Best of success in your projects!

Philippe Saugier
CarboSchools Coordinator

Soil ecologist Arwyn Jones explains Climate Change Activities at JRC-IES during JRC schoolsday in May 2004 that attracted some 1400 young people from secondary schools in the surroundings of Ispra

Contents

Resources on the Internet

Where to find what is not in this booklet

For information on the greenhouse effect and climate change in general:

A wide variety of documents provide an introduction to the problem (in many languages), the majority of which are available on the Internet. Some are objective; others are more or less subjective. For a neutral and comprehensive approach, the United Nations Convention on Climate Change offers a number of very good introductory publications: *www.unfccc.int*: click on 'essential background' then on 'background publications', or use the direct link:
http://unfccc.int/essential_background/background_publications_htmlpdf/items/2625.php
(see in particular 'climate change information kit', available in French, English, German, Spanish and Russian)

We also recommend the multilingual EU environment website for young people, where you will find an introduction to climate issues (and many other issues) *http://europa.eu.int/comm/environment/youth/index_en.html,* and the Manicore site, which has the great interest, from an educational point of view, to be structured around questions and is pleasantly readable (in French and English)
http://www.manicore.com/anglais/documentation_a/greenhouse/index.html

For scientific data on the problem:

The reports of the IPCC (Intergovernmental Panel of experts on Climate Change) are the world reference source on this subject.

We recommend starting with the summary of the most recent report (2001), presented by the GreenFacts International Foundation:
http://www.greenfacts.org/fr/dossiers/changement-climatique/index.htm (available in French, English, Spanish and German)

You can also obtain information from the source by downloading the 'summary for decision-makers' and the three working group summaries of the 2001 report: www.ipcc.ch (available in English, Arabic, Chinese, Spanish, French and Russian). These summaries are addressed to a non-scientific audience, but because the problem is so complex, and a vast amount of information is presented, they are aimed at readers already familiar with the issues.

For scientific news:

Coverage of articles from the specialised media: all the new discoveries are presented in a language accessible to all, at www.ghgonline.org
Glossary:
You will easily find several climate change glossaries from any search engine on the Internet. We also recommend that of the GreenFacts Foundation:
http://www.greenfacts.org/studies/climate_change/toolboxes/glossary.htm (in English, also available in French, German and Spanish)

For knowledge and notions involved:

ESPERE climate encyclopaedia
www.espere.net (French, English, German, Spanish, Polish, Hungarian, Norwegian, partially in Portuguese)

For examples of actions that can be carried out by everyone in daily life:

http://www.climnet.org/publicawareness/index.htm (Spanish, French, German and English)
Other useful resources (English only):

On research: *www.exploratorium.edu/climate/* and *http://climate.nms.ac.uk/*

On the effects of the problem: a world map of observed occurrences of climate change. *http://www.climate-hotmap.org/*

To calculate emissions of CO_2 by you, your family, school, etc.:
http://www.co2.org/calculator/index.cfm / *http://www3.iclei.org/co2/co2calc.htm*

What we know and what we do not know

Key questions and research on global change

> *'Our knowledge of the structure and functioning of terrestrial ecosystems is not developed to a sufficient degree to understand – much less predict – the consequences of climate change either on the systems themselves or on subsequent atmospheric interactions.'*

(International Geosphere-Biosphere Programme, 1991)

Close-up of Briksdalsbreen, at Jostedal Glacier National Park in Norway

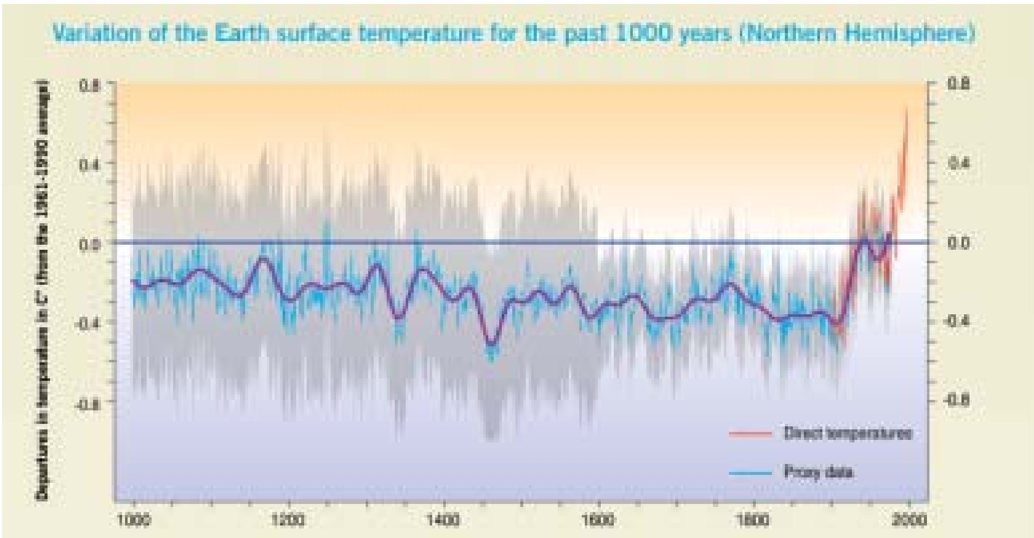
1. Predicting the future?

Many things are already known…

Today we are certain that climate change is taking place at a global level, and that the changes are characterised in particular by:

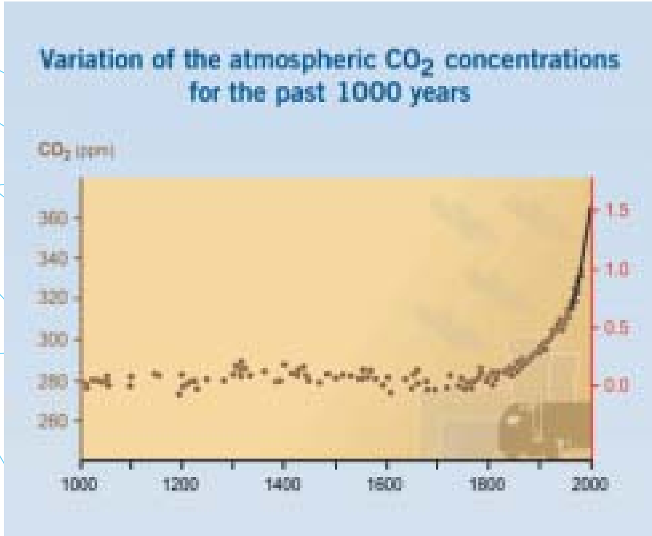
- an average *observed* temperature increase of 0.6°C compared to the beginning of the 20th century, with the period 1990-1999 being the hottest decade;
- an average *observed* increase in the concentration of a number of greenhouse gases[1] in the atmosphere, and of carbon dioxide in particular, for which levels have increased from 280 to 370 ppm[2] between 1750 and 2000;
- the extreme *nature of the changes observed* with regard to geological scales and of dimensions and at a speed not witnessed for at least 10 000 years.

Furthermore, all the evidence leads us to suppose that this current change in climate is not a natural phenomenum such as ice ages, but is *human in origin*. The increase in carbon dioxide in the atmosphere is due to the combustion of fossil fuels (e.g. petrol and coal) since the beginning of the industrial era, as well as to large-scale changes in the use of land (in particular deforestation in tropical zones). Other greenhouse gases, such as methane and nitrous oxide, are also increasing undeniably due to human activity over the last 200 years.



1) Greenhouse gases play an essential role in maintaining Earth's temperature at levels suitable to sustain life. Without them, the average temperature of our planet would be -18°C instead of the current +15°C. However, more greenhouse gases in the atmosphere will basically mean a higher average temperature on Earth.

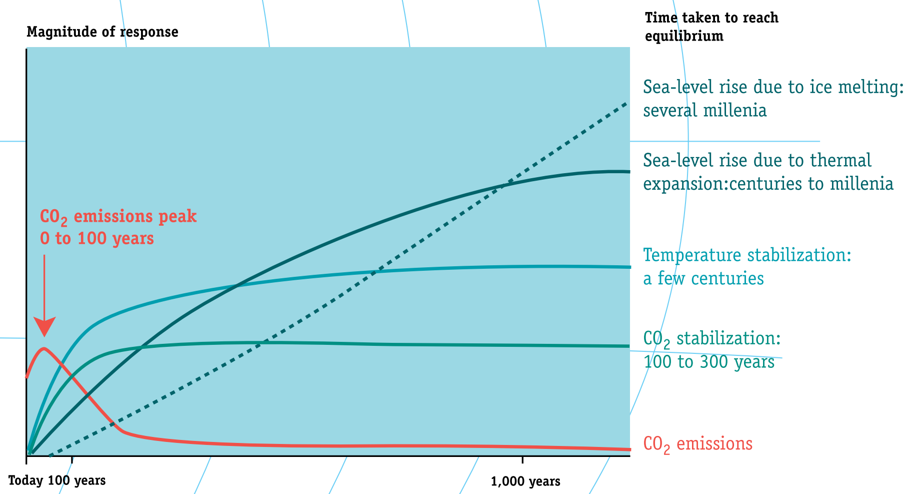
2) ppm = parts per million: a unit used to measure small quantities as a fraction by either volume or mass (in this case: the fraction of CO_2 by the volume in the atmosphere). 370 ppm (or 0.037%) indicates that in 1 million cm^3 of air there is 370 cm^3 of pure CO_2.



© Intergovernmental Panel for Climate Change

We also know that, even if we were to stop all emissions today, these changes will continue, and get stronger, over the course of the next few centuries due to the lifespan of these gases in the atmosphere and the inertia of the system.

CO_2 concentration, temperature, and sea level continue to rise long after emissions are reduced



© *Intergovernmental Panel for Climate Change*

...but there is so much more that we do not know!

The world is asking a crucial question: how is this situation going to evolve? This simple question poses a colossal challenge for science. *Our current knowledge is clearly insufficient* to predict with precision the evolution and consequences of climate change. What we can be sure of is that the average temperature will rise further over the course of the 21st century; but it is impossible to state with certainty whether it will be by 1°C or by 6°C[2]… and that makes a world of difference!

As for the *consequences* of global warming, the situation is no better. We know that global warming will cause a rise in sea-level and intensify precipitation (snow and rain) but here it is also impossible to say with certainty by how much. In addition, we still do not know with sureness whether global warming will intensify extreme climate phenomena (e.g. storms and cyclones).

We are also concerned with the risk of *unexpected responses* in the Earth's climate system if certain limits are exceeded. This is the 'elastic band' principle: as long as you stretch it without exceeding a given level of tension, the elastic holds firm and can return to its initial position; but if the tension exceeds its resistance it snaps once and for all. For example, some fear that global warming will one day weaken or even shut down the North Atlantic current (known as the 'Gulf Stream') and consequently lead to a regional cooling over Europe. This is the scenario that inspired the film *The Day After Tomorrow*, which although highly elaborated is based on a real possible outcome of climate change. Even though we suspect such limits exist, we do not know exactly where they lie.

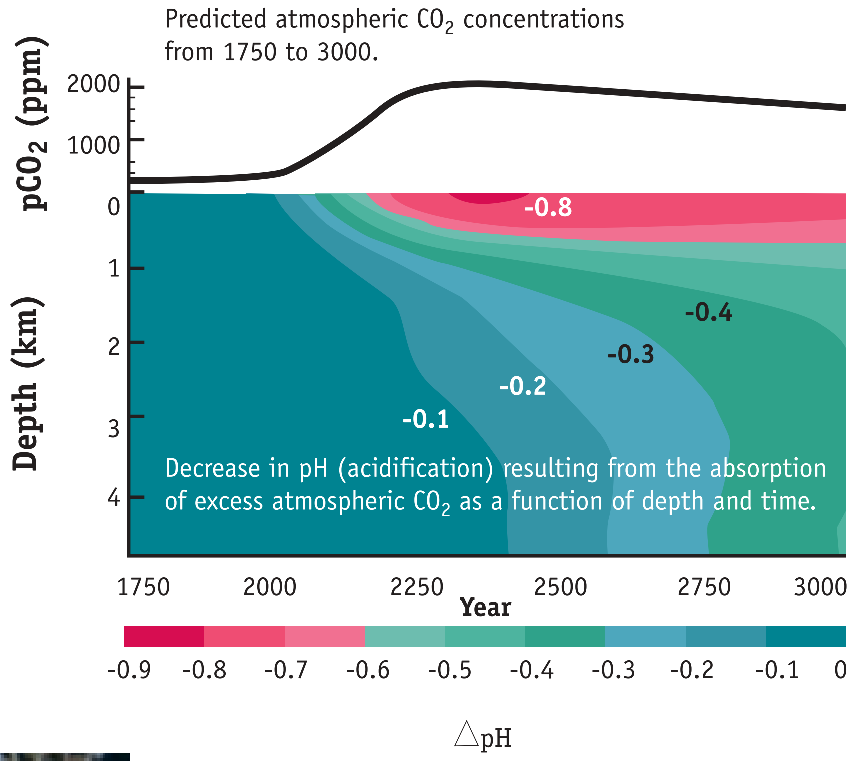
To complicate matters further, *climate change is not uniform over the Earth's surface*. For example, the average warming that is currently observed in the Alps is 1°C (and even 2°C in some places) compared with the planetary average of 0.6°C. Moreover, what we are all interested to know, apart from the general trend, is what is going to happen *in the place where we live*. Currently, we are not able to give precise answers and the most we can do is to identify trends, but depending on the assumptions made, the predictions may vary a lot.

3) From the state of our knowledge in 2005, an increase of less than 1.5°C is very unlikely, if not impossible. To keep below an increase of 2°C, as compared to pre-industrial levels, is a primary goal of international negotiations.

The acidification of oceans: the hidden side of the iceberg?

The *entire Earth-system* is being disrupted as a result of the increase in CO_2 in the atmosphere, and warming is only one of the consequences! Almost half the CO_2 that we emit into the atmosphere ends up in the oceans and in vegetation, and thanks to this fact the warming is much less intense than if all our emissions were to accumulate in the air. It is often said that nature "helps" us by mitigating the harmful effects of our interference, but this is not without consequence underwater: *the more CO_2 the ocean absorbs, the more acidic it becomes.*

Beyond a specific acidity threshold, organisms containing calcium carbonate, such as coral, molluscs, crustaceans and phytoplankton are at risk. The acidification of oceans therefore threatens the survival of a large number of marine species and the entire ocean foodchain.



© *Caldeira & Wickett (2003, Science)*

Lophelia pertusa*, the dominant stony cold-water coral, threatened by ocean acidification*

© *Ifremer*

We know that:

- To this day, human *CO_2 emissions have already led to an average decrease of 0.12 units of pH* in surface waters.
- By 2100, if CO_2 emissions continue to increase at the current pace, the pH will inevitably decrease to about 0.5 units below the pre-industrial level, reaching an unprecedented acidity in several tens of millions of years and at a speed 100 times greater than has ever been observed previously.
- Tens of thousands of years will be required by oceanic chemistry to return itself to its pre-industrial state (provided that the atmospheric concentration was also to come down). The acidification of the oceans is irreversible on a human inter-generational scale. At this rate, we have good reason to fear that numerous species will not have time to adapt, in particular those whose growth cycle is the slowest, such as coral reefs, with critical consequences for their environment. In contrast to global warming, for which both the extent (ie. +1 to +6°C by 2100) and consequences are largely uncertain, the extent of acidification is well known, only its total impact is less well understood. The scope of acidification (for instance, on the surface is 0.5 units of pH less by 2100 if emissions continue to be released at the current rate) is linked to well-known chemical phenomena, and is thus estimated with a great degree of confidence.

Therefore, global warming is perhaps only the tip of the iceberg in terms of the disruption to our natural environment. Other consequences, such as ocean acidification, may be equally worrying. One thing is certain: we must stop thinking in a compartmentalised way by considering the ocean separately from the atmosphere. Instead, we must realise that the CO_2 we emit into the atmosphere and is absorbed into the oceans does not disappear, but has consequences for marine ecosystems and this must be considered in the balance of risks in political decision-making.

CO_2 from the air to the sea

CO_2 knows no boundaries: it is spread over the entire world surface and affects all countries, major and minor polluters alike. CO_2 also does not distinguish between air and sea but migrates between these two environments and endeavours to cover them as uniformly as possible. Here as everywhere else, nature strives towards equilibrium i.e. for the ocean and atmosphere to contain the same proportion of CO_2.

While it is relatively stable in the air over the oceans, as soon as it enters the water CO_2 is the subject of two main fates:

1) CO_2 reacts with water molecules to form other forms of inorganic carbon dissolved in seawater: 'carbonate' and 'bicarbonate'. The ocean is an insatiable consumer of CO_2: as it continually seeks to contain as much CO_2 as the air, as soon as it transforms CO_2 into carbonate it is again 'hungry' for more CO_2 and therefore absorbs more of it, etc., and this until it reaches a balance between the various forms of carbon in the water. This balance varies notably as a function of pH, i.e., the water's acidity. With the current acidity, approximately 1% of the total carbon in surface water can be found in CO_2 compared to 99% as carbonate and bicarbonate.

The immediate chemical transformation of CO_2 when entering the sea surface illustrates what we call the 'buffer capacity' of the water: the capacity of the ocean to keep its pH at nearly the same overall value as CO_2 enters the sea, when the amount of CO_2 involved is not disrupted by man. However, in a future with increasing amount of atmospheric CO_2 and an ocean that will absorb more carbon than it used to, the buffer capacity of seawater will be reduced. This means that the water will not be able to resist the pH changes as well as before, its pH will decrease, and the seawater will become more acidic.

2) CO_2 enables the growth of phytoplankton (or green algae) exactly as it does for all other plants. Phytoplankton are at the base of the entire marine food web and 'grow' using light, carbon and various nutrients. When phytoplankton die, or are eaten, their remains sink to greater depths in the ocean, and because they are mostly composed of carbon, their life-cycle removes carbon from the surface water. However, while sinking downwards the dead organisms are broken down into inorganic material (i.e. are remineralised), carbon is brought back into solution (i.e. dissolved into the water) and due to the vertical movements of water in the sea, a part of this carbon goes back to the surface layer; but a certain proportion always manages to travel through deeper layers of the ocean and eventually the sediments, where it gets stored.

This biological consumption of carbon never rests; it is always active somewhere on Earth. It is believed that it is not strongly affected by the increase in atmospheric CO_2. Since carbon is available for photosynthesis in such quantities in the water, the increase that affects the 1% present in the form of dissolved CO_2 is supposed to be imperceptible. However, recent research results might lead us to reconsider this belief.

Two great unknown factors

Why is it so difficult to predict climate change?

Firstly, our understanding of the *natural phenomena* involved is limited: human activities that produce greenhouse gases are known, but the natural processes that release, absorb, and store these gases are not yet fully understood. The way in which carbon is transferred from one natural reservoir to another (the carbon cycle) is very complex and we have a limited understanding of how this cycle reacts to human interference.

We are also faced with another great unknown: *the future of human society*. How will the global population evolve? How will the poorest countries, which currently emit very low levels of CO_2, develop? How will emissions evolve in economies with fewer oil and coal reserves? What decisions will be made by politicians in the future to limit emissions? Will we perhaps be able, thanks to technologies as yet uninvented, to make use of energy sources that do not emit greenhouse gases? So many questions that are, of course, impossible to answer over the course of a century.

It is not possible to shed light on most of the unknown factors linked to the future of human activity. That is why we treat them in the framework of a number of *socio-economic scenarios* corresponding to different possibilities for the evolution of global population, economic growth, environmental policies, etc.[3]. On the other hand, progress can certainly be made in our understanding of natural phenomena.

From the human body to planet Earth

Some say that, in our knowledge of planet Earth, we are at a similar point to where doctors were at the beginning of the 19th century with their knowledge of the human body. At that stage, they were only just beginning to reach an understanding of blood flow, respiration and the nervous system, and to determine the functioning of the various organs: lungs, heart, brain, digestive system, etc.

It is true that our understanding of the ‘organism’ planet Earth is currently very limited. We know the key players in life cycles: oxygen, carbon, nitrogen and hydrogen. We also know the major ‘organs’: the oceans, the atmosphere, and the vegetal and animal world. But how do the first travel through the latter, what controls what, how and why?

For a long time we have believed that, for example, plants are controlled by physical factors such as light, precipitation and temperature. But in reality, does plant life itself not occur within a cycle, and is it not subsequently capable of influencing in turn these physical factors?

We do not yet truly know how to go about answering these fundamental questions.

We do, of course, have many advantages over 19th-century doctors: accuracy of measuring instruments, satellite images, exchange of information and ideas, continual scientific collaboration on a global level, and the power of computers that enable us to process all this information.

However, we also have huge obstacles to overcome:

- the planet is a particularly cumbersome ‘body’ and not easy to examine. To go from one ‘organ’ to another, we often have to travel thousands of kilometres! Furthermore, it is very difficult to ‘see’ the elements in the life cycle and to follow them in their travels. For example, we use carbon-14 (an isotope of carbon) to trace the exchanges of carbon dioxide between ‘organs’ because this is not visible directly, but since carbon-14 only exists in infinitesimal quantities (on average $1x10^{-12}$ – i.e., a thousandth of a billionth of the carbon contained in a sample) we also require very specialised techniques to measure it. The study of *fluxes* (i.e., movements of all water, gases and nutrients between soils, plants, oceans, rivers, the atmosphere, animals, etc.) can be a little haphasard on the basis of limited observations over time and space, and consequently contain a considerable margin of error.
- we *only* have *one Earth*! Experimental science has always been based on the possibility to test hypotheses and to compare the results in order to uncover the laws of nature. In the case of the Earth, it is impossible to take a sample Earth, inject it with CO_2, wait for 100 years and compare the results with another sample Earth for which CO_2 is maintained at normal levels.

3) For more information: the principal scenarios within the framework of the third evaluation report of the IPCC are presented on pages 10-11 of the ‘summary for decision-makers’, available on www.ipcc.ch

Understanding the system in its entirety

Lastly, we are faced with a difficulty not previously experienced in the history of science. Up until the Renaissance, great intellectuals such as Leonardo da Vinci were still able to approach all fields of human knowledge: art, philosophy, mathematics, biology, physics, history, etc. However, with the acceleration of scientific progress during the last two centuries, the organisation of knowledge into disciplines has become increasingly specialised.

LBA Carbonsink project – A micro-meteorological tower in the midst of dense rain forest in the Amazon Basin, Brazil

© CarboEurope – John Grace

The problem is that we are not able to understand the system in its entirety through specialist disciplines alone. While we must continue to isolate certain components to study them better, at the same time we must also connect them with each other, as they are in reality, to try to understand their exchanges and feedbacks. Climate change concerns the interaction between human societies and the whole earth-system; therefore, we need to integrate the various disciplines in earth science, and also the social sciences. It is a true revolution, in the sense that it turns our patterns of thought upside down and obliges us to re-examine our education systems.

It is from this need for a global vision, in particular, that the British scientist James Lovelock started imagining the Earth as a kind of macro-organism, which he calls Gaia. The so-called "Gaia Theory" sees the Earth as a kind of self-regulating organism in which the laws of nature perpetually keep the system in balance and sustaining life.

This theory gives us hope that the system will inevitably end up being rebalanced. But we can just as easily worry about the enormous quantities of fossil carbon, gradually stored throughout the geological ages, that we abruptly release today. Nature alone did not intend that. Will it be able to ensure the rebalancing of the organism to still allow an environment suitable for human life?

In short: we observe that mankind is in the process of bringing about brutal and lasting changes to climate and ecosystems by upsetting the equilibria that have been slowly established throughout geological ages. We are able to determine some of the consequences of these changes, but we are not in a position to predict them with either certainty or precision, partly because we still have a poor understanding of most of the natural processes involved, and partly because future human activity is unpredictable in the long term.

Micrometeorological tower from the air, Renon/Ritten, Italy

© CarboEurope – Stefano Minerbi

2. Key questions about natural processes

The essential objective is clear: developing our overall understanding of the earth system.

In every natural system, there are always actions/interactions/feedback, there is no beginning and no end, but rather causes and effects that continually act on each other: one heck of a headache. The questions we ask, therefore, are themselves interdependent and consequently can be formulated in a great number of ways. But whatever the focus, the questions that emerge are essentially these:

Arctic Sun – Trans-Arctic cruise on the Swedish icebreaker Oden

How does the carbon cycle react to the increase in CO_2 levels in the atmosphere?

How do carbon exchanges take place between the various components of the cycle (sediments, soils, plants, oceans, living organisms, etc.)? How do these components react to the increase in CO_2 levels in the atmosphere? What is the natural capacity of vegetation and oceans to absorb the excess carbon we release into the atmosphere? Does biodiversity influence carbon storage? What types of forestry and agricultural management favour carbon storage? (see *'the urgent question as regards carbon: natural sinks'*).

How does the water cycle react to the increase in temperatures?

Water vapour is the most abundant natural greenhouse gas. Will increased evaporation lead to greater levels of water vapour in the atmosphere, and consequently, a greater number of clouds, increased precipitation, and therefore less sunshine and mitigate the greenhouse effect? Or will more clouds rather trap more heat at the earth's surface and accentuate the greenhouse effect?

How does the nitrogen cycle interact with the other cycles and how will this interaction respond to human interference?

Nitrogen (which forms 78% of the atmosphere) is a fundamental element for life, essential to all living things, including plants. The availability of nitrogen is one of the limiting factors governing their growth: cultivated land is treated with nitrogenous fertiliser (hence the designation 'nitrates') to increase crop yield. But what happens when the atmosphere becomes richer in CO_2? Will the rate of photosynthesis by plants increase, or will it be limited by other factors such as the availability of nitrogen from soil?

How do the oceans transport heat, and how will ocean currents react to global warming?

How will ocean currents be affected by global warming? What effects will this have in turn on climate? Do we have reason to fear irreversible changes in global climate regulation by oceans? Is there a risk of 'surprises' linked to events of very low probability, but which have very serious consequences?

© CarboOcean

How will the oceans evolve in a CO_2-enriched world?

Will the acidification of the oceans, resulting from the absorption of great quantities of CO_2, disrupt the marine food chain and lead to the disappearance of some marine species? Will these ecological disruptions in turn affect the capacity of oceans to absorb atmospheric CO_2?

What are the effects of climate change on the various ecosystems, and what feedbacks will these have in turn with regards to climate?

How do forests, wetlands, cultivated fields, prairies, etc., at different latitudes react to climate change? Do increases in atmospheric CO_2 levels and in temperature lead to increased rates of photosynthesis, and consequently of carbon storage in plants? What are the consequences of significant land-use changes, such as deforestation? Will increased temperatures melt the permafrost in arctic regions, and, if this is the case, will that lead to further emissions of greenhouse gases that will further increase the temperature?

Plateau Rosa, Italy: one of the highest atmospheric monitoring stations in the Aerocarb project.

© CarboEurope – Francesco Apadula

What is the local and regional impact?

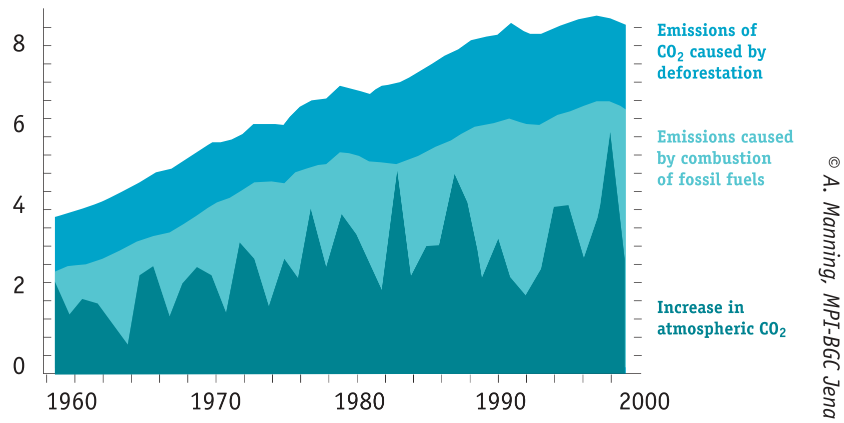
How will the changes (increases in temperature, precipitation, etc.) vary between the regions of the world? Will the Alps be deprived of snow? Will the Mediterranean regions turn to desert? How will our water sources be affected? What will happen if water normally stored as snow in winter flows directly into rivers? What will be the consequences for agriculture, food and habitats?

Do we have reasons to fear an increase in extreme meteorological phenomena, if so, at what latitudes?

Will hurricanes and other storms become more frequent and more extreme? Will droughts and flooding become more prevalent, and in which regions?

Needless to say, we already have part of the answers to most of these key questions, in a more or less precise way. But we are also aware that we will probably never have the full answers. In this field of research, where there will always be some things we don't know, it is more a question of *reducing uncertainties*. This is essentially what we aim to achieve.

3. The urgent question with regard to carbon: 'natural sinks'



One very surprising fact is that *only ca. 55% of the CO_2 from fossil fuel burning accumulates in the atmosphere*. The oceans and biosphere absorb the rest, and we therefore refer to these as 'natural carbon sinks', as they considerably offset (or slow down) the harmful effects of human interference in the atmosphere.

However, we ask the following questions with some anxiety:

- For how long will the oceans and plants be able to continue absorbing a significant portion of the carbon that we release into the atmosphere?
- What will become of the absorbed CO_2, and what effects will CO_2 enrichment have on the land biosphere and, in particular, on the oceans?

Our understanding of natural sinks is generally well founded, however, there is still considerable uncertainty in the *quantities* absorbed, the *causes of inter-annual variability*, the *future behaviour* of these sinks, and their *vulnerability* to constant CO_2 enrichment.

Quantities remain very imprecise

At present, of the 6.3 Gt (giga-tonnes, which means 10^9 tonnes) of the average annual CO_2 emission from fossil fuel burning, it is estimated that 2.8 Gt +/- 0.5 Gt are absorbed by the combined effect of the oceans and the terrestrial vegetation – that is to say between 36 and 53% of our emissions, i.e. an average of 44.5%.

But trying to determine the carbon dioxide uptake by each of the natural sinks separately is more difficult. Therefore, the level of uncertainty is even greater:

- Oceans absorb 1.9 Gt +/- 0.7 Gt[5], i.e., between 19 and 41% of our emissions.
- Terrestrial vegetation absorbs 1.2 Gt +/- 0.8 Gt[5], i.e., between 6 and 32% of our emissions.

We are trying by all available means to reduce these considerable levels of uncertainty, particularly by considering the inter-annual variations separately, which are natural in origin (inherent to the system), and the variations due to human interference.

Surprising inter-annual variations

The figures mentionned above are only averages: in reality, natural sink activity can vary considerably from one year to the next.

While human emissions (deforestation and fossil fuel combustion: upper two lines, in Gt/year) increase in a relatively regular manner, the consecutive increase in the atmosphere (i.e., the portion that remains in the air and is not absorbed by the oceans or biosphere: bottom line) is very irregular. Some of these variations can be attributed to other natural phenomena (El Nino in particular), but for the most part we know very little about the mechanisms that cause them. What are the respective roles of the oceans and the biosphere? What causes these variations? By what precise amount does the uptake by the respective natural sinks vary, and what is the most likely future scenario in an atmosphere that is becoming increasingly enriched in CO_2?

Terrestrial sinks: the weight of history

Terrestrial carbon sinks do not only depend on the type of vegetation and the physical parameters (of weather, daily and seasonal variations, etc.), but also on the history of land use over several hundred years. Two prairies, similar in appearance, may have a very different carbon balance if, for example, one has been cultivated for several hundred years and the other was still a forest only twenty years ago. The European continent has been strongly marked by the presence of humans for a number of millennia. In order to reconstruct fluxes without making too many mistakes, a great deal remains to be done!

5) These figures don't exactly add up (ie. they only add up within the uncertainty range), basically because they are calculated using different sets of measurements. The combined sink effect of the oceans plus the terrestrial biosphere is calculated from the change in atmospheric CO_2 concentrations (accounting for the amount of CO_2 emitted by industrial activity), whereas the separate ocean sink and biosphere sink cannot be determined directly, but, only with the additional measurements of 'tracers' like carbon-14, carbon-13 etc. so different measurements - different uncertainties - different numbers. Keeling & Garcia (2002)

The biosphere's slogan of choice: 'slow in, fast out'

The sequestration of atmospheric CO_2 by the vegetation, through photosynthesis, is the result of a long and complex process ('slow in'). By contrast, with combustion, the release of carbon into the atmosphere is sudden and unavoidable ('fast out').

Furthermore, the terrestrial biosphere contains between two and five times as much carbon as the atmosphere: changes in carbon stocks present in vegetation, therefore, have significant effects on CO_2 concentrations in the air. The majority of carbon absorbed by photosynthesis is actually only retained temporarily (in leaves, wood and fruit) before returning to the air through decomposition and respiration. Only a small proportion is durably retained in humus in more stable forms. We know little about what determines this distribution.

Russian forest research site – Fyodorovskoye, Siberia. Taking air samples in a remote forest, for analysis in Western European laboratories, is a logistical challenge.

Are terrestrial sinks vulnerable in the short term?

Recent studies show that attempts to artificially store carbon in vegetation (mainly by planting new forests) will be exhausted in approximately 200 years, once a new balance has been established between tree growth and felling. Only the oceans will retain their capacity for absorption for a number of centuries to come. Some terrestrial ecosystems could even become natural sources, releasing large quantities of CO_2 and could cancel out all our efforts to reduce human emissions.

We can only hope that this scenario is excessively alarmist and that the reality will not be so severe. In any case, this shows that it is more urgent than ever for us to make progress in our understanding of natural sinks and their evolution over time. For terrestrial and marine sinks respectively, CarboEurope and CarboOcean represent the large-scale efforts of the EU to contribute to this task.

Starting CO_2 measurements aboard MS Falstaff *cargo ship*

Scientific research: probing at reality

© MPI-BGC Jena

Facing a surprising phenomenon such as global warming, our starting point as researchers is first and foremost to ask ourselves *questions*, like those summarised in the previous pages.

Next, we think up one or more *hypotheses*: we identify the suspects! For example, we could say that the combustion of fossil fuels (i.e. mankind) is responsible for the increase in CO_2 levels.

We then begin the investigation. We look for all possible clues by which we can either confirm or reject our hypothesis: traces, signals, footprints (we actually use all these words). We carry out experiments, make measurements, gather samples, and perform laboratory analyses. This often involves some unusual activities: spending an afternoon at the top of a tower above treetops, planting a thermometer in the ground, gathering air pockets all night long in the middle of a field, making planes constantly ascend and descend without landing, digging holes on mountain tops and in the ocean floor, etc.

We cross-check multitudes of information until we obtain a 'bundle of presumptions' sufficiently solid to allow conclusions to be drawn. It is often the accumulation of a great quantity of information on a given issue that allows statistical trends to be identified. On other occasions, *extreme values*, data that cannot be explained, can lead us on to new research paths.

We usually need several years and lots of perseverance to go from question to answer. On occasion we are unable to do so, or only to a very partial extent, or not in the manner intended. Sometimes a conclusion casts doubt on a previous result that had been thought to be well-established. It also happens that answers are accidentally found to questions that we did not think to ask ourselves!

In the majority of cases, our conclusions do not provide a clear answer to the initial question, but lead to new questions and hypotheses on which we have to begin working all over again! Put simply, we constantly ask ourselves questions, question what we know, and strive to 'see' what it is not easy to see.

4. How do we deal with these questions?

Observation: placing the planet under medical surveillance

The aim is simple: to collect the greatest possible amount of data on the largest possible number of parameters, as often as possible, in as many locations as possible, in order to provide as accurately as possible, an overall picture of the planetary climate situation. In short, to answer the question: *'what is really happening, when and where?'*

Observational activities are very diverse. For example, we are measuring:

- stocks (e.g. how much carbon is present in vegetation and in soils)
- fluxes (e.g. in order to estimate the quantity of CO_2 released or absorbed by a forest, cultivated field, natural prairie, phytoplankton bloom etc.)
- concentrations of greenhouse gases in the atmosphere
- oceanic currents
- meteorological parameters
- data from satellites, which provide us with information on a multitude of parameters (for example, surface and atmospheric temperatures, vegetation coverage, etc.)

This is a kind of planetary 'monitoring', comparable to that needed in medical diagnosis: we place the Earth under surveillance in order to monitor the evolution of all the parameters that we are able to measure. We seek to increase the frequency and diversity of measured points, so as to have an ever-clearer picture of the situation, and to develop new instruments that are more accurate and more reliable.

In addition to observations in the present, we also study the past with considerable attention. The Earth has a great many archive systems, where you can find very accurate traces of past climates, for up to hundreds of millions of years ago. For example, air samples can be found in glaciers in mountainous regions and in polar ice caps, on the basis of which, the history of our climate can be reconstructed.

Anders Olsson determines freons in seawater by gaschromatography on board R/V G.O. Sars

© Yoshie Kasajima, Bjerknes Centre for Climate Research, Bergen, Norway

Experimentation: understanding the mechanisms that control the organism, Earth

It is all very well to make observations, but the question that constantly obsesses us is: '*why and how does this happen*?'

This is the very heart of research, where we attempt to advance the frontiers of knowledge and to progress in our understanding of phenomena about which little or nothing is known. It is here that we find all our key questions, producing a kind of enormous puzzle for which each researcher attempts to shed light on a small piece allowing it to progress as a whole.

In this way, researchers work on 'their' own questions. For example, consider a forest that is thought to be a carbon sink: atmospheric measurements have shown that the forest is taking carbon out of the atmosphere, but at the same time only a much smaller increase in biomass (vegetation) is measured. The trees are storing only part of the carbon absorbed by the forest. What happens to the rest? What really takes place between the atmosphere and the trees, and then between the trees and the earth, between the earth, bedrock and underground waters, and between plant-life and animals? Why does this happen, and how?

In order to answer this type of question, there is only one way to proceed: to make a hypothesis and to attempt to test it through experimentation. One needs to see what is happening, to take samples, to compare results, and to question what is already known: to put it simply, to search!

Modelling: a mega-simulation game for time travel

The Earth is a complex system, with very slow reaction times in terms of human life-span, and impossible to isolate in a sealed container to carry out laboratory experiments on. Under such conditions, it is difficult to check *in situ* whether our hypotheses about the climatic system are true or false, and it is even more difficult to predict the future.

However, we have super-computers with which we create virtual planet 'Earths' in their entirety and these are known as models. Models are a kind of mega-computer game that we 'play' by artificially modifying parameters to see what will happen.

As in any good simulation, there are squares (that we refer to as a 'grid'). The squares contain numerous parameters (temperature, humidity, CO_2 levels, wind direction, vegetation, etc.) and are linked by a series of equations that reproduce what is known about the interactions between these various parameters in reality. Then there are 'time steps', units of time (for example in hours, days, weeks, etc.) that determine the virtual rate at which the computer is asked to recalculate the parameters for each square on the basis of equations, and in this way to simulate reality in various timescales.

It is, therefore, possible to calculate the change in climate over the last 1,000 years in the space of only a few days. Using climate archives available from drilled cores (of ocean sediment or glacial ice), we are able to compare the simulation with reality. Differences in the comparison demonstrate insufficiencies in the model that must then be adjusted. The more we are able to check its reliability for the past and the present, the more we can rely on its predictions for the future evolution of climatic factors, in 50, 100 or even 1,000 years time.

Models are tools for prediction: one of their most common applications is to forecast the weather. Weather forecasting is also a good test of the models' limits: sometimes forecasts are incorrect and the further into the future they try to predict, the more imprecise they become. This is quite simply because equations remain merely an approximation of reality. A forecast provides trends but not certainties. The smaller the squares and units in time, and the more numerous and accurate the data and equations (in other words the higher the resolution of the model), the clearer the picture, and the closer the forecasts become to reality.

While weather forecasts regularly mislead us, climate models are still far from perfect. There are two considerable fronts on which we are trying to make breakthroughs:

- *Integration of all components into a unique global model:* We first build separate models for vegetation, oceans, the atmosphere, etc. It is then a question of "coupling" all these elements (as in reality) to create a global model capable of reproducing the whole of the Earth's systems. One of the most substantial obstacles is that, as yet, little is known about some of the components (such as soil), and this makes them difficult to reproduce.
- *Reducing the scale:* While we are able to simulate climate relatively well at the planetary level, models are, however, still rather poor at prediction at the regional level (for example, the continent of Europe). Furthermore, it is precisely at regional level that we currently suffer the most from a lack of information. This is a problem, not only due to limits in computer power (the more models are complete and accurate, the more calculations they need), but also due to the limits in our understanding of the phenomena in question.

Everything is related

The three primary pillars of research: observations, experimentation and modelling are very closely linked: models are fed with data from observations and their equations are adjusted based on what we have learnt from experiments, and each time a model produces a result far from the range of observations, we uncover a process that we need to investigate more closely, and so the whole process of observation, experimentation, and modelling begins again.

Stocks in belowground biomass are a great unknown in the terrestrial carbon budget. JRC researchers are working hard to get out complete root systems of a poplar stand in Parco Ticino, Italy, where fluxes of greenhouse gases were studied for several years before logging.

MS Atlantic Companion, *a cargo ship with* CO_2 *measurement equipment aboard*

5. What are we doing to solve the problem?

Although we are faced with immense scientific challenges, we have not waited for a time of certainty to alert the public and the authorities.

Since its creation in 1988, the Intergovernmental Panel for Climate Change (IPCC) has been organising regular assessments of the advancement of knowledge in all specialities on a global scale. Relying on several thousand scientists, the IPCC has already published three assessment reports, and these are the most authoritive reports on the subject. These were published in 1990, 1995 and 2001, and the next is scheduled for 2007.

These reports are at the interface between science and policy and are the main tool for defining public policies. In 1992, at the World Summit in Rio de Janeiro, the United Nations established the Framework Convention on Climate Change (UNFCCC) on the basis of the first IPCC report. Its ultimate purpose *'is to achieve (…) stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system'*.

The Kyoto Protocol: a considerable challenge or an insignificant gesture?

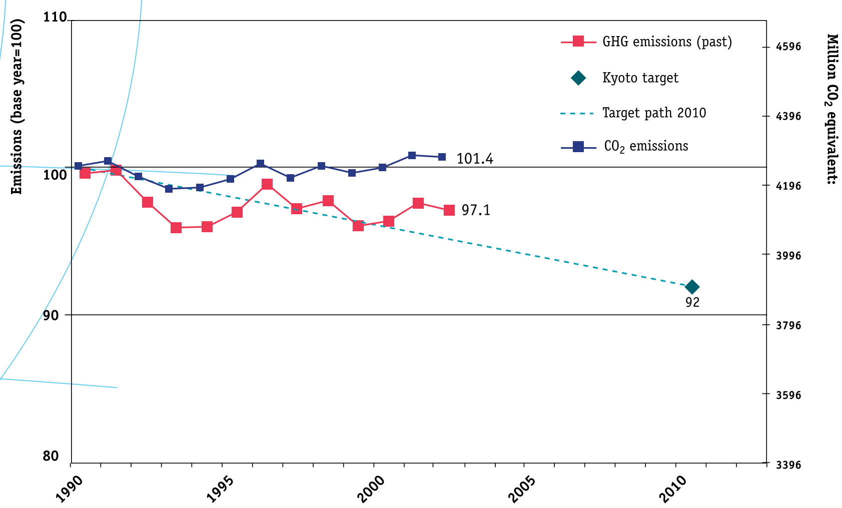
The Kyoto Protocol was established by UNFCCC in 1997 and sets binding objectives for developed countries, which must reduce their emissions of greenhouse gases between 2008 and 2012 by at least 5% on average compared to 1990 levels.

This objective may seem to be both a potentially challenging task as well as an insignificant gesture.

Insignificant gesture: from a scientific point of view, since 5% will not change the trends in any way. This will allow at most, the limiting of the growth in an imbalance that is increasing all the time.

Potentially considerable because:

- This objective to reduce emissions is not an end, but a beginning. The Kyoto protocol is a changing framework: commitments to reductions in emissions are made in five-year periods. Period by period, the international community may, should it so choose to, set limits that are more and more binding.
- The objective is defined by comparison with 1990, but since this date emissions have continued to increase. In this way, a 5% reduction by 2012 as compared to 1990 levels is in reality much more when compared to present levels! We may, however, question ourselves about the capability of certain countries to keep their commitments. An extreme example is that of Spain: in 2002 it exceeded its 1990 emission levels by 39%[4].



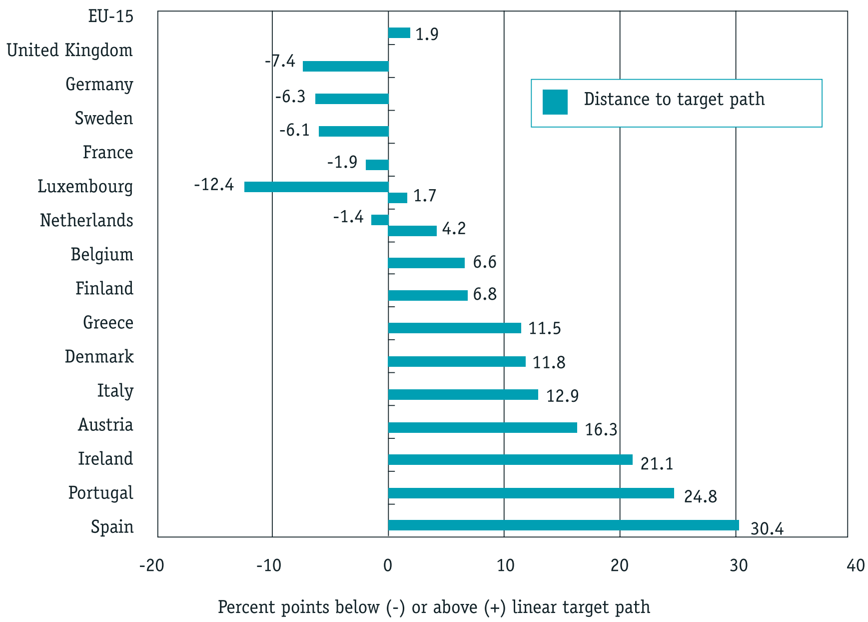
Total emissions of greenhouse gases by the EU-15 compared with the Kyoto objective

4) The gap is much smaller for the EU-15: in 2002 emissions only exceeded 1990 levels by 1.4%, mainly due to the continued increase in road transport

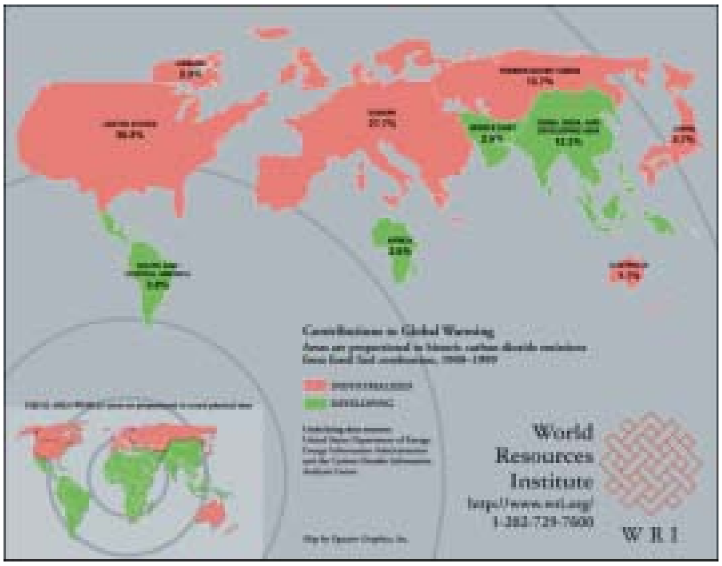
- For the first time in history, an international agreement on the environment was made in the form of a binding legal commitment for signatory countries, with actual sanctions in the event of non-compliance.

It took nearly eight years from the signing of the protocol, in 1997, to its 'ratification by at least 55 countries representing 55% of total CO_2 emissions' that allowed it to enter into force on 16 February 2005. Due to the opposition of Australia and the United States, the latter being responsible for the greatest amount of emissions, this event almost failed to take place.

The 15 EU Member States (at the time of the Kyoto conference), totalling 24.2% of the worldwide emissions, ratified the protocol in May 2002. They agreed to set their reduction commitment at 8% on average compared to 1990 levels. Some countries are going much further, such as Germany and Denmark, who in 1998 made a unilateral commitment to reduce their emissions by 21%.



The 'distance compared to the linear regression objective' represented by the bars indicates the gap that separates the hypothetical objective set for 2002 and the actual emissions in 2002. The hypothetical objective set for 2002 supposes that the authorised emissions of Member States between 1990 and 2012 will follow a linear trajectory. The distance compared to the regression objective is expressed as a percentage.



Contribution to global warming, 1900-1999
The size of the countries is proportional to their emission of CO_2 from fossil fuel combustion.

In or out of the cycle?

All forms of combustion release CO_2, but not all CO_2 emissions necessarily increase the amount of CO_2 in the carbon cycle: it all depends on what one burns!

- The carbon contained in any fuel of vegetable origin (e.g., wood) is already in the cycle. It was in the atmosphere, from where it was "sequestered' by the plant through photosynthesis, and to where it is 'returned' in burning; and will be returned sooner or later, combusted or not, when the plant dies. This carbon is in the cycle. This emission is said to be neutral on one condition, and it is a demanding one: that for every single tree burnt or felled, another tree is replanted.
- On the other hand, fuels of fossil origin (coal, oil and natural gas) are no longer in the cycle. They are stable stores of carbon accumulated over geological ages, and provide a formidable source of energy but at a big cost. When fossil fuels are burned they deliver CO_2 into the air, which had not been there for millions of years. It is as though a tap was opened into a very complex, closed, but balanced system, and is adding increasingly larger quantities of one of the components, and its flow is continuously increasing in spite of signs of disruption to the whole system.

That is why substituting a fossil fuel with a fuel of vegetable origin (bio-gas, wood, and other fuels of vegetable origin), provided that it does not diminish forest surface area, replaces a CO_2 emission that was out of the cycle with a CO_2 emission that is already in the cycle. From now on, this can be carried out without affecting atmospheric concentrations. The same logic applies to houses, when one replaces their cement or bricks (which have a very high energy cost) with wood (which retains the carbon it contains).

How can we reduce emissions?

This is the key question posed to human society by the challenge of climate change.

The most obvious way is to reduce emissions at the source: the cleanest energy is that which we do not use. Increased use of public transport, bicycles, renewable energy, recycling, etc. are the best methods.

Another way is to develop new sources of energy and clean technology, capable of increasing energy efficiency and reducing, or even eliminating, greenhouse gas emissions altogether: co-generation, bio-gas, fuel cells, electricity produced by nuclear fusion, etc.

Since all possible means should be put to use, the Kyoto protocol also authorises the natural sequestration of carbon by the planting of new forests. The motivation is clear: until we can implement technological solutions or change our behaviour in order to considerably reduce emissions, all other solutions allowing us to gain time are most welcome.

However, from a scientific point of view we are not entirely sure that this will work. We know that trees in the peak of their growth period are a means of temporarily retaining CO_2 in plant form, but we do not know exactly how this storage method behaves over time. How does the absorption capacity evolve over 10, 100 or 300 years? How long can we consider this carbon, 'artificially' stored in forests, as actually remaining captured there? What types of forest and what methods of forest management best favour carbon storage?

A global and ethical questioning of our development models

From a philosophical point of view, we might ask ourselves '*has humanity truly taken stock of the threats to its future*?'

On its own, the Kyoto protocol is a demonstrative response: not only are the first binding commitments far too tentative to reverse the process, but seven years after they were agreed to, it seems obvious that some countries will be unable to keep to their promises.

At the other end of the chain of responsibility, i.e., at an individual level, things are not any further ahead. In the developed countries (responsible for most emissions), people who have truly changed their ways of life and work in order to reduce their own emissions remain a very small minority.

Spurred on by the media and environmental movements, *public awareness* has, beyond any doubt, progressed hugely, but whether on an individual or a collective level, reality shows that *words, generally speaking, have not yet become action*.

Three serious obstacles can be identified:

1) Global change cannot be seen; it has no smell, and no perceptible effects in the short term, or close to its sources. Furthermore, due to its global nature, people often feel that what they can do as individuals will always remain too marginal to make a difference.

2) The extent of the risk is uncertain. How can we take action today to protect against problems tomorrow if we do not fully know what these problems will be? On this subject, as on many others (genetic engineering, animal feed, nuclear energy, etc.), two opposing opinions emerge:

    - some consider that *as long as we have no clear proof of risks*, we can continue the experiment.

    - others consider that due to the irreversible character and the seriousness of the risks with which we are faced, we must stop *early, as we have no proof of an absence of risk*: these are the supporters of the 'precautionary principle', and is one of the foundations of the Kyoto Protocol.

3) Great forces of inertia and resistance to change (through industrial lobbies as well as populations) prevail in our societies, expressing the permanent tension between collective interests and individual interests.

Lastly, global change refers us back to the question of poverty and large-scale imbalances between countries in the north and in the south.

- The phenomenon is caused by only a portion of humankind (the industrialised world) but the effects are suffered by all. Some see this as *an environmental act of aggression* by developed countries towards the rest of the planet.

- The poor and disadvantaged, since they have the most limited capacity for adaptation, will be the most severely affected by the harmful effects of climate change.

All in all, and even when science brings us new answers to important questions, this is a matter of balancing opposing needs in society (e.g., energy, mobility versus preservation of resources), and opposing interests (those of the present economy, those of ecosystems and biodiversity, those of future generations, those of the industrialised and the non-industrialised, rich and poor etc.), which in the current dominant and unsustainable concept of growth are in great imbalance. Beyond scientific evidence, this difficult quest calls for ethical criteria that are independent from factual knowledge.

The challenge of global change forces us to question our entire relationship with nature, with the preservation of equilibria, with the sharing of resources and wealth, and with the notion of growth. More than ever, development shall mean building new alliances on a global level, as opposed to retaining interests of particular groups, countries or even groups of countries. Will we be able to implement solutions together, as a single humanity on a single planet that will allow us to adapt to the changes we have already brought about, and to pursue our development without further jeopardising the system's equilibrium?

Polar bear tracks - Trans-Arctic cruise on the Swedish icebreaker Oden

CARBOEUROPE

Understanding and quantifying the carbon balance of Europe

What is the role of the European continent in the global carbon cycle?

More precisely, what is Europe's carbon balance? How much CO_2 does it emit, and how much does it absorb? How can we reduce the uncertainties in our estimates of this balance at a local, regional and continental level? What mechanisms control the CO_2 exchanges in the biosphere, and how are they affected by changes in land use, management and climate? Are European efforts to reduce CO_2 emissions detectable in the atmosphere?

Since January 2004, CarboEurope has mobilised hundreds of European researchers on these questions, crucial from the scientific and the political point of view. Flux towers, flying laboratories, intensive observation campaigns, a new generation of computer models: with a budget of more than €30 million (of which €16 million are provided by the EU) and 90 institutions from 17 participating countries for a duration of five years, CarboEurope is presently the world's largest scientific initiative to address the carbon cycle.

The atmospheric monitoring station at Lutjeward, on the North Sea coast (The Netherlands)

1. What are our objectives?

Quantifying the carbon exchanges of the European continent

How does carbon travel within the vast number of natural and human systems present on the European continent? What is Europe's carbon balance? How is it distributed over space and how does it evolve over time? Where are the carbon stocks and how do they vary?

Europe is far from being a homogeneous surface. Populations are distributed very irregularly, and there are many climatic and geographic sub-regions. With regard to CO_2 fluxes, it is a real mosaic of sources and sinks varying continuously with season, meteorological conditions, land use, management etc. We will determine the sources and sinks of this mosaic and their evolution in time, from the local to the continental scale, with unprecedented accuracy and precision.

Towards a better understanding of what explains these changes, on all possible levels

What mechanisms control the carbon cycle in European ecosystems, and thus determine our mosaic of carbon fluxes? How do human disturbances, in particular climatic and land use changes, influence these mechanisms and therefore the European carbon balance? For example, can increases in growth rate in certain forests (up to 40% or more in 50-year-old forests) be observed due to the increase in atmospheric CO_2?

CarboEurope will provide new answers to these questions for each large system compartment: vegetation (forests, meadows, wetlands, cultivated fields), soils, atmosphere etc. on three levels: local, regional and continental. We will seek in particular to understand:

- the distribution of CO_2 fluxes between the three fundamental causes of exchange: 'breathing' of the biosphere by decomposition of organic material, harvest and fires; assimilation by plants; and combustion of fossil fuels
- the way in which this distribution evolves in time and space, and according to human activities.

Understanding goes beyond a mere description: it means discovering the ecological relationships and the mathematical laws behind all these mechanisms.

Puechabon micrometeorological tower, France

© CarboEurope – JM Ourcival

Providing the EU with the scientific instruments required for the verification of commitments taken on within the Kyoto Protocol

In order to fulfil its commitments for emissions reductions, the EU can take measures to reduce the emissions at source (by means of policies favouring public transport, clean industries, renewable energies, etc.) and to increase the natural sequestration of carbon (in particular with the management of existing forests and with new plantations). Will we be able then to measure the reduction in atmospheric CO_2 that is expected as a result of our efforts? How can we check that the objective, to reduce emissions, has truly been met and that the method used to meet it is truly effective?

CarboEurope will provide the EU with an observation system to detect changes in carbon stocks and fluxes. Moreover, in anticipation of the negotiations for the following commitment period envisaged by the protocol (2013 to 2018), we will lay the foundations for an accurate accounting system for carbon stocks and fluxes to be applied to all countries of the European Union.

2. What do we rely on?

CarboEurope is continuing work on a cluster of European projects on various aspects of the carbon cycle that have been running since 1996. These projects have assured the development of the major measurement networks on which research relies today, and in particular of the flux tower methodology.

These flux towers can be seen as the skeleton of CarboEurope: they constantly, 24 hours a day, measure carbon fluxes, that is, the quantity of CO_2 absorbed or released by a specific measured area, as a function of time of day, weather conditions, season, etc.

That is how we were recently able to uncover a fundamental piece of data: the forests and prairies of the EU naturally absorb significant quantities of carbon, between 7 and 11% of European emissions of CO_2 from fossil fuels. But this key information leads us back to the major unknown factors: what happens to the carbon absorbed by these natural European sinks? Is it stored durably or temporarily? How vulnerable are natural sinks to climate change?

SkyArrow, the world´s smallest certified research aircraft, measures the fluxes of CO_2 and water vapour.

© CarboEurope - Marcus Schumacher

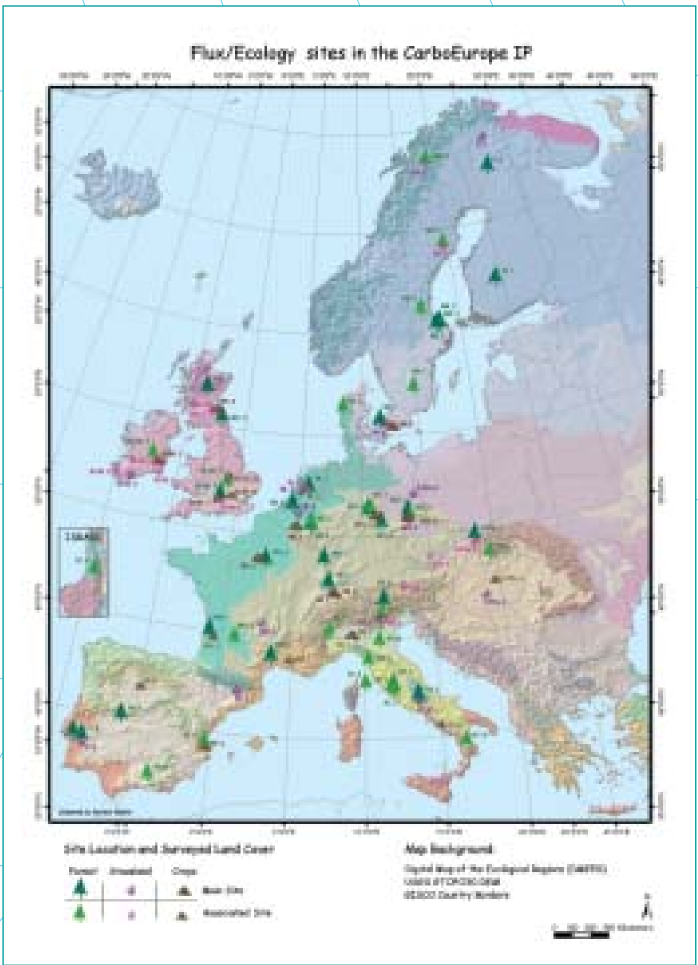
3. How do we proceed?

A multitude of methods and observation sites

The general principle is simple: in order to estimate Europe's carbon balance as accurately as possible, and to better understand the mechanisms that govern it, we need to multiply the number of measurement sites, increase the frequency of our observations, and articulate more coherently our observation and modelling activities. Based on this a great many coordinated actions are implemented:

- A network of around one hundred measurement sites, each equipped with a flux tower.
- A network of a dozen very tall towers, up to 400 m in height, capable of 'observing' fluxes for an entire region (of around 500 km², compared to only 1 km² for classic flux towers) and of measuring the concentrations at different altitudes of the lower atmosphere.
- A network of ground stations in surroundings with very little human interference (on islands or alpine summits) in order to distinguish natural mechanisms from the 'noise' generated by human activity.
- Six aerial bases where various scientific aircraft can carry out regular flights to collect air samples.
- An intensive regional campaign linking all instruments and technologies available to work at the highest possible degree of accuracy. This campaign will take place in France in the Bordeaux region in 2007.
- An army of networked computers and calculators for building models, sharing and integrating data.

These activities will allow us to 'view' the carbon cycle in as clear a manner as possible for the whole continent. One of our biggest problems is that it is very difficult to maintain the focus while increasing the scale.



Fluxes and concentrations

A flux is a quantity of material (in this case CO_2 or carbon), which passes through a unit of area in a unit of time. The fluxes considered here are positive or negative in the vertical direction, depending on whether they are released upwards (emission) or downwards (absorption). For example: +7 g of carbon per day and per square metre.

A **concentration** is the portion of a gas (in this case CO_2) in a mixture (here the air). It is therefore expressed as a relative value, at a given point, and at a specific moment in time: e.g. at the end of the 20th century, the atmosphere contained around 370 ppm (parts per million) of CO_2.

Fluxes are very localised both in space and time: by function of vegetation type, latitude, season and meteorological conditions, they constantly vary from one point to another and from one moment in time to another. By contrast, **atmospheric concentrations are more global and change less**: CO_2 is spread very rapidly through the atmosphere, and concentrations are in a way a global 'smearing' of the cumulative effects of all fluxes on the scale of a whole region. However, there remain a number of differences that are very revealing. For example, levels between 3 and 4 ppm greater on average are observed for the northern hemisphere: this is because the majority of emissions are located there. Concentrations are lower above large forests, which are the principal natural sinks of CO_2.

The larger you make it, the fuzzier it becomes …

The dilemma is a simple one:

- The smaller the thing you study, the clearer you see it, but the less representative it is, as a opposed to:
- The bigger the thing you study, the more you see the overall picture, but the less detailed (the fuzzier) it becomes.

Our grand quest is therefore to see the details increasingly clearly, on ever-increasing scales within the continent of Europe. Since we are unable to cover the whole of Europe with flux towers at one-kilometre intervals, we have to find a trick.

The key word is extrapolate: to provide yourself with methodologies, using as a basis the small number of precise but local observations available, to deduce what is happening on the largest scale while making as few mistakes as possible over space and time.

And the trick, in other words CarboEurope's methodological response, is to integrate the greatest possible diversity of investigation methods: by multiplying data sources, measuring, and calculation techniques, we will be able to handle the maximum possible amount of information and to progressively uncover more and more accurate trends. This is what is known as a 'multiple constraint' approach.

Maintenance work in micrometeorological tower – Hainich national park, Germany

… and the more you integrate, the clearer things will be

This maximum integration strategy poses three considerable scientific challenges:

1) Integration of scales: by associating instruments that 'view' lots of things on a small scale (for example, flux towers) with others that view fewer things on a larger scale (for example, tall towers, planes and satellites), we can compare their respective data and consequently extrapolate with greater confidence.

2) Integration of all the components where exchanges take place – forests, prairies, cultivated land, wetlands, earth, atmosphere, etc., with measurement sites in the main European climates, from the Mediterranean to the Arctic Circle.

3) Integration of modelling techniques:

   - The direct method goes from 'bottom' to 'top'. On the basis of what we already know about the natural processes involved and true fluxes for the small number of points fitted with a tower, we create a simulation of fluxes for an entire territory, then we calculate the supposed effect of these fluxes on the global concentration of CO_2 in the atmosphere. We fine-tune the model until the concentrations measured correspond with those simulated.
   - The inverse method goes from 'top' to 'bottom'. On the basis of variations in atmospheric concentrations measured on the scale of a territory, the model is made to work inside-out, so as to recreate in as localised a manner as possible, the fluxes that are supposed to have caused these variations in concentrations.

While both methods have their strengths and their weaknesses, a combination reveals a picture that is closer to reality. CarboEurope will use both methods for the first time simultaneously in order to produce weekly to monthly maps of the European carbon balance at a 50 x 50 km^2 resolution.

At the atmospheric monitoring station Lutjeward on the North Sea coast (The Netherlands), biweekly-integrated CO_2 samples are taken by absorption of CO_2 in sodium hydroxide

© CarboEurope – Rolf Neubert

The CO_2 map of Europe: how can the gaps be filled in?

One of CarboEurope's most important objectives (i.e., to map the CO_2 fluxes in Europe) is a good illustration of the way in which the 'multiple constraint' approach works to determine the carbon balance of a continent.

What information can we rely on in drawing this map?

1) We have the data from the flux towers: these are continuous measurements but very localised. This produces a map that is almost entirely blank, with only a small number of visible spots here and there but for which we have a large amount of information.

2) At the opposite end of the scale, measurements of concentrations provide information that is representative on a continental scale but tell us very little about the origin of CO_2 measured. On the other hand, small variations in concentrations are caused by variations in fluxes. With concentrations, we see the effect of fluxes mapped out over all of Europe, but the image is so blurry that it merges into almost a single colour that changes little from one day to the next. Variations in this 'colour', even very slight, are a most valuable indication.

3) Lastly, we have satellite data, which is both localised and far-reaching: it provides accurate information for each point of the map and covers the whole of the continent. However, it is still not exactly the flux map that we want (satellites do not know how to view fluxes). Satellite images are instead a series of other maps, detailed and without 'gaps', for phenomena that interact with fluxes: for example, energy exchanges at ground level, or meteorological data.

By superimposing these three groups of observations, we obtain a map that is at the same time full of gaps and full of information. To summarise, it is a series of equations with multiple unknowns, and the secret to solving equations with multiple unknowns, is to place them one after another and to use the 'clues' from one equation to reduce the unknowns in the other equations, and so on. The more diverse the sources of information are, the more the problem is constrained, and the greater the chance of finding the answers. That is where our computer models take the stage: they are wonderful machines for solving complex equations.

Put simply: a very accurate map that is 99% incomplete (from flux towers) + a very blurry complete map (from measurements of concentrations) + accurate maps for data indirectly linked to CO_2 exchanges (from satellites) + good computer models + five years' worth of measurements, calculations, errors and approximations = a wonderful European map of fluxes by the end of CarboEurope!

CARBOOCEAN

Reducing uncertainty about sinks and oceanic sources of carbon

Arctic moon – Trans-Arctic cruise on the Swedish icebreaker Oden

© Toste Tanhua – Leibniz Institute of Marine Sciences at Kiel University, Germany

It is estimated that the oceans currently absorb 20 to 40% annually of all CO_2 emitted into the atmosphere by human activities, resulting in a substantial delay in global warming. But is it closer to 20% or to 40%? With such a margin of uncertainty, it is difficult to precisely predict climate evolution!

What is precisely the quantity of CO_2 absorbed? What are the exchange processes? How is CO_2 transported and stored in the oceans? What are the consequences of CO_2-enrichment for water? How will all this develop into a global environment that is increasingly disrupted by man?

These important questions have involved 40 institutions from 15 countries in a second EU 'integrated research project', CarboOcean, since January 2005. For five years, with an EU contribution of €14.5 million out of a total cost of about €30 million, we will dispatch a comprehensive flotilla of oceanographic ships, cargo ships equipped with measuring instruments, buoys for underwater experiments, etc., to traverse the world's seas in an unprecedented European observation, analysis and modelling effort in this area.

1. What are our objectives?

CarboOcean addresses a goal that is both simple and very ambitious: to know with *two times more precision* the quantity of CO_2 absorbed by the oceans globally, and with *four times more precision* by the Atlantic Ocean and the Southern oceans.

In order to achieve this (encompassing a period from -200 to +200 years) we will attempt to:

- describe in time and space the exchanges of CO_2 between air and sea with unequalled precision, as well as the evolution of these exchanges and multiple related parameters (carbon concentrations in the water, temperature, salinity, biological factors, etc.) in response to increasing atmospheric CO_2. We intend to produce yearly maps of CO_2 concentrations in the North Atlantic, which CarboEurope can then use to better refine the terrestrial CO_2 maps.
- better understand the many physical, chemical and biological processes that govern the exchanges of CO_2 between the atmosphere and the ocean, and between the surface and the deep waters.

In the end, CarboOcean will help answer two crucial questions that climate change challenges society with: 'what will become of us?' and 'how much will it cost us?' By more precisely estimating the quantity of CO_2 absorbed by the oceans, we will in fact be able to predict with greater precision:

- the degree of warming in function of various CO_2 emission scenarios.
- the degree of efficiency of the different types of solutions envisaged (reduction of emissions, adjustment measures, etc.) compared to their cost.

USCGC Healy

© CarboOcean

© Dorothee Bakker - University of East Anglia, UK

2. What do we rely on?

CarboOcean was established after several national and international oceanographic projects, progressively set up over the last ten years, to form a global observation network for marine carbon. This global network, of which CarboOcean is the European contribution, is our main source of data for research on the marine carbon cycle.

Recent studies have thus been able to show that, during the 19th & 20th centuries (i.e. most of the industrial period), approximately 30% of CO_2 from human sources (released by deforestation and the combustion of coal and oil) was absorbed by the oceans, totalling 118 giga-tonnes with an uncertainty of +/- 19 Gt[5].

But while it was possible to acquire this figure with relative precision *for the last two centuries*, we don't know exactly what amounts were *annually* exchanged between air and sea, and the ocean doesn't absorb CO_2 consistently from year to year. Depending on seasons, years, and on still poorly known phenomena, the exchanges vary a lot naturally. We need to better understand this natural variability if we want to characterise the human contribution. This is currently one of the biggest challenges for understanding of the global carbon cycle.

3. How do we proceed?

Just as in CarboEurope, it is by combining as closely as possible the observations, experiments and modelling (aimed at, respectively, the description, the understanding and the predictions) that we will make progress.

Deployment of gravity corer in the Faroe-Shetland Channel during a NO-Clim cruise on board R/V Håkon Mosby

© *Dag Inge Blindheim, Bjerknes Centre for Climate Research, Bergen, Norway*

A CO_2–observation system in the Atlantic

How much carbon from human sources is contained in the oceans? Obtaining these basic data is in itself quite a challenge: not only is the carbon distributed irregularly depending on latitude, currents, seasons etc., but the part linked to human emissions is extremely small compared to the total volume of carbon in the ocean[6]. That is why the only way to obtain an image of its distribution that is not too vague, is to collect data as often and in as many locations as possible.

For approximately a decade, the fine-tuning of automatic CO_2 measuring instruments has enabled us to equip commercial ships and to use their routine voyages to collect data: we call these 'VOS lines', for 'voluntary observing ships'. Along with these ships' itineraries, we can observe variations in concentrations in space and time, owing to the regular operation of these commercial lines. Using computer models, we then try to extrapolate these variations to the entire ocean and to reconstruct, little by little, a map of concentrations.

5) Source: Sabine et. al. 2004

6) About 118 Gt of carbon of human origin out of a total of about 40 000 Gt of carbon in the ocean, i.e. less than 0.3%; while the atmosphere contains about 165 Gt of carbon of human origin out of a total of about 750 Gt, i.e. 22%.

Why is the carbon cycle in the oceans much less known than on land?

- The oceans still remain somewhat unexplored. While progress has, and still is, being made on the land, the oceans remain relatively under-sampled, partly due to their enormous expanse (covering 71% of Earth's surface) but also due to their remoteness. Furthermore, the ocean is far from homogeneous and many factors affect its capacity to store CO_2: for example, the higher the temperature, the less likely water is to dissolve gas (this can be easily observed when taking a fizzy drink out of the fridge in the summer: the more the bottle warms up, the more bubbles appear and release gas). It is this temperature dependence that allows the cold waters of the high latitudes to absorb big amounts of CO_2 from the air, transport it to the bottom ocean, slowly carry it towards the equator, and release it back at the surface in the tropics where they warm up and hence release their CO_2. Due to that:

a) the distribution of carbon in the ocean is very irregular. Depending on currents, temperature, salinity, biological activity, seasons and even inter-annual differences, its concentration varies considerably from one point to another, from one day to another, and from one year to the next. This is in contrast to the atmosphere, which is a very turbulent environment where CO_2 mixes so well that the average concentration over the entire Earth can be found from a number of measurement sites.

b) fluxes (CO_2 exchanges between air and sea) are not at all homogenous. In some locations and at some times, the ocean releases CO_2, and in other locations and at other times, it absorbs it. The total sum of these oceanic sources and sinks provide us with the approximate estimate of 20 to 40% for the oceanic absorption of CO_2 from human sources. What determines their evolution depending on latitudes, seasons, years, etc. is not properly understood.

- The ocean is difficult to access and there is currently no other means besides in situ measurements to obtain data on dissolved CO_2. To this day, no technology enables us to do so from space. Sea missions are always costly and risky and often under difficult circumstances, which limits measuring and experimenting options.

- Time scales in the ocean largely exceed those of human lives. For example, the average duration of a full water mass renewal cycle is in the order of a millennium (under the combined effect of wind, the Coriolis force and changes of seawater density, the ocean is in constant movement around the globe).

- The ocean is a complex system interconnected with continents and the atmosphere, where a great number of closely linked biological, geological and chemical cycles interact over numerous timescales. It is a kind of annoying brain-teaser where, each time something changes, chain reactions and counter-reactions are set in motion, at various speeds and scales. A great number of these chain reactions are still not well understood. The consequences of disruptions caused by human activity are therefore very difficult to quantify and all the more so because not everything goes in the same direction: certain counter-reactions enhance the initial disruption, others dampen it.

To supply our models with more data and to place more accurate limits ('constraints') on them, we also take advantage of a network of measuring stations (providing a 'time-series'). These stations are types of automated buoys that continuously measure the same data as the ships but from the same position. Last but not least, another kind of automated buoy called 'Carioca' (for 'CARbon Interface OCean Atmosphere') can be launched in ocean currents and transmit by satellite continuous surface carbon measurements for more than a year.

VOS lines, time-series and Carioca buoys are more or less the marine equivalent of the terrestrial flux towers network of CarboEurope: a network of measuring points grouped as densely as possible to increase the 'constraints' on computer models.

These various instruments take part in a worldwide observation effort coordinated by UNESCO's Intergovernmental Oceanographic Commission. You can discover the itineraries of VOS lines and the locations of time-series stations throughout the world on http://ioc.unesco.org/ioccp/ObsNet.htm

The major constraint of automated systems is that they only take measurements in surface waters. Yet we also need to know what is going on below the surface. To do so, we will test a new type of instrument, the 'autonomous profiling float', a kind of mini-submarine that collects information at various depths, and subsequently resurfaces to transmit its data via satellite, before moving on to carry out another series of measurements elsewhere.

Mario Hoppema of the Alfred Wegener Institute in Bremerhaven taking a water sample during a research cruise in the Southern Ocean on R.V. Polarstern

Sea campaigns to better understand the process of CO_2 exchange, transport and storage within the oceans

All this descriptive data informs us about the 'what', but not about the 'why' or 'how'. Once the CO_2 is absorbed at the surface, what becomes of it? To solve this question, there is no other solution than to sail off to carry out measurements and samplings that cannot be automated!

Namely, the big questions are: what becomes of the carbon absorbed in the surface waters, how does it penetrate the ocean, and how is it transfered to deep waters? It is, in particular, in the North Atlantic where man-made CO_2 penetrates the deepest, that we hope to find some answers. In fact, we face big disagreements between computer models and the data measured at sea, in terms of the quantity of CO_2 absorbed in the Atlantic as well as in terms of absorption and storage regions.

We seek answers in regions where ocean currents pull surface waters to the bottom, ie. in the polar regions, and several expeditions to the Greenland and Barents Seas are scheduled to track down changes in carbon content to as far as the seafloor.

These expeditions will also enable us to observe any signs of change in global ocean circulation. Sooner or later, atmospheric warming will affect the way in which oceans store and transport heat around the globe, and these changes in currents will have repercussions on CO_2 exchanges that we are not yet able to predict and quantify.

In the Mediterranean and North Sea: learning to combine air, water and earth

Dorothee Bakker (University of East Anglia) watching operations on deck during the first CROZEX cruise on RRS Discovery

There is obviously no separate carbon cycle on the continents, another one in the atmosphere and a third one within the oceans: there is a single cycle withi n the earth's system, made up of various 'compartments' that continuously interact with each other.

CarboOcean studies the flux of carbon in the sea; CarboEurope, that on land. How do we then graduate from this compartmentalised vision to an integrated vision of what really happens in nature? In the North Sea and in the western Mediterranean, a pilot study, to be conducted jointly by the two programmes, will allow the creation of an overall carbon assessment taking into account all the atmospheric, terrestrial and marine components. For the first time from in situ measurements, and not just in the framework of computer simulations, we will attempt to quantify experimentally the sum of fluxes between air, sea and land. The results of this study will be very valuable in improving our ability to combine on a global scale these various components that we study separately.

University of Las Palmas (ES) – Faculty of marine sciences' Department of chemistry. With their ship MSC Gina, *ULPGC-QUIMA is working on a new VOS line from UK to Cape Town.*

© ULPGC-QUIMA

Modelling: to integrate and predict

How to progress from the raw data being output continuously from the numerous instruments deployed at sea, to a series of useable graphs and maps? Exactly as in CarboEurope, the method is captured in a single word: integration, and thus, modelling.

For the oceans, the general principle is the same as for the continents: the more the sources of information (VOS lines, time-series, buoys, remote sensing, etc.) are multiplied and diversified, the more one refines the calculations, the more one reduces the approximations and the more one manages:

- to represent reality accurately
- to predict the future evolution of this reality and the various parameters.

Taking into account many sources of data, the physical (currents, reliefs, temperatures) and the biological complexity of the ocean, modelling operations represent one of the greatest scientific challenges of CarboOcean.

Winch operation - Trans-Arctic cruise on the Swedish icebreaker Oden

© Toste Tanhua, Leibniz Institute of Marine Sciences at Kiel University, Germany

The oceans, a vast dumping ground for atmospheric waste?

Among the rather ingenious and practical solutions devised to face the challenge of climate change, two ideas have emerged; both aim to accelerate the CO2 sequestration by the oceans in order to decrease its concentration in the atmosphere:

1) Boosting the natural absorption capacity of the oceans by fertilising surface waters through the massive spreading of iron, an essential element for the growth of plankton. This phenomenon occurs in a natural way due to the influence of winds: significant plankton blooms are regularly observed when sand from the Sahara, rich in iron, is deposited on the oceans by the Sirocco. However, the excess CO2 temporarily absorbed in this manner may return just as quickly to the atmosphere, and it is not known what the ecological consequences would be of any large-scale artificial fertilisation of the oceans.

2) Directly injecting concentrated CO_2 solution into the ocean depths. CO_2 would be pumped at the emission source into a reaction chamber containing seawater and other reagents to form a CO_2-rich solution, before being transported to sea and injected by pipes directly into the lower levels of the ocean. How would these kinds of artificial CO_2-rich layers spread at the bottom of the ocean behave? What physical, chemical and biological processes would govern the progressive dilution of these CO_2-rich masses, and what would be the consequences?

These types of solutions rely on a very mechanical vision of the planet, linked to the conviction that there are technological answers to all problems and to the old fashioned idea of considering the sea as a large bin, able to digest everything; in this case, our CO_2 waste. We have no idea of their long-term consequences, except that increased acidification would be without any doubt dangerous for ecosystems. Precaution should keep us from using it, but there is an actual risk that some countries will attempt to do it anyway as a means of complying with their commitments to the Kyoto protocol.

That is why CarboOcean will also conduct experiments on a small scale to better understand the effects of these solutions, to be able to argue on equal terms with their potential promoters, and to provide decision-makers with the means of making well-informed decisions.

Research in action

Two examples for the field

1. Pianosa, a scientific treasure island

Sunset at the Pianosa carbon flux tower

© Institute of Biometeorology – National Research Council

From an old abandoned penitentiary on a deserted island off the Tuscan coast, we are endeavouring to gain a better understanding of the carbon cycle in Mediterranean terrestrial ecosystems. How does it contribute to the global carbon cycle, and how does it respond to climate and land-use change? What carbon dioxide exchanges take place between the air, soil and vegetation, according to season and climatic conditions and, above all, how can such exchanges be explained? Some answers to these key questions are being uncovered here in the 'Pianosa lab'[7], an open-air lab for Earth sciences in the Mediterranean, and one of CarboEurope's measuring sites.

Hidden between Corsica and Elba, appressed with heat, fragrant with scrub, Pianosa is simply a deserted island. This former prison island, which covers ten square kilometres, was abandoned when the custodial facility was closed in 1992, but is still very strictly regulated and is essentially off-limits to all visitors. Since our first missions in May 2000, it has become our very own treasure island, home to the scientific wonder of a micro-ecosystem sheltered from all human interference.

On Pianosa, we hope to uncover a few missing pieces from the great puzzle of the global carbon cycle: those corresponding to the Mediterranean scrublands. Climate sciences currently work intensively at the regional level: while current computer models know more or less how to reproduce climate evolution globally, on smaller scale simulations they often represent reality poorly, which highlights gaps in our knowledge.

Three cheers for unexplained phenomena!

How do we look for scientific treasure on an island? This may be summarised in two words: observation and experimentation.

Observation here means the most comprehensive monitoring possible of the island's carbon exchanges. With this aim in mind, we installed a 'flux tower' at the centre of the island to record weather data (pressure, humidity, wind, rainfall, luminosity, etc.), and CO_2 fluxes, i.e. the amount of CO_2 that the island as a whole emits or absorbs over time. Measurements are taken continuously, providing us with CO_2 flux data for the island the whole year round. As a result, we know, for example, that the island is overall a CO_2 sink; it absorbs more carbon from the atmosphere than it emits back.

Experimentation is what helps us to understand what the tower measurements tell us. Although the tower provides us with comprehensive data on the CO_2 exchanges on Pianosa, it reveals nothing about *the origins of these exchanges*, i.e. who emits and how much; who absorbs and how much; when and why? This is like a series of equations for which we know only the result, but not the underlying figures and formulae. But our overarching goal is to be able to model, i.e. to reproduce these equations in a computer program, so as to simulate the behaviour of Mediterranean ecosystems by extrapolations based on the Pianosa scenario.

Therefore, all the time we are not able to say *why* the flux measured by the tower evolves in a certain way, we are unable to simulate it in a model, and to be able to say why, we need to link the reactions of all of the elements involved (trees, soil, meadows, etc.) to seasonal variations, weather change, and so on. In short, we cannot limit ourselves to determining the fluxes and their variations. We must also be able to describe their *causes*. This is the very heart of research, the very purpose of all measurements and experiments carried out in the field.

7) Consortium of nine Italian laboratories and four Italian universities coordinated by IBIMET in Florence (Italy).

Observation and experimentation go hand in hand. What thrills us most is *observing something we do not understand*: this is what advances the frontiers of our knowledge, and therefore, the direction in which research must go, and the questions that have to be investigated. An *unexplained phenomenon* is not a supernatural event to us, but simply *a phenomenon that we do not yet know how to explain!*

Did you know that the soil was respiring? With this 'soil chamber' we are measuring how much CO_2 Pianosa's ground is emitting

© Institute of Biometeorology – National Research Council

Massive carbon emissions in the middle of summer

Speaking of oddities, we have been delighted in Pianosa. A very strange anomaly appeared in the data recorded by the tower after the summer thunderstorms. In general, the flux is positive before rain: the island releases CO_2 into the atmosphere. This is a normal sign of water shortage: during the summer drought plants protect themselves by closing their stomata, which interrupts photosynthesis and therefore the absorption of CO_2. On the other hand, for as long as they are alive, they obviously continue to breathe, that is to say to emit CO_2. When a thunderstorm hits, and during its immediate aftermath, the flux measurement is zero and it is assumed that, having quenched their thirst, the plants will resume their photosynthesis. It is even expected that they will absorb an increased quantity of CO_2 over the subsequent hours.

However, 12 hours after the rainfall, instead of absorbing more CO_2, as would be logical, the island suddenly begins to emit extraordinary quantities: *ten times more* than before the downpour! Then, several days later, the flux slowly returns to a normal level. The first time this occurred, we thought we had a problem with our instruments. But these natural CO_2 emissions after the summer rains were reproduced every single time. This was a tremendous surprise, the significance of which we could not suspect: we calculated that these emissions reduce the total average quantity of CO_2 absorbed each year by Pianosa by 10 to 15%.

Sudden CO_2 emissions, infringing the laws of nature (at least the ones we know about), and distorting our computer models (or rather highlighting their gaps!): Who is involved? Why did this happen each time 12 hours after rainfall, and not 6 hours, or 24 hours? We have to find the culprit; we have to uncover the mechanisms involved. The tower has put us on the right track, now it is time to launch our investigations and seek out clues at the very sites where these CO_2 exchanges are taking place: leaf surfaces, around roots, in the soil, etc.

What effect does water have on the respiration of the soil? What is the contribution of vegetation to the CO_2 fluxes measured, and what plants respired the extra CO_2 that can be found in the air? What becomes of carbon in the soil? Numerous questions such as these will keep our various teams on tenterhooks for many years of treasure hunting to come.

To know more about Pianosa:

http://www.ibimet.cnr.it/biosphere/File_progetti/01_pianosa_lab.htm

2. 'Mesocosms': experimental mini marine worlds to simulate the future

The mesocosms raft

© IFM-GEOMAR

Between microcosms and macrocosms, lie mesocosms! Due to the impossibility of carrying out comparative research on a macroscopic scale (which would require a second Earth for ruthless climate manipulation), but much better than laboratory experiments at scales that are often too microscopic to extrapolate to a global scale, we can experience the reaction of oceans thanks to mesocosms, i.e. literally, 'medium worlds'.

From the Espegrend Marine Biological Station, near Bergen in Norway, we are working in the middle of a fjord on a very special raft. On the raft, a wooden cabin houses a mini laboratory to which nine large plastic tents, full of tubes and sensors, are linked and immersed all around. As with icebergs, the immersed part is the largest: carefully wrapped in plastic that only allows light to pass through, a 10-metre water column, which is well separated from the rest of the fjord but nevertheless *in situ*, extends under these tents. Together this set-up forms our mesocosms, on a scale that can be easily manipulated by humans, and yet huge with regards to its millions of small inhabitants: the plankton we aim to study.

The air is artificially maintained at 370 ppm of CO_2 (i.e., the current ambient concentration) in the first three mesocosms, 750 ppm in the three others (concentration expected by 2100 if emissions continue at their current rate), and 1150 ppm in the last three ones (expected concentrations by 2150). In this way, we will be better able to observe what is likely to happen in reality by 2100 and 2150.

Ocean CO_2 uptake: a curse for marine life?

The principle of the experiment is simple. On the first day, we introduce a cocktail of nutrients into each mesocosm to induce a phytoplankton 'bloom' and then we study the effects on the largest number of parameters possible over five weeks. We then compare the three types of mesocosms.

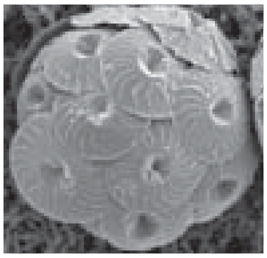
The results of our mesocosm experiments confirm what we have seen in previous laboratory experiments: what comes as a blessing for our climate system, ie. the uptake of large amounts of man-made CO_2 by the ocean, can become a curse for marine life.

Calcium carbonate is the predominant material used by many marine organisms to produce their skeletal structures. Corals, snails, mussels, sea urchins and sea stars are marine calcifiers we are all familiar with. But as seawater acidity increases with the uptake of CO_2, the concentration of carbonate ions in seawater decreases making it energetically more costly for calcifying organisms to form their calcareous structures.

Two times less calcification in mescocosms artificially enriched in CO_2

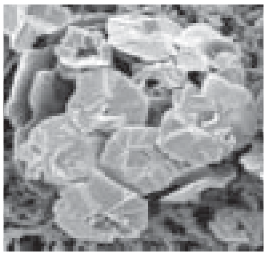
In our mesocosms we do not grow mussels or urchins, but a plankton species called 'coccolithophores', single-celled microalgae covered with a dense layer of calcite platelets (coccoliths). Invisible to the naked eye due to their minuscule size (a hundred times smaller than the head of a needle), they are nevertheless the most productive calcifying organisms on our planet.

In our mesocosms, coccolithophore calcification at high CO_2 levels was reduced to *almost half* of that at low CO_2 conditions! Laboratory experiments show increased numbers of coccolith malformations and incomplete cell coverings of coccolithophores grown in high CO_2 conditions. These two pictures show very clearly the level of disturbance:



With current CO_2 concentration

© M. Geisen, AWI



With CO_2 concentration expected in 2100

© M. Geisen, AWI

But while these results alarm us about possible negative effects of ocean acidification, they leave us with more questions than answers. What does reduced calcification and increased malformation mean to the ecological fitness of the coccolithophores? If incapable to cope with ocean acidification, will coccolithophores be replaced by other non-calcifying groups? What will this mean for the ecosystem?

Marine ecosystems are likely to become more vulnerable

Other questions relate to the validity of our findings. While there is an immense genetic diversity in the marine plankton, even within a single species, for statistical reasons we are likely to end up with those genetic strains in our experiments which are most abundant in the present ocean. Are any of the strains presently in the ocean, but less abundant, better able to deal with high CO_2 conditions? We also have to keep in mind, that for practical reasons, we typically apply relatively abrupt CO_2 enrichments in our experiments. In reality, it will take 100 years to reach the high CO_2 levels applied in our experiments. For slow growing organisms like corals, this may not make much of a difference, but coccolithophores, with lifespans of a day or two, can go through up to 30,000 generations in 100 years. Is this sufficient time to get adapted to a more acidic ocean?

It is too early to predict what the consequences of ocean acidification will be. It is probably safe to say, however, that marine ecosystems are likely to become less robust and hence more vulnerable to other environmental impacts, such as climate change, fisheries and pollution. Reducing CO_2 emissions to the atmosphere appears to be the only practical way to minimize the risk of irreversible damages to marine ecosystems. Clearly, ocean acidification is a powerful reason, in addition to that of climate change, to act quickly on developing alternative energy strategies.

If you are interested in the 'mococosm experiment':

- **PDF description:** **http://www.carboocean.org/Menue/News/Mesocosm.pdf**
- **Experiment website:** **http://spectrum.ifm.uni-kiel.de/peece/**
- **Mainz group weblog:** **http://www.atmosphere.mpg.de/enid/Diaries_from_the_field/CarboOcean_4ps.html**

Sincere thanks to Maria-Francesca Cotrufo and Ulf Riebesell for their welcome in Pianosa and Espegrend respectively.

CarboSchools Educational booklet

English version December 2005

Free quotation and reproduction allowed for educational and non-profit purposes.

DG JRC coordination: Günther Seufert

Text, coordination: Philippe Saugier (saugier@netcourrier.com)

Corrections in English and creation of the Carboschools logo: Rona Thompson

Reviewing:
Aline Chipaux, Annette Freibauer, Marion Gehlen, Nadine Gobron, Giacomo Grassi, Kjeld Hansen, Christoph Heinze, Alexander Knohl, Thierry Lerévérend, Mats Olsson, Ulf Riebesell, Michael Schallies, Bernard Saugier, Ingunn Skjelvan, Rona Thompson, Elmar Uherek, Andrea Volbers

This publication is funded by the European Commission DG Joint Research Centre, CarboEurope and CarboOcean Integrated Projects. The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the European Commission, the JRC functions as a reference centre of science and technology for the Union. Close to the policy-making process, it serves the common interest of the Member States, while being independent of special interests, whether private or national.

More information on:

www.carboschools.org
www.carboeurope.org
www.carboocean.org
http://ies.jrc.cec.eu.int/fp6ccu.html

On board the sailing ship Carola*, students from the Staedtische Gymnasium in Bad Segeberg, Germany, are preparing for their journey to sample the marine fauna and flora in the Baltic Sea as part of the NaT-Working project of the Leibniz Institute of Marine Sciences IFM-GEOMAR in Kiel, Germany.*
© A. Antia

We, several hundred scientists within CarboEurope and CarboOcean (two EU research projects on climate change running between 2004 and 2009), are involved in the great quest of progressing knowledge of the Earth system and how it is disrupted by mankind through the release of massive amounts of greenhouse gases into the atmosphere.

Through the CarboSchools initiative, we wish to promote partnership projects between scientists and secondary school teachers in order to raise young people's awareness of the local and global consequences of climate change, to encourage them to discover scientific research and to act locally to reduce emissions of greenhouse gases.

Proposed as a reference resource for teachers, as well as for anyone else interested in the topic, this booklet attempts to give an overview of global change research: What are the key questions? How do we acquire new knowledge through scientific research? What is the current contribution of European research to the pressing carbon cycle question?

Join us in a great scientific adventure, share our fascination for the planet, and imagine solutions for the future!