THE CLIMATE IN OUR HANDS

Climate Models

A teacher's handbook for high school

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Classroom tests
Many thanks to the teachers and students who tested the activities and gave us their feedback! Their work has involved over 100 young people across Europe. We hope there will be many more!

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Information
English, French and Spanish versions are already available. Information on the work of the Office for Climate Education, as well as extra copies of this document can be obtained at the following address:

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GRANT AGREEMENT
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EARTH SYSTEM MODELS FOR THE FUTURE

ESM2025 is an ambitious European project co-ordinated by Météo-France – Centre National de Recherches Météorologiques. ESM2025 relies on an international team of 19 European research institutes and an Australian university. ESM2025 strengths international collaboration in Earth system modelling by bringing together five European ESMs in one project: the ESMs of the Centre National de Recherches Météorologiques (CNRM), the Institut Pierre-Simon Laplace (IPSL) and the Max Planck Institute for Meteorology (MPI-M), as well as the Norwegian Earth System Model (NorESM) and the United Kingdom Earth System Model (UKESM).

The project's aim is to develop the next generation of Earth System Models (ESMs) which will provide relevant climate simulations for the deployment of ambitious and realistic mitigation and adaptation strategies. With an improved set of climate projections, ESM2025 will support European climate services and IPCC assessments. Relying on key stakeholder communities, ESM2025 will provide relevant scientific knowledge and guidance, which will help establish strong policies needed for societal transformations that will lead to a future net-zero carbon and climate-resilient society.

Finally, ESM2025 also wants to specifically target the younger generation by creating educational and pedagogical resources, to empower young European citizens to increase the general public's understanding of climate change and related topics and to foster the societal transformations needed to achieve the goals of the Paris Agreement.

United Nations
Educational, Scientific and
Cultural Organization

Office for
Climate
Education

UNDER THE AUSPICES OF UNESCO
AND THE FOUNDATION LA MAIN À LA PÂTE

THE OFFICE FOR CLIMATE EDUCATION

Created in 2018 on the initiative of *La main à la pâte* foundation and the scientific community, the Office for Climate Education (OCE) aims to organize strong international cooperation between scientific bodies, NGOs and educational institutions. This cooperation is essential to educate present and future generations about climate change.

The mission of OCE and its partners is to promote climate change education worldwide through high-quality teaching resources, professional development courses and design and implementation of national and international operational projects.

In 2020, the Office for Climate Education became a category 2 center under the auspices of UNESCO to promote climate change education internationally, focusing in particular on emerging countries.

As part of the ESM2025 project, OCE is developing free, multilingual, free-licensed resources that have been tested in the classroom: multimedia animations, handbooks for teachers, serious games and training guides for trainers. The OCE also organises, together with Météo-France, training courses for teachers and trainers from all over Europe (Climate Education Summer University) and Climathons.

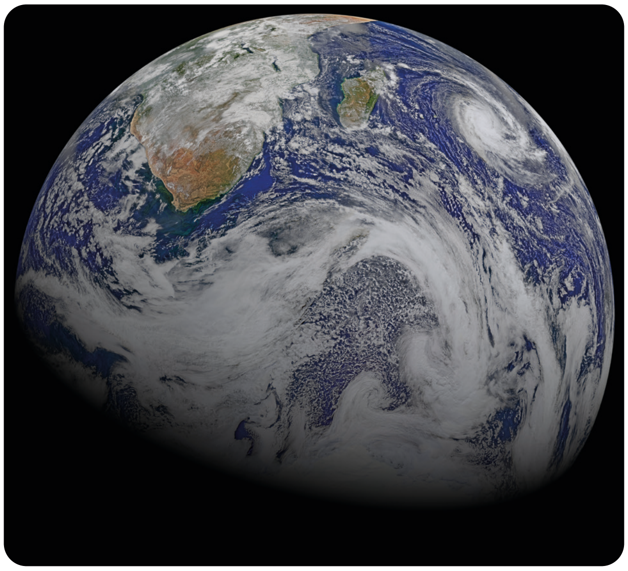
CONTENTS

INTRODUCTION

Content of this guide

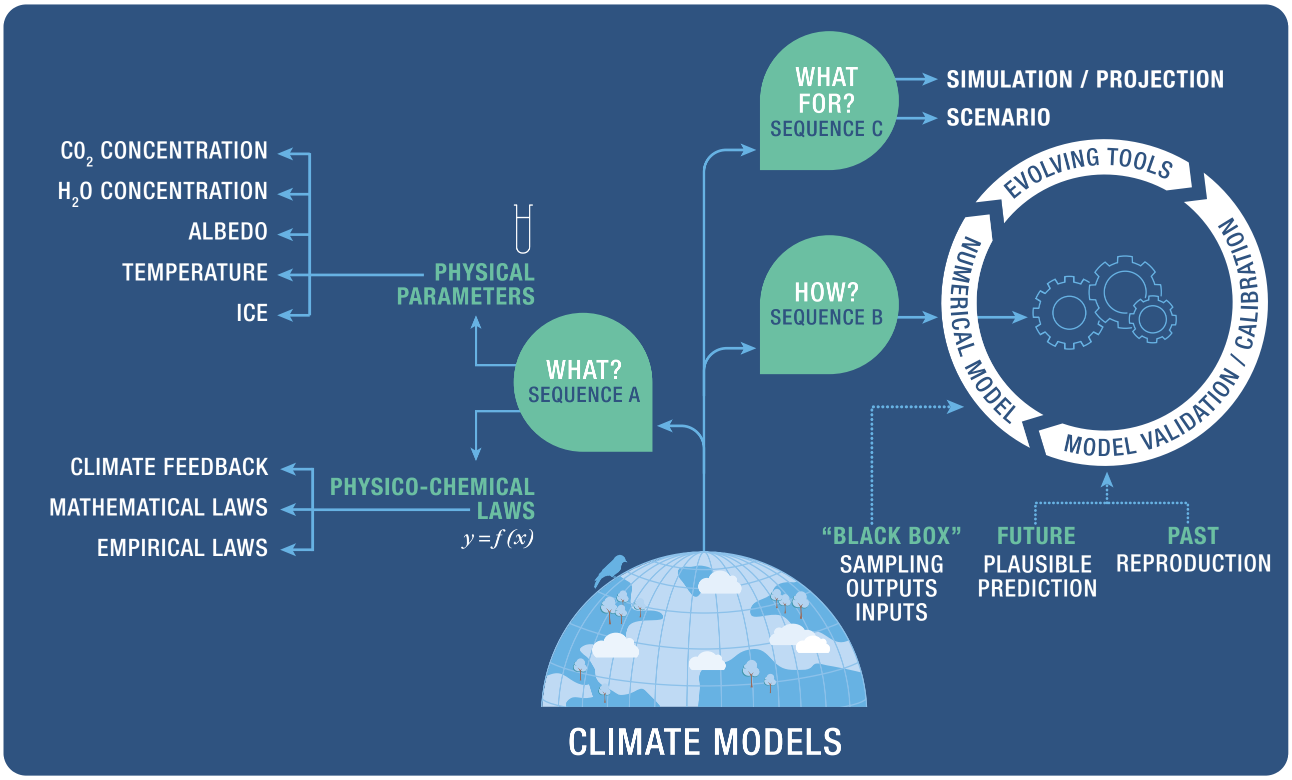
LEARNING OUTCOMES OF THE SET OF ACTIVITIES

Learners will be able to:
- Differentiate between weather and climate.
- List some parameters studied by climate scientists and evidence that climate is changing.
- Demonstrate that the current global warming trend is due to human activities and leads to many climate perturbations.
- Understand the complexity of the Earth's climate system.
- Explain the link between greenhouse gas emissions, greenhouse gas concentrations in the atmosphere and global climate changes by using a basic numerical model.
- Understand the projections assessed by IPCC.
- Differentiate between adaptation and mitigation, as well as between co-benefits and trade-offs with regard to the Sustainable Development Goals (SDGs).



Satellite view of the Earth with its cloud layer, one of the fundamental components of the Earth's climate system.

CONCEPTS COVERED IN THIS HANDBOOK



LESSON PLAN: THREE PROGRESSIVE AND COMPLEMENTARY TEACHING UNITS

WHAT?

SEQUENCE A
THE EARTH'S CLIMATE SYSTEM

1 **The components of the climate system**

The students review the evidence that climate change is happening, and they list all physical parameters that should be studied when tackling climate change (ice extent/thickness, precipitation, CO_2 concentration in the atmosphere/the ocean, surface temperature, albedo, greenhouse gases, etc.)

2 **The laws of physics**

The students carry out a few experiments involving some of the parameters listed above in order to understand that each parameter depends on (one can also say 'is a function of') several others. This interdependence can be thoroughly described.

3 **Modelling the climate using a board game**

The students establish a link between climatic environments and physical mechanisms.

HOW?

SEQUENCE B
CLIMATE MODELLING

4 **Models to represent reality**

The students discover the concepts of input, sampling and output. They take and modify a Python code to confirm that changing the inputs impacts the outputs.

5 **Climate models are evolving**

They understand the analogy between the evolution of a video game and the evolution of a model.

6 **Validation of numerical models**

The students discover how the reliability of digital models can be assessed: reproduction of past events or prediction of plausible future events.

WHAT FOR?

SEQUENCE C
CLIMATE MODELS TO PREDICT FUTURE

7 **Building scenarios and observing model responses**

The cows' milk production model: the students make choices to build and observe projections.

8 **Urban Heat Islands (UHI)**

Using a multimedia animation, the students differentiate between mitigation and adaptation scenarios. They also differentiate between co-benefits and trade-offs regarding the SDGs.

9 **Futures literacy**

By using one of the scenarios studied in the last lesson and applying it to their own city, students create desirable and realistic stories of the future.

TABLE OF COMPETENCES USED IN THIS MANUAL (BASED ON THE GREENCOMP [1])

DOMAIN 1 EMBODYING SUSTAINABILITY VALUES

GREENCOMP	DESCRIPTION	ACTIVITIES
1.1 Valuing sustainability	To reflect on personal values; identify and explain how values vary among people and over time, while critically evaluating how they align with sustainability values. *E.g.:* Plan the impact of a weekend plane trip.	7
1.2 Supporting fairness	To support equity and justice for current and future generations and learn from previous generations for sustainability. *E.g.:* Initiatives against deforestation	9
1.3 Promoting nature	To acknowledge that humans are part of nature; and to respect the needs and rights of other species and of nature itself in order to restore and regenerate healthy and resilient ecosystems. *E.g.:* Using educational resources to understand how nature works.	1

DOMAIN 2 EMBRACING COMPLEXITY IN SUSTAINABILITY

GREENCOMP	DESCRIPTION	ACTIVITIES
2.1 Systems thinking	To approach a sustainability problem from all sides; to consider time, space and context in order to understand how elements interact within and between systems. *E.g.:* Biofuel production and increased competition for land.	1 - 5 - 6
2.2 Critical thinking	To assess information and arguments, identify assumptions, challenge the status quo, and reflect on how personal, social and cultural backgrounds influence thinking and conclusions. *E.g.:* Critical understanding of the issues involved in mass sales of electric cars.	3 - 6
2.3 Problem framing	To formulate current or potential challenges as a sustainability problem in terms of difficulty, people involved, time and geographical scope, in order to identify suitable approaches to anticipating and preventing problems, and to mitigating and adapting to already existing problems. *E.g.:* Controversy mapping-type activity.	2 - 5

DOMAIN 3 ENVISIONING SUSTAINABLE FUTURES

GREENCOMP	DESCRIPTION	ACTIVITIES
3.1 Futures literacy	To envision alternative sustainable futures by imagining and developing alternative scenarios and identifying the steps needed to achieve a preferred sustainable future. *E.g.:* Writing workshop activity.	9
3.2 Adaptability	To manage transitions and challenges in complex sustainability situations and make decisions related to the future in the face of uncertainty, ambiguity and risk. *E.g.:* Proposals for energy-saving measures in buildings.	8 - 6
3.3 Exploratory thinking	To adopt a relational way of thinking by exploring and linking different disciplines, using creativity and experimentation with novel ideas or methods. *E.g.:* Imagining circular consumption patterns on a school scale.	4

DOMAIN 4 ACTING FOR SUSTAINABILITY

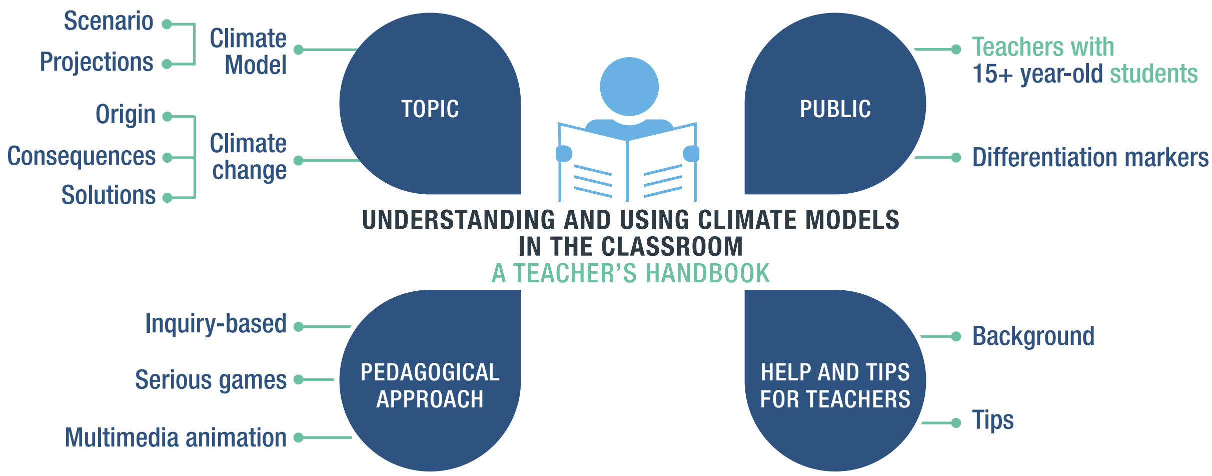
GREENCOMP	DESCRIPTION	ACTIVITIES
4.1 Political agency	To navigate the political system, identify political responsibility and accountability for unsustainable behaviour, and demand effective policies for sustainability. *E.g.:* Students engagement.	8
4.2 Collective action	To act for change in collaboration with others. *E.g.:* Take part in a participatory science project, *e.g.* 'Who protects the oaks?' project [2].	9
4.3 Individual initiative	To identify their own potential for sustainability and to actively contribute to improving prospects for the community and the planet. *E.g.:* Increase the proportion of trips made by bicycle.	8

1 European Commission, Joint Research Centre, GreenComp, the European sustainability competence framework, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2760/13286

2 https://sites.google.com/view/oakbodyguards/home/english_1

Methodology of this guide

HOW TO USE THIS GUIDE TO PREPARE A LESSON?



HOW ARE ACTIVITIES ORGANIZED?

The DURATION includes preparation time (for you) and activity time (with your students)

The AGE GROUP is given as a rough guideline

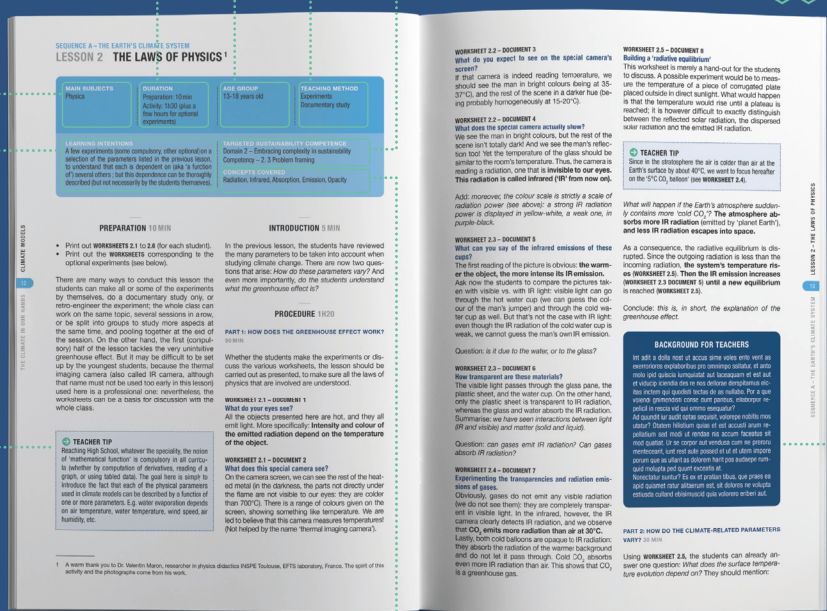
PEDAGOGICAL METHOD(S) proposed in this activity

The main sustainability competence your students will acquire through this activity (GREENCOMP)

Quick overview of the MAIN TOPIC

The main LEARNING OUTCOMES (knowledge and skills) your students will acquire during this lesson

The TEACHER TIP section gives you some advice on the methodology, or some specific points on which to focus



List of the CONCEPTS related to this activity

Some of the lessons have a BACKGROUND FOR TEACHERS' box, with information about the specific topic of the lesson

LEVELS

The targeted age group is 15+ year-old students (high school). Note that each activity has been tested in classroom of this specific age-group during the calibration phase of the lesson plan. Of course, this does not mean that you cannot conduct the lesson plan with another age group, but it gives you an idea of the ability level of the activities involved.

LEVEL OF DOCUMENT DIFFICULTY

Most of the lessons include a variety of documents with different levels of difficulty. Some documents are easier to understand, while others are designed for more advanced students. Keep in mind that **this is only a recommendation:** you are the only one able to choose the documents most suitable for the level of your class. The different levels are:

How to teach climate change?

The purpose of this teacher's handbook is to help teachers propose activities that allow students to actively participate through questioning, experimentation, observation, trial and error, debate and the implementation of local, concrete solutions to address climate change issues. This 'active learning' can take different forms. **The two approaches that we strongly promote throughout this handbook are inquiry-based learning and project-based learning.**

WHAT IS INQUIRY-BASED LEARNING?

While it would be oversimplifying to use a fixed model of inquiry-based learning, the approach generally has three phases:

1. **Questioning:** initiated by the teacher or students to help formulate hypotheses.
2. **Formulating a hypothesis and conducting research:** carrying out experiments or investigations, making observations, using models, analysing documents.
3. **Structuring and constructing knowledge** (discussion on information/data collected or produced): the purpose of this phase is to draw some broad conclusions, which in turn can lead to more questioning, more research, etc.

WHAT IS PROJECT-BASED LEARNING?

Project-based learning is a full-fledged method of active learning. First described in the early 20th century (initially by John Dewey, who also introduced inquiry-based learning), it was long confined to primary education before gradually spreading to secondary and higher education.

Project-based learning has evolved as a method of instruction that addresses core content through rigorous, relevant hands-on learning. Projects are typically framed with open questions that push students to investigate, research or construct their own solutions. For example: *How can we reduce our school's carbon footprint?*

The main benefits of project-based learning are that **students are learning within contexts that are meaningful to them.** Moreover, the practical aspect of the project usually motivates them even further. They acquire cross-functional skills, such as decision-making or planning skills. They realise that making errors and failed attempts are part of the learning process, and that cooperating is the key to success. Finally, the outcome of the project can inspire other classes, families and the community as a whole.

WHY USE AN INTERDISCIPLINARY APPROACH IN CLIMATE EDUCATION?

While 'traditional' scientific disciplines are essential to understanding the physical and biogeochemical mechanisms of climate change and its consequences, the humanities and social sciences allow students to understand the social, political and economic issues of sustainable development and climate justice. The arts and language disciplines are also valuable for encouraging students to express their feelings and engage with certain forms of action (such as public awareness). Disciplines such as engineering, agriculture and technology are of use in developing practical solutions. **Teaching climate change means taking into consideration all its dimensions, and this requires a interdisciplinary approach.**

WHY USE POSITIVE THINKING IN CLIMATE EDUCATION ?

Worldwide, climate change issues and projections of futures under climate stress have led to a strong mobilisation of young people, often marked by strong emotions and reactions, especially amongst the youngest, who talk of 'civilisation collapse' or the 'end of our planet'. The term 'eco-anxiety' has been coined to describe this cimate anguish (Glenn Albrecht).

We propose here to take account of and mitigate this anxiety by:

- **Raising awareness on climate change:** not denying its seriousness and challenging aspects, but focusing on scientific facts instead of on catastrophic speech (see Sequence A – The Earth's climate system). This approach is important, but not sufficient, considering the high emotional charge of climate change consequences.

- Encouraging students to **acknowledge their emotions and feelings** and to connect with others rather than remain in isolation (see lesson D2 in the 'The climate in our hands' series 'Climate Change and Land').

- Realising that it is necessary, and still possible, **to act at different levels** – individual, school, community, etc. (see Sequence C - Climate models to predict future).

- Encouraging students to take part in **a concrete plan of action,** through projects (see the 'We act' section in the 'The climate in our hands' series 'Ocean and Cryosphere' and 'Climate Change and Land') that will lead to mitigation or adaptation.

LESSON 1 THE COMPONENTS OF THE CLIMATE SYSTEM

MAIN SUBJECTS
Physics
Natural Sciences
Geography

DURATION
Preparation: 10 min
Activity: 2h

AGE GROUP
13-18 years old

TEACHING METHOD
Documentary analysis

LEARNING OUTCOMES
Students review the difference between climate and weather. Scientists use physical parameters to describe climate (e.g. temperature, precipitation). Each specialist studies a set of physical parameters. These physical parameters must be studied simultaneously when studying climate (e.g. H_2O, CO_2, temperature, albedo, greenhouse gases, etc.). Students study the evolution of these parameters, which are all – at different scales – markers of a warming world.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2.1 Systems thinking

CONCEPTS COVERED
Weather, climate, parameters, climate change, extreme events, reliability

PREPARATION 10 MIN

- Print out **WORKSHEET 1.1** (for each student). If possible, print it out in A3 format to give students more space for their answers.
- Print out **WORKSHEETS 1.2 TO 1.6** (one worksheet for each group of students).
- Optional: you can print out the **WORKSHEET 1.1, CORRECTED VERSION,** so that the student have all the right scientific elements to remember.

INTRODUCTION 30 MIN

To reactivate the concepts of climate and weather with your students, you can start this sequence in a fun way, by watching the 'Climate Elvis' video, a song by Josh Willis.

WATCH THE VIDEO ↗

Case 1: If you live in a region of the world that has a seasonal climate (summer/winter or wet/dry): Start by asking the students: *How are you dressed today? What about last week, last month, or during the last holidays? What guides your choice of clothes/equipment?* They will probably state that: it depends on whether the day is sunny or rainy, cold or warm; that it depends on the weather. *What about different regions of the world? How can you distinguish climate from weather?*

Case 2: If you live in a place without a seasonal climate: *Is the weather the same all year round? Is the weather the same as everywhere else in the world? Do other regions have the same temperature and rainfall? How can you distinguish climate from weather?*

1. To remind the students of the difference between weather and climate, read the suggested sentences. The students must choose and justify whether the sentences are about climate or weather (for each sentence, you'll find the correct category in brackets).

'Look out of the window, the sun is now shining through the clouds and it's beautiful.' (WEATHER)

'My grandmother tells me that when she was little, there was always snow in winter. Sometimes it even kept her from going to school.' (CLIMATE)

'It's going to be very windy this weekend. We could try out our new kite.' (WEATHER)

'My Australian friend had a water fight at his school; it's always hot there!' (CLIMATE)

'It rained on May 8^{th}.' (WEATHER)

2. Ask your students to explain the difference between climate and weather (look at the concepts and their definitions in the glossary). **The climate tells you which clothes to buy and the weather tells you what to wear!**

Students work in groups: they play the role of 'Botanists' and fill in the boxes corresponding to their documents.

PROCEDURE 1 HOUR

1. From the previous activity, students should have learned that the weather may change quickly. Ask: *Do you think that the climate has changed? Rapidly or not? How can we prove this knowing that climate occurs over a long period of time?* The students will have to conduct a documentary analysis.

2. Introduce **WORKSHEET 1.1** and give a copy to each student. The worksheet has to be filled out at the end of the lesson.

3. Divide the students into groups of no more than four, and explain that each group will play the role of a scientific expert (oceanographers, glaciologists, botanists, etc.). Distribute **WORKSHEETS 1.2** to **1.6** (one per group). Using the documents, the students will have to complete the cards corresponding to their expertise and put them on the document 'The components of the climate system'. They will have to find the parameters and time/spatial scales studied in their specialty and briefly explain the evidence for climate change.

4. After each group has analysed and discussed its documents, one member of each group completes the boxes corresponding to its scientific specialty on the whiteboard or presents their findings to the other groups orally, so that each student can complete **WORKSHEET 1.1**.

BACKGROUND FOR TEACHERS

In this lesson, the time scale can hinder students' understanding. Indeed, young (and old!) people tend to only perceive events that are directly related to their personal lives. However, the changes caused by global warming are often gradual, and can only be observed over long periods of time (30 years, 100 years or more). These changes may therefore be difficult to perceive. Here are a few tips to help you:

~ Start with concrete examples and progressively introduce changes of scale;
~ Use examples that are familiar to the students (current events and/or examples the students think of);
~ Analogies with everyday objects can be useful to familiarise students with orders of magnitude (example **WORKSHEET 1.2, DOCUMENT 1**: compare the 120 years on the x-axis with the average lifespan of a human being in your country).

WRAP-UP 30 MIN

Conclude that scientists use **physical parameters and bio-geo-chemical parameters** to study the weather or climate: temperature (°C or °F), relative humidity (% water vapour in air), precipitation (mm of water per hour), concentration of greenhouse gases: H_2O, CO_2, CH_4 (ppm), aerosols or pollutant concentration (µg/m^3), ice (volume in Gigatons, or surface in km^2), etc.

The physical parameters are the same in both weather and climate; except that some parameters with **slow evolution** (e.g. surface of ice) are more relevant for **climate**. On the other hand, parameters with **short time scales** (like precipitations) are more relevant to the study of **weather**.

Each specialist studies a **set of physical parameters** (e.g. the glaciologist looks at the ice volume and the albedo). This can be illustrated by watching 'The Earth's Climate system' CLIM video, in which Fiona O'Connor (MET Office Science, United Kingdom) explains how she takes into account different parameters (water vapour, liquid water, methane concentration) to study atmospheric chemistry.

WATCH THE VIDEO ↗

These physical parameters have to be considered **simultaneously when studying climate** (and when tackling climate change!). They can be used to describe trends on a global or smaller (e.g. regional) scale. **In any case, meteorologists and climatologists have to study a set of parameters simultaneously in order to describe how the climate has evolved.**

Conclude by pointing out that just as the weather varies, **climate has changed over the past century: this is climate change.** There is solid scientific evidence that the climate has changed in various regions of the world: global temperature and sea level have increased, glaciers and sea ice are melting, flowers bloom earlier, droughts and heavy rainfalls are more frequent, etc.

You can also mention the **IPCC as one of the most reliable sources of information** on climate change.

WORKSHEET 1.1

WORKSHEET 1.1 CARDS

OCEANOGRAPHERS
DOCUMENT 1
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

OCEANOGRAPHERS
DOCUMENT 2
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

HYDROLOGISTS
DOCUMENT 7
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

ATMOSPHERIC SCIENTISTS
DOCUMENT 3
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

ATMOSPHERIC SCIENTISTS
DOCUMENT 4
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

HYDROLOGISTS
DOCUMENT 8
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

GLACIOLOGISTS
DOCUMENT 5
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

GLACIOLOGISTS
DOCUMENT 6
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

ECOLOGISTS
DOCUMENT 9
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

ECOLOGISTS
DOCUMENT 10
Physical parameters:
Scale (local, global, regional?):
Evidence of climate change:

WORKSHEET 1.1 CORRECTED VERSION

OCEANOGRAPHERS
DOCUMENT 1

Physical parameters: sea level (mm).

Scale: global scale.

Evidence of climate change: since 1900, sea level has risen by approximately 200 mm in average globally. The rise in sea level is very regular over time.

OCEANOGRAPHERS
DOCUMENT 2

Physical parameters: temperature anomalies (°C).

Scale: global scale.

Evidence of climate change: the difference between the average temperature in 2022 and the average temperature over the period 1880-2010 is positive overall. This is an indication of warming since the end of the 19th century. Warming is more pronounced over the continents and at higher latitudes.

ATMOSPHERIC SCIENTISTS
DOCUMENT 3

Physical parameters: atmospheric CO_2 concentration (ppm).

Scale: global scale.

Evidence of climate change: the atmospheric CO_2 concentration has increased since the industrial revolution. Large amounts of CO_2 have been emitted into the atmosphere due to human activities. This additional atmospheric CO_2 increases the greenhouse effect and therefore contributes to global warming.

ATMOSPHERIC SCIENTISTS
DOCUMENT 4

Physical parameters: temperature anomaly during the summer 2023 (°C).

Scale: regional scale.

Evidence of climate change: temperature anomalies are positive for most of Europe in the summer of 2023 (for example, between +1°C and +3°C in France, Spain and Switzerland, several of these countries having experienced heatwaves). This indicates that the temperatures observed are warmer than the reference temperatures: this is climate change.

GLACIOLOGISTS
DOCUMENT 5

Physical parameters: qualitative data from field observations of the glacier, size of the cryosphere (tons of ice).

Scale: a global conclusion can be drawn from local observations in many parts of the world (ice sheets in Alaska, Antarctica, Greenland).

Evidence of climate change: ice sheets are shrinking all over the planet: each one is losing gigatons of continental ice every year. This is a sign of global warming and rising sea levels.

GLACIOLOGISTS
DOCUMENT 6

Physical parameters: Arctic sea ice area (million km^2), sea ice albedo index (million km^2).

Scale: regional scale (Arctic).

Evidence of climate change: Arctic sea ice extent has been declining since at least 1979. The albedo for the entire Arctic region is declining as well. Global warming is responsible for the melting of sea ice, which reduces the albedo. As a result, the Arctic ocean absorbs more solar radiation.

HYDROLOGISTS
DOCUMENT 7

Physical parameters: trends in precipitation over land between 1951 and 2010 (% per decade).

Scale: global scale.

Evidence of climate change: since 1951, rainfall has increased in certain regions, such as Northern Europe and Eastern USA (e.g. +4% per decade in the UK between 1951 and 2010). On the other hand, there is less rainfall around the Mediterranean, in West Africa or in South-East Asia (-10% per decade in Senegal, e.g.). Climate change is therefore having an impact on rainfall patterns, which have changed all over the planet, and very unevenly.

HYDROLOGISTS
DOCUMENT 8

Physical parameters: temperature anomalies (°C) over land and over ocean since 1880.

Scale: global scale.

Evidence of climate change: temperature anomalies over land have risen by almost 2°C since 1880 on land, confirming global warming. This is more pronounced over continents than over oceans.

ECOLOGISTS
DOCUMENT 9

Physical parameters: carbon flows (arrows, without unit) and reservoirs (figures, % of carbon stored).

Scale: regional and global scale.

Evidence of climate change: With climate change, precipitation patterns are changing all over the planet. This is affecting soils and plant activity: carbon flows and reservoirs are being modified in many ecosystems. This is just one example of how human activities are changing the Earth's carbon cycle.

ECOLOGISTS
DOCUMENT 10

Physical parameters: blossoming period, number of extreme events.

Scale: local and global scales.

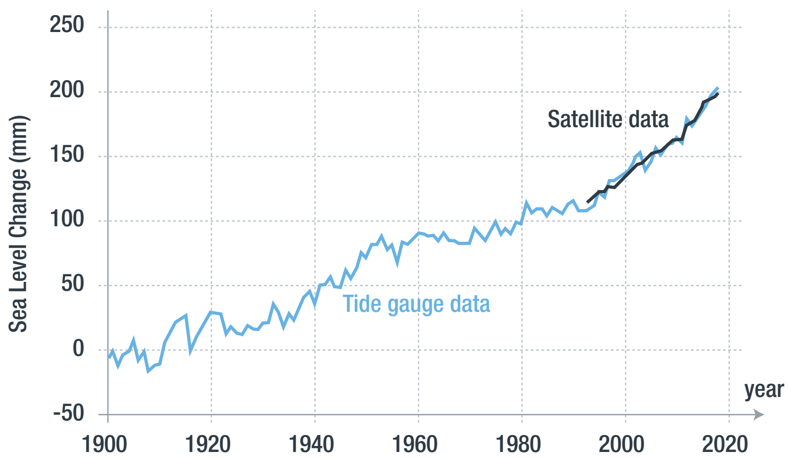
Evidence of climate change: the date of the beginning of Japanese cherry tree blossoming has changed from late April in 1550 to early April in the 2000s. Global warming causes plants to flower earlier.

The number of extreme events has been rising steadily since 1960. Their frequency and intensity are increasing with climate change, causing significant damage to the environment and plants, among other things.

OCEANOGRAPHERS

→ **You are scientists specializing in the oceans and you have seen how sea levels have changed over the last century.**

DOCUMENT 1. SEA LEVEL VARIATIONS SINCE 1900



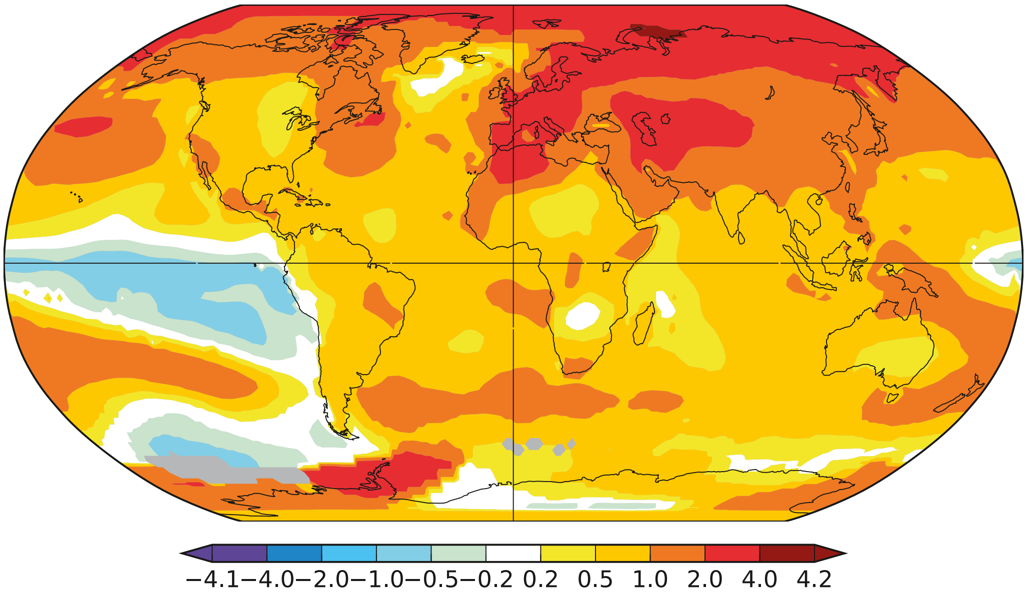
Measurements have been obtained using satellites revolving around Earth and by continuously recording sea levels.

Older data come from coastal tide gauges. A sea gauge is a recording device that measures the sea – or river – level in a specific place for a certain amount of time.

Adapted from NASA's Goddard Space Flight Center/PO.DAAC. Source: 2020, Frederikse et al., published on the NASA website (https://climate.nasa.gov/vital-signs/sea-level/).

DOCUMENT 2. CHANGES IN MEAN ANNUAL SURFACE TEMPERATURE IN 2022 COMPARED TO THE PERIOD 1880-2010

The map shows temperature anomalies, i.e. in this case, the difference between the annual average temperature in 2022 and the average temperature over the time period 1880-2010.



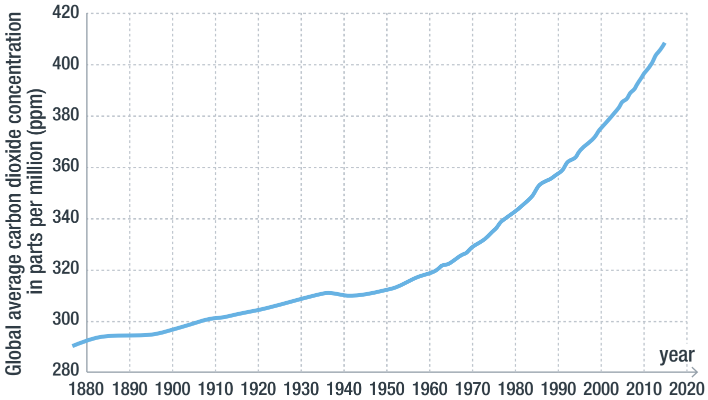
Sources: 2023, Land Surface Air Temperature: GHCNv4, Sea Surface Temperature: ERSST_v5. Published on the NASA website (https://data.giss.nasa.gov/gistemp/maps/index_v4.html).

A NASA video is also available to help visualise the increase in temperature since 1880: https://svs.gsfc.nasa.gov/4882

ATMOSPHERIC SCIENTISTS

→ **As atmospheric scientists, you would like to know how the temperatures of the atmosphere and its composition have changed over time.**

DOCUMENT 3. GLOBAL AVERAGE CARBON DIOXIDE CONCENTRATION IN PPM

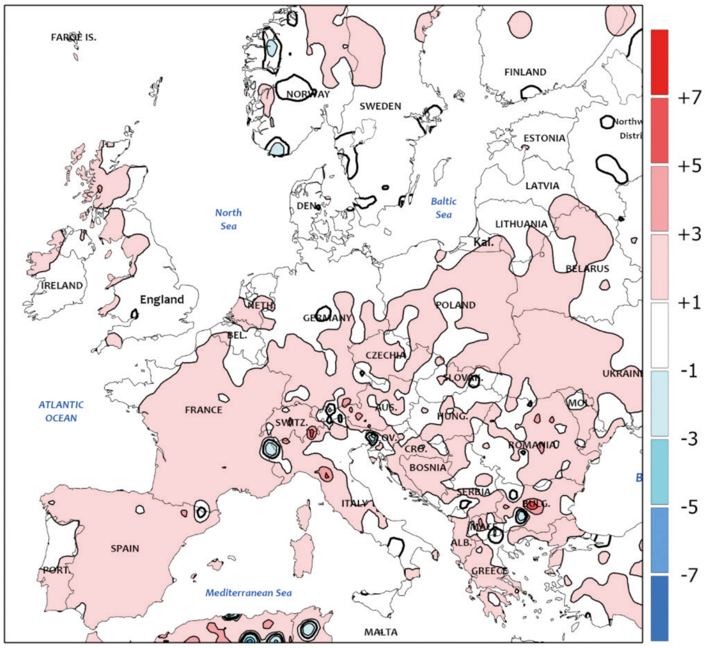


Adapted from NOAA. Source: 2021, ESRL/ETHZ/NCEI. Published on the NOAA website (https://www.climate.gov/media/13560).

Carbon dioxide is a greenhouse gas. Solar radiation crosses the atmosphere, is absorbed by the Earth's surface and warms it. The absorbed solar radiation is transformed into infrared radiation (heat). Some of this infrared radiation is 'trapped' on its way towards space by greenhouse gases in the atmosphere – heating it up even more.

Technical progress since the industrial revolution is not only related to the steam engine, but also to unprecedented scientific, technological, economic and political changes affecting all sectors of human societies. All these developments have contributed to an unprecedented increase in the human population. More people and greater energy consumption have contributed to increase greenhouse gas emissions.

DOCUMENT 4. TEMPERATURE ANOMALY DURING SUMMER 2023



Source: 2024, NOAA, Center for Weather and Climate Prediction. Published on the NOAA website (https://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/europe.shtml).

Scale studied: Europe
Physical parameter studied: temperature anomaly (°C) over 3 months (June-August) in 2023.

In this case, the temperature anomaly is the difference between this 3-month period and the long-term average temperature. A positive anomaly indicates that the observed temperature was warmer than the reference value, while a negative anomaly indicates that the observed temperature was cooler than the reference value.

In July 2023, Europe experienced exceptionally hot weather, setting all-time high temperature records in France, Germany and Spain. Extreme weather events are unusual events for a given location, like strong hurricanes, droughts, extreme temperatures, heat waves, torrential precipitations, flash floods, droughts, etc. IPCC experts tell us that many extreme events are becoming more frequent and more intense with climate change.

WORKSHEET 1.4

CURIOUS

GLACIOLOGISTS

→ **You are scientists specializing in glaciers, studying the impact of climate change on them.**

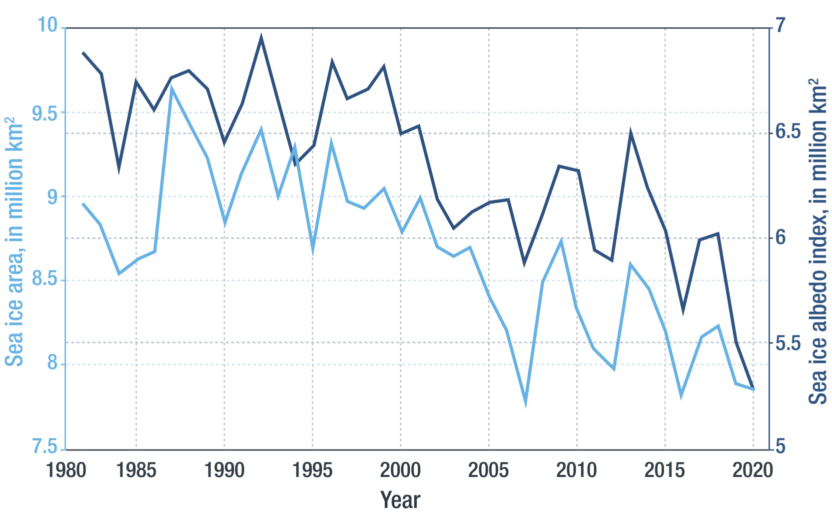
DOCUMENT 5. EVOLUTION OF CONTINENTAL ICE

Continental ice represents all the ice and snow on the continent. It includes glaciers, ice sheets, seasonal snow, frozen lakes and rivers and permafrost (soil, rock or sediment that is permanently frozen for at least two consecutive years).

Sources: Left: August, 1941. Muir Glacier taken by glaciologist William O. Field. Right: August, 2004. Muir Glacier taken by geologist Bruce F. Molnia of the United States Geological Survey (USGS). Published on the NASA's Global Climate Change image bank (https://climate.nasa.gov/interactives/global-ice-viewer#/1/4).

Source: Adapted from NASA. Published on the NASA's Global Climate Change image bank (https://climate.nasa.gov/climate_resources/125/infographic-sea-level-rise/).

DOCUMENT 6. TRENDS OF SEA ICE AREA AND ALBEDO FROM MARCH TO SEPTEMBER IN THE ARCTIC



The Arctic ocean is partially covered by sea ice, which is frozen seawater that floats on the ocean's surface.

Albedo means 'whiteness' in Greek. It measures the fraction of sunlight that is reflected by an object or surface. As the sun's rays are reflected back into space, they do not heat the Earth's surface.

Source: 2023, Adapted from Hao, H. et al., Radiative Effects and Costing Assessment of Arctic Sea Ice Albedo Changes, Remote Sens., https://doi.org/10.3390/rs15040970. Published on the MDPI website, CC (https://www.mdpi.com/2072-4292/15/4/970).

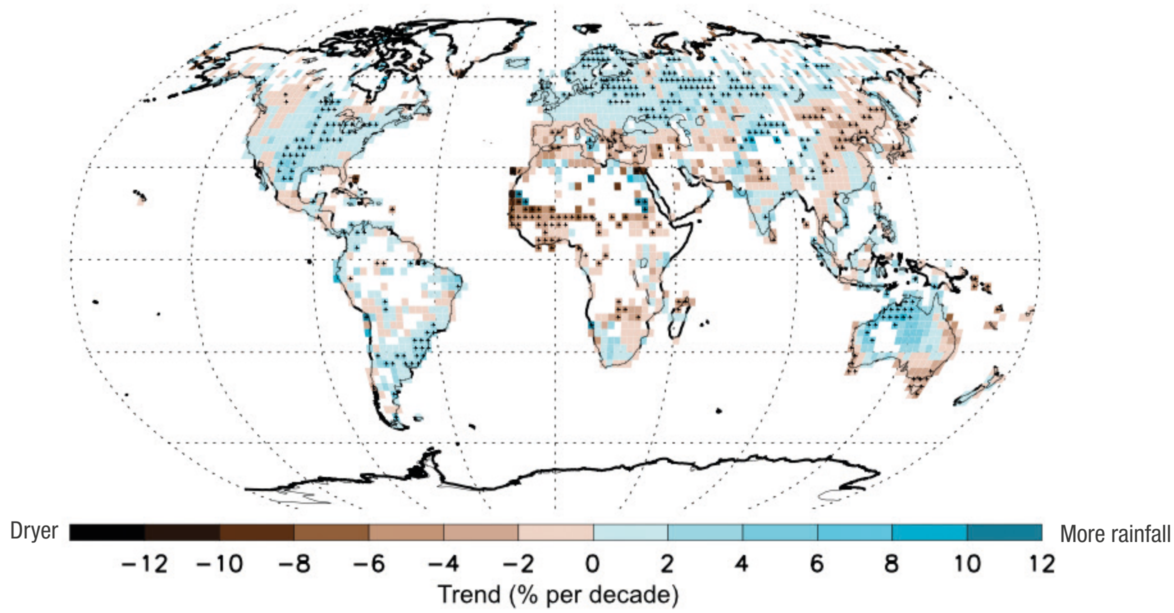
WORKSHEET 1.5

EXPERT

HYDROLOGISTS

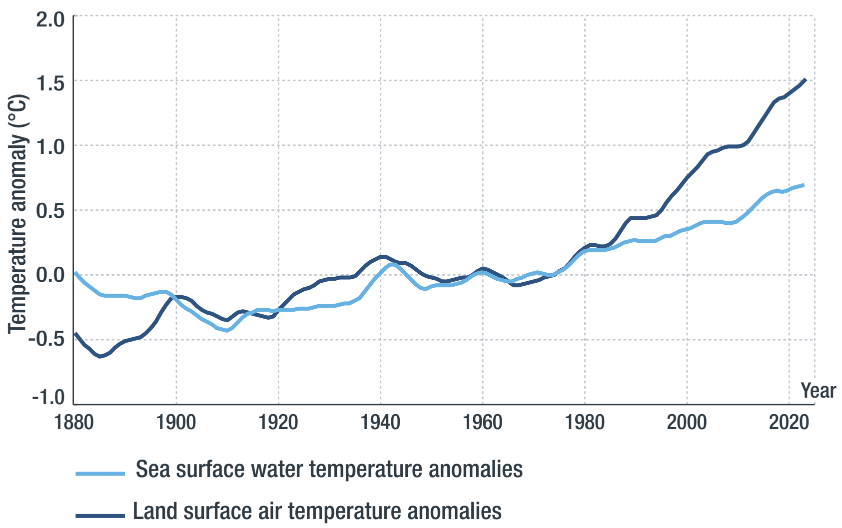
→ **You are scientists specializing in the water cycle. You are interested in precipitation, surface water and evaporation.**

DOCUMENT 7. TRENDS IN PRECIPITATION OVER LAND BETWEEN 1951 AND 2010, IN % PER DECADE



Adapted from IPCC. Source: 2013, Assessment Report 5, WG1 (The Physical Science Basis). Published on the IPCC website (https://www.ipcc.ch/report/ar5/wg1/).

DOCUMENT 8. TEMPERATURE ANOMALIES OVER LAND AND OVER OCEAN SINCE 1880



Source: 2024, NASA/GISS/GISTEMP v4. Adapted from NASA (https://data.giss.nasa.gov/gistemp/graphs_v4/)

These measurements were obtained using different stations across the globe. The curves show temperature anomalies, i.e. in this case, the difference between the annual average temperature and the long-term average temperature(1951-1980).

The **evaporation** of water is the transition from a liquid to a gaseous state. This transition into water vapour occurs over oceans and continents (lakes, soils, etc.). Plants and animals also lose water in the sun. They transpire, producing water droplets which evaporate: this phenomenon is known as **evapotranspiration**.

Evaporation and evapotranspiration depend on **temperature**, the **amount of water** in the subsoil and the **type of vegetation**.

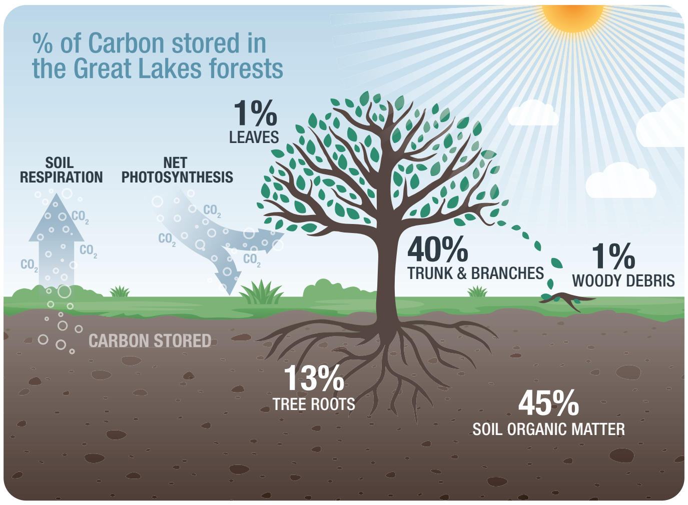
WORKSHEET 1.6

CURIOUS

ECOLOGISTS

→ **You are plant specialists, studying the links between plants and climate change.**

DOCUMENT 9. WHAT HAPPENS TO THE CARBON DIOXIDE IN PLANTS?



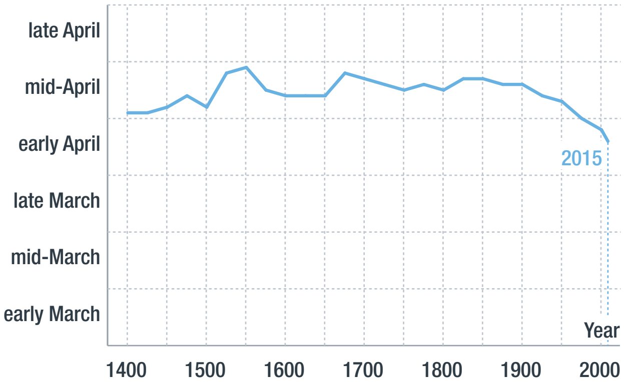
In sunlight, plants grow by absorbing carbon dioxide from the atmosphere (this is called **photosynthesis**). As they breathe both day and night, plants release some carbon dioxide back into the atmosphere (this is called **respiration**). The remaining carbon is stored in leaves, trunks, roots and the soil: all are **carbon reservoirs.**
Young, growing forests are an important **carbon sink** on Earth: there is a carbon **flux** from the atmosphere into the organic matter of trees. It has recently been demonstrated that old-growth forests are carbon sinks as well. Furthermore, both types of forest store an immense quantity of carbon: they are known as **carbon reservoirs.**

Carbon thus circulates between different reservoirs of the Earth: atmosphere, biosphere, soil, etc. This is the **carbon cycle** and plants play a major role in it.

IPCC experts tell us that with climate change, precipitation patterns are changing all over the planet. This is affecting soils and plant activity: carbon flows and reservoirs are being modified in many ecosystems.

DOCUMENT 10. PLANTS ARE AFFECTED BY CLIMATE CHANGE

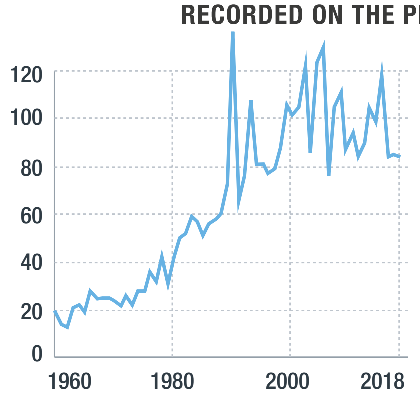
EVOLUTION OF THE BLOSSOMING DATE



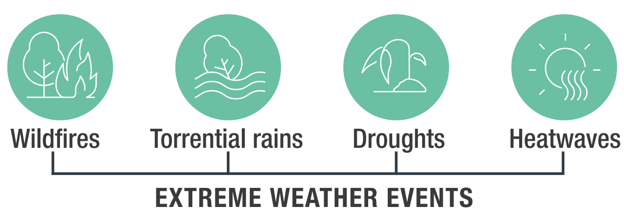
Flowering occurs when the weather is warm enough. The following graph shows the evolution of the blossoming date of cherry trees in Japan over a 600-year period. Balooming occurs when temperatures are high enough.

Source: 2015, Adapted from Aono and Kazui, 2008; Aono and Saito, 2010; Aono, 2012), Aono (2012; Chikyu Kankyo (Global Environment), 17, 21-29). Published on the Yasuyuki Aono website (http://atmenv.envi.osakafu-u.ac.jp/aono/kyophenotemp4/).

NUMBER OF EXTREME WEATHER EVENTS RECORDED ON THE PLANET



Source: 2019, EMDAT, OFDA/CRED International Disaster Database, Bruxels, Belgium. Available on the Our World in Data website (https://ourworldindata.org/natural-disasters, CC).



LESSON 2 THE LAWS OF PHYSICS [1]

MAIN SUBJECTS
Physics

DURATION
Preparation: 10 min (without optional experiments)
Activity: 1h30 (plus a few hours for optional experiments)

AGE GROUP
15+ year-old students

TEACHING METHOD
Experiments
Documentary study

LEARNING OUTCOMES
A few experiments (some compulsory, others optional) on a selection of the parameters listed in the previous lesson, to understand that each is dependent on (aka 'a function of') several others. This dependence can be thoroughly described, but not necessarily by the students themselves.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2. 3 Problem framing

CONCEPTS COVERED
Radiation, Infrared, Absorption, Emission, Opacity

PREPARATION 10 MIN

- Print out **WORKSHEETS 2.1** to **2.6** (for each student).
- Print out the **WORKSHEETS** corresponding to the optional experiments (see below).

TEACHER TIP
Reaching high school, whatever the speciality, the notion of 'mathematical function' is compulsory in all curricula (whether by computation of derivatives, reading of a graph, or using tabled data). The goal here is simply to introduce the idea that each of the physical parameters used in climate models can be described by a function of one or more parameters. E.g. water evaporation depends on air temperature, water temperature, wind speed, air humidity, etc.

There are many ways to conduct this lesson: the students can do some or all of the experiments by themselves, or engage in a documentary study; the whole class can work on the same topic, several sessions in a row, or be split into groups to study more aspects at the same time, and collaborate together at the end of the session. The first (compulsory) half of the lesson tackles the very unintuitive greenhouse effect. It may be difficult for the youngest students to set this up since a professional thermal imaging camera (also called IR camera, although that name should not be used too early in the lesson) is used here. Nevertheless, the worksheets can serve as a basis for discussion with the class.

INTRODUCTION 5 MIN

In the previous lesson, students have reviewed the many parameters to be taken into account when studying climate change. There are now two questions that arise: *How do these parameters vary?* And even more importantly, *do the students understand what the greenhouse effect is?*

PROCEDURE 1H20

PART 1: HOW DOES THE GREENHOUSE EFFECT WORK?
50 MIN

Whether the students conduct the experiments or discuss the various worksheets, the lesson should be carried out as presented to make sure all the laws of physics that are involved are understood.

WORKSHEET 2.1 – DOCUMENT 1
What do your eyes see?
All the objects presented here are hot, and they all emit light. More specifically: **the intensity and colour of the emitted radiation depend on the temperature of the object.**

WORKSHEET 2.1 – DOCUMENT 2
What does this special camera see?
On the camera screen, we can see the rest of the heated metal (in the darkness, the parts not directly under the flame are not visible: they are colder than 700°C). There is a range of colours on the screen, showing something like temperature. We are led to believe that this camera measures temperatures! (Not helped by the name 'thermal imaging camera').

1 A warm thank you to Dr. Valentin Maron, researcher in physics didactics INSPE Toulouse, EFTS laboratory, France. The spirit of this activity and the photographs come from his work.

WORKSHEET 2.2 – DOCUMENT 3

What do you expect to see on the special camera's screen?

If the camera is indeed reading temperature, we should see the man in bright colours (being at 35-37°C), and the rest of the scene in a darker hue (being probably homogeneously at 15-20°C).

WORKSHEET 2.2 – DOCUMENT 4

What does the special camera actually show?

We see the man in bright colours, but the rest of the scene isn't totally dark! And we see the man's reflection too! Yet the temperature of the glass should be similar to the room's temperature. Thus, the camera is detecting a radiation, one **invisible to our eyes. This radiation is called infrared ('IR' from now on).**

Add: *moreover, the colour scale is strictly a scale of radiation power (see above): a strong IR radiation power is displayed in yellow-white, a weak one, in purple-black.*

WORKSHEET 2.3 – DOCUMENT 5

What can you say of the infrared emissions of these cups?

The first reading of the picture is obvious: **the warmer the object, the more intense its IR emission.**
Now, ask the students to compare the pictures taken with visible vs. with IR light: visible light can pass through the hot water cup (we can guess the colour of the man's jumper) as well as the cold water cup. But that's not the case with IR light: even though the IR radiation of the cold water cup is weak, we cannot guess the man's own IR emission.

Question: *is it due to the water or to the glass?*

WORKSHEET 2.3 – DOCUMENT 6

How transparent are these materials?

The visible light passes through the glass pane, the plastic sheet, and the water cup. On the other hand, only the plastic sheet is transparent to IR radiation, while the glass and water absorb the IR radiation.
Summarise: *we have seen interactions between light (IR and visible) and matter (solid and liquid).*

Question: *can gases emit IR radiation? Can gases absorb IR radiation?*

WORKSHEET 2.4 – DOCUMENT 7

Experimenting with the transparencies and radiation emissions of gases.

Obviously, gases do not emit any visible radiation (we do not see them): they are completely transparent in visible light. In the infrared, however, the IR camera clearly detects IR radiation. We observe that **CO_2 emits more radiation than air at 30°C.**
Finally, both cold balloons are opaque to IR radiation: they absorb the radiation of the warmer background and do not let it pass through. Cold CO_2 absorbs even more IR radiation than air. This shows that **CO_2 is a greenhouse gas.**

WORKSHEET 2.5 – DOCUMENT 8

Building a 'radiative equilibrium'

This worksheet is simply a hand-out for the students to discuss. A possible experiment would be to measure the temperature of a piece of corrugated plate placed outside in direct sunlight. What would happen is that the temperature would rise until a plateau is reached; however, it is difficult to distinguish exactly between the reflected solar radiation, the dispersed solar radiation and the emitted IR radiation.

> **TEACHER TIP**
> Since the air in the stratosphere is colder than air at the Earth's surface by about 40°C, we want to focus hereafter on the '5°C CO_2 balloon' (see **WORKSHEET 2.4**).

What will happen if the Earth's atmosphere suddenly contains more 'cold CO_2'? **The atmosphere absorbs more IR radiation** (emitted by 'planet Earth'), **and less IR radiation escapes into space.**

As a consequence, the radiative equilibrium is disrupted. Since the outgoing radiation is less than the incoming radiation, **the system's temperature rises** (**WORKSHEET 2.5**). **Then the IR emission increases** (**WORKSHEET 2.3 DOCUMENT 5**) **until a new equilibrium** is reached (**WORKSHEET 2.5**).

Conclude: *in short, this explains the greenhouse effect.*

> **TEACHER TIP**
> **WORKSHEET 2.5** can be used to explore how many climate feedbacks work. For instance:
> - → The ice caps melt away, the albedo decreases: the outgoing (reflected) visible flux decreases; to compensate, the outgoing IR flux must increase (by an increase in temperature).
> - → More water vapour in the atmosphere: H_2O is a greenhouse gas too, and the reasoning is exactly the same as the CO_2 excess discussed with the class.
>
> The students will study both these feedbacks in the board game used in lesson 3. If need be, these feedbacks are more thoroughly explored in Ocean and Cryosphere Lesson C3 'The white cryosphere and its albedo'.

PART 2: HOW DO THE CLIMATE-RELATED PARAMETERS VARY? 30 MIN

Using **WORKSHEET 2.5,** the students can already answer one question: *What does the change in surface temperature depend on?* They should mention:

- the incoming solar radiation R_{sun}
- the reflected solar radiation $R_{reflected}$
- the IR emission power $R_{IR\ emission}$
- etc.

TEACHER TIP

The 'etc.' on the previous page is very important. There are some factors that may play a role but that were not noticed by the students, not well established by scientists, not yet met with consensus, and so on. These factors explain the discrepancies between one climate model and another, feed uncertainties and error bars, and fuel more research to determine how important they are.

As a conclusion, write this as a formula (note the '...' that represent the mathematical ' ') where f means 'is a function of':

$$T_{surface} = f(R_{sun}, R_{reflected}, R_{IR\ emission}, \ldots)$$

Explain that the students themselves do not need to know the exact expression of the function f (and sometimes, neither do the scientists. Simple experiments can be conducted to find them (like the ones they did for the greenhouse effect), some tabulated data made by in-situ measurements may replace analytical expressions, and there is always room for improvement. (This will be the focus of lesson 5).

Using **WORKSHEETS 2.1** to **2.4**, the students can answer the question: *What does the IR radiation emitted by the atmosphere depend on?* It depends on the following parameters:

- the Earth's surface temperature $T_{surface}$
- the air temperature T_{air}
- the height of atmosphere H
- the amount of greenhouse gases m_{CO_2}, m_{H_2O}, m_{CH_4}, ...
- etc.

Or, written in a formula:

$$R_{IR\ emission} = f(T_{surface}, T_{air}, H, m_{CO_2}, m_{H_2O}, m_{CH_4}, \ldots)$$

The students can readily notice that these two formulas are mathematically connected via the parameters $T_{surface}$ and $R_{IRemission}$, showing that there is a feedback loop in this system.

WORKSHEET 2.6 – DOCUMENT 9

What speeds up the evaporation of water?

Remind the class that amongst the greenhouse gases present in the Earth's atmosphere, H_2O is in fact the most important one. Indeed, it is responsible for most of the greenhouse effect, and therefore for the planet to be hospitable to the life forms we know, by increasing the surface temperature from -18°C to +15°C.

Then ask them: *What do you think could determine whether water evaporates more or less (over a given period of time)?*
The students will probably think of water temperature, wind speed, air temperature...

TEACHER TIP

You may want to carry out the following experiments. Pour some water in a bottle, place a glass dish on its mouth, and put an ice cube in the dish.

→ Experiment 1: vary the water temperature (cold, warm, and hot water).
→ Experiment 2: vary the air temperature (cold, warm, and hot air).

In both cases, you'll have to estimate visually the quantity of water condensed onto the glass dish.

An everyday question: *What makes your laundry dry faster?* To help the students, hand out **WORKSHEET 2.6**. The students should come to the following conclusion: the quantity of water ($m_{H_2O\text{-}evap}$) that evaporates in a given period of time depends on:

- the air temperature T_{air}
- the water temperature T_{water}
- the amount of solar radiation R_{sun}
- the presence of wind and/or its speed V_{wind}
- the air humidity H_{air}
- the actual area of the air/water interface $S_{interface}$
- etc.

Or, written in a formula:

$$m_{H_2O\ evap} = f(T_{air}, T_{water}, R_{sun}, V_{wind}, H_{air}, S_{interface}, \ldots)$$

OPTIONAL EXPERIMENTS

The following experiments can be done in any order: they can be conducted in parallel by different groups, for instance.

REFLECTED SOLAR RADIATION DEPENDS ON... 1H30

Carry out or refer to the experiment investigating the albedo in lesson C3 of the teacher's handbook Ocean and Cryosphere. The conclusion is that the solar radiation that an object or a surface sends back to space depends on:

- the amount of solar radiation reaching the object/surface R_{sun}
- the reflectivity of the object/surface, called albedo: $A_{surface}$
- etc.

$$R_{back} = f(R_{sun}, A_{surface}, \ldots)$$

CO_2 NATURAL EMISSIONS DEPEND ON... 1H

Carry out or refer to the experiment investigating photosynthesis in lesson A5 of the teacher's handbook Climate Change and Land. This experiment shows that vegetation can act both as a sink and as a source of CO_2. Whether photosynthetic plants are a carbon sink, depends on:

- the mass of photosynthetic organisms $m_{photosyn.\ org.}$
- the amount of solar radiation reaching the plants R_{sun}
- etc.

$$m_{CO2\ photosyn} = f(R_{sun}, m_{photosyn.\ org.}, \dots)$$

Respiration of living organisms (including photosynthetic ones) is a source of carbon, depending on:

- the mass of living organisms $m_{living\ org.}$
- etc.

$$m_{CO_2\ respiration} = f(m_{living\ org.}, \dots)$$

CO_2 ANTHROPIC EMISSIONS DEPEND ON... 1H30

Carry out or refer to the experiment investigating combustion found in lesson A6 of the teacher's handbook Climate Change and Land. The quantity of CO_2 emitted by combustion $m_{CO_2\ \text{combustion}}$ depends on the mass of the various combustibles actually burnt:

$$m_{CO_2\ combustion} = f(m_{coal\ burnt}, m_{oil\ burnt}, m_{wood\ burnt}, m_{gas\ burnt}, \dots)$$

FLUID MOVEMENTS DEPEND ON... 1H30

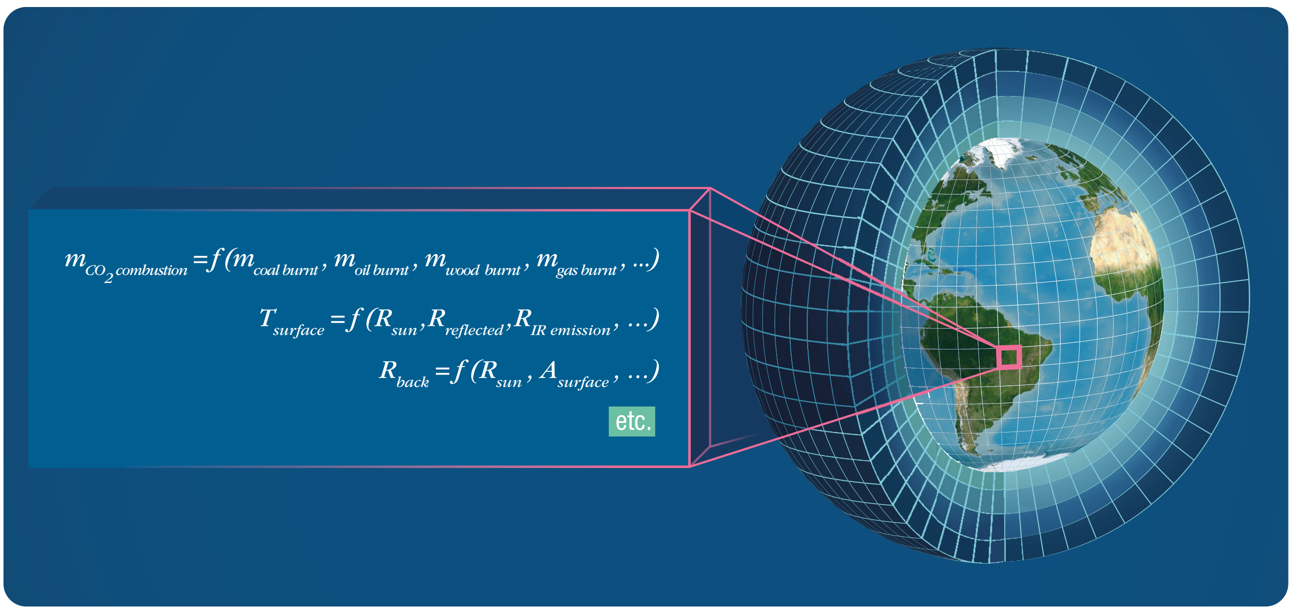
Carry out or refer to the experiment investigating oceanic currents found in lesson C5 of the teacher's handbook Ocean and Cryosphere. The displacement speed of a given volume of fluid (gas or liquid) V_{fluid} depends on:

- the difference between the temperature of the fluid and the surrounding temperature (ΔT)
- the difference between the salinity of the fluid and the salinity of the surrounding environment (ΔS)
- the local relief height H_{relief}
- etc.

$$V_{fluid} = f(\Delta T, \Delta S, H_{relief}, \dots)$$

WRAP-UP 5 MIN

The goal of this exercise was to show how scientists have to find out all the dependencies between physical quantities. These dependencies can be translated into a set of equations involving all these physical quantities, also called variables. **Connecting all the variables through formulas** is the very principle of **climate modeling.**

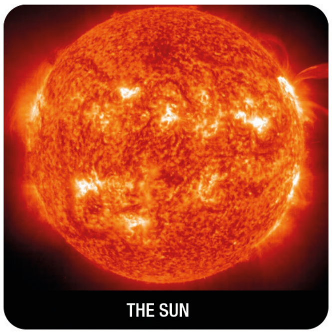


The principle of climate modeling: a set of interconnected physical variables.

WORKSHEET 2.1

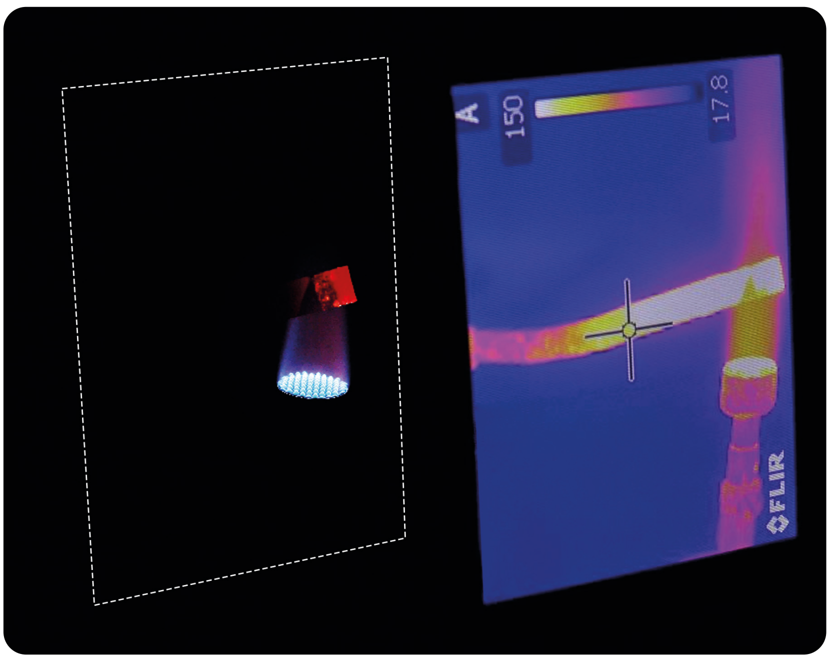
DOCUMENT 1. WHAT DO YOUR EYES SEE?

Question 1. What do you see in these pictures?
Question 2. How do you explain the colours?



DOCUMENT 2. WHAT DOES THIS SPECIAL CAMERA SEE?

Question 3. What does this special camera see?



Left: a copper bar is heated, in the dark, until incandescence is reached.
Right: the setup as viewed with a ‘thermal imaging camera’.

WORKSHEET 2.2

DOCUMENT 3. WHAT DO YOU EXPECT TO SEE ON THE SCREEN?

Question 4. What do you expect to see on the screen?

DOCUMENT 4. WHAT DOES THE SPECIAL CAMERA ACTUALLY SHOW?

Question 5. What does the special camera actually show?

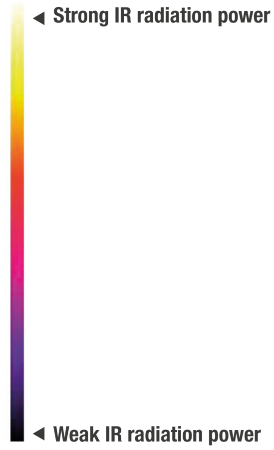
WORKSHEET 2.3

DOCUMENT 5. WHAT CAN YOU SAY ABOUT THE INFRARED EMISSIONS OF THESE CUPS?

Question 6. What can you say about the infrared emissions of these cups?

A cup of **hot water** and a cup of **cold water.**

The same setup as viewed with and IR camera



Scale of IR radiation power

DOCUMENT 6. WHAT DOES THIS SPECIAL CAMERA SEE?

Question 7. How transparent are these materials?

Glass pane

Glass pane

Plastic sheet and cup filled with water

WORKSHEET 2.4

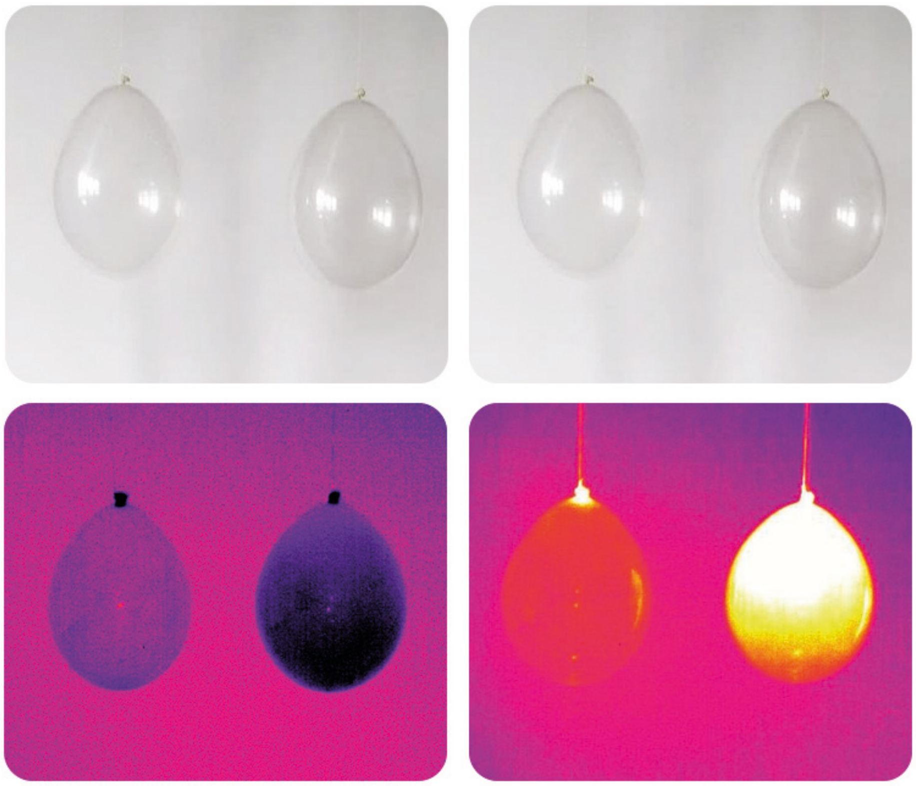
DOCUMENT 7. EXPERIMENTING WITH TRANSPARENCIES AND RADIATION EMISSIONS OF GASES

Question 8. Can gases emit visible radiation?
Question 9. Can gases emit infrared radiation?
Question 10. Are gases transparent to visible radiation?
Question 11. Are gases transparent to infrared radiation?

Background temperature: 20°C | Background temperature: 20°C

VISIBLE LIGHT

THERMAL IMAGING CAMERA



Balloon filled with	Balloon filled with	Balloon filled with	Balloon filled with
AIR	**CO_2**	**AIR**	**CO_2**
[0.04% CO_2]	[100% CO_2]	[0.04% CO_2]	[100% CO_2]
5° C	**5° C**	**30° C**	**30° C**

Scale of IR radiation power

Weak IR radiation power — **Strong IR radiation power**

WORKSHEET 2.5

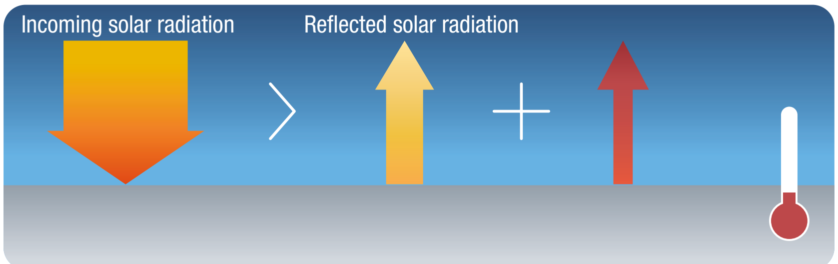
DOCUMENT 8. BUILDING A ‘RADIATIVE EQUILIBRIUM’

Question 12. What will happen to the Earth’s outgoing infrared emission if there is more ‘cold CO_2’ in the Earth’s atmosphere? (hint: use **WORKSHEET 2.4 – QUESTION 11**)

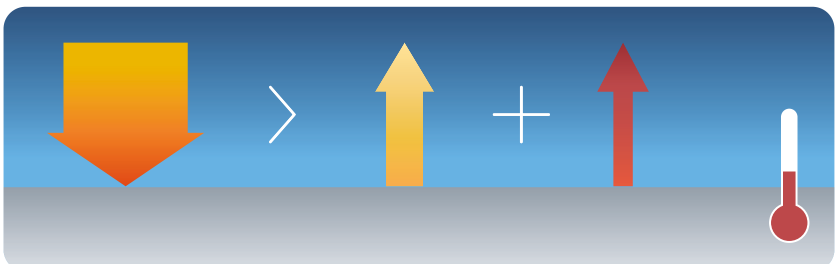
Question 13. What is the only way for the ‘planet Earth’ system to reach radiative equilibrium again?

Let us consider an object (in grey), placed outside in the void (in blue).

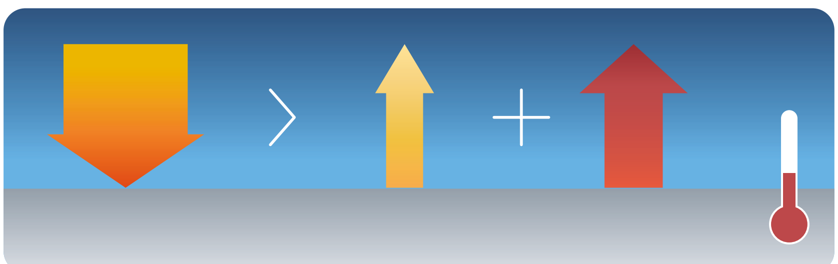
As seen in **WORKSHEET 2.1**, objects emit radiation depending on their temperature. If the temperature is below 700°C, this radiation lies in the infrared only.



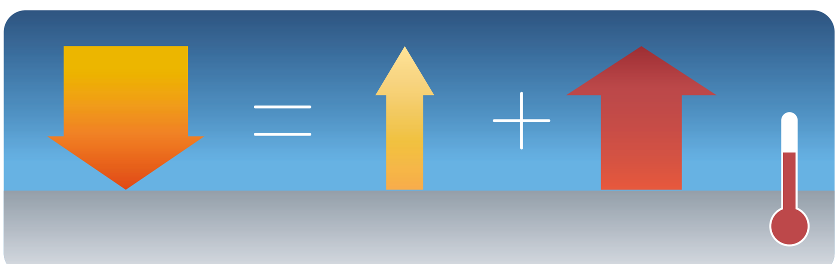
If the sun illuminates our object (yellow down arrow), then part of this incoming radiation can be reflected back, and the other part is absorbed by the material.



This state is not equilibrium, as the sum of the outgoing energy is smaller than the incoming energy: the temperature of the material rises.



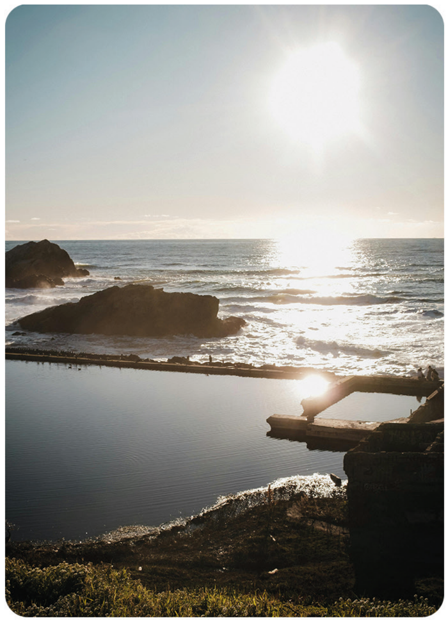
As seen in **WORKSHEET 2.3 – DOCUMENT 5**, the warmer the body, the more powerful its emission. Thus the infrared emission of our object increases.



The object’s temperature rises until equilibrium is reached, at which point the temperature rise stops. This is called **‘radiative equilibrium’**. The same process occurs in the ‘planet Earth’ system.

DOCUMENT 7. WHAT SPEEDS UP THE EVAPORATION OF WATER?

Question 14. Look at the pictures. In which situation does water evaporate faster? What are the parameters that speed up evaporation?



SEQUENCE A – THE EARTH'S CLIMATE SYSTEM

LESSON 3 MODELLING THE CLIMATE USING A BOARD GAME

MAIN SUBJECTS
Physics
Chemistry
Natural Sciences
Geography

DURATION
Preparation: 1h
Activity: 1h

AGE GROUP
15+ year-old students

TEACHING METHOD
Serious game (board game)

LEARNING OUTCOMES
After having identified the global drivers of regional climate (lesson 1 and 2), the students explore and understand how they are connected to form the Earth's climate system. They realise that different environments interact with each other, since they are under the influence of the same variables (e.g. temperature, humidity). Changing the variables may lead to positive or negative feedback loops within the climate system.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2.3 Critical thinking

CONCEPTS COVERED
Greenhouse effect, water cycle, carbon cycle, albedo, model, unperturbed climate, perturbed climate, interactions, feedback, level of confidence, uncertainty, consensus

PREPARATION 1H

HOW TO SET UP THE BOARD GAME

- Board game: Print out **WORKSHEET 3.1** in A2 format (poster format), one board game per group of 6 students. If possible, laminate it.
- Elements to be placed on the board game: Print **WORKSHEET 3.2** (2 pages) and cut out the various items (elements and flux), for each group. Put them into an envelope so that they can easily be reused.
- We suggest you to use BluTack to fix the different elements to the board.
- Print out a set of booklets of **WORKSHEET 3.3** (5 pages) for each group. You can choose to keep the whole sheet or cut out the cards to make a small booklet (by cutting out the dividing lines, then superimposing the different cards or stapling them together).

You can print out the correction elements of your choice **(WORKSHEET 3.5,** 3 pages**)** so that the students have, for example, a summary diagram to remember.

◄ 2 players during Round 3 of the game. Eva reads her booklet and follows the instructions. She links two environments together with positive feedback arrows (reinforcement of climate change) and explains her choices to Simon. For each arrow, she chooses the right color according to the level of scientific consensus.

HOW TO PLAY

- The Earth system game contains five distinct environments. At the beginning, the climate is **unperturbed by human activities,** so the five environments are empty. The aim of **Round 1** is to reconstitute the environments and the processes therein by following the instructions on the cards and placing the different items (sometimes, the same variables: e.g. temperature, humidity, albedo, etc.) on the board.
- In **Round 2,** the climate is now **changed by human activities** and the students have to modify the environments accordingly. At the end of this round, the students explain what they have found to their groupmates.
- **Round 3** is suited for advanced students [EXPERTS]. This round deals with the concepts of 'climate feedback' and 'level of consensus of a scientific assertion'.

INTRODUCTION 5 MIN

Have students recall the difference between **climate** and **weather**. Show them 'The Earth's Climate system' CLIM video, in which Fiona O'Connor (MET Office Science, United Kingdom) reminds them that many **parameters** are taken into account when studying the atmosphere: greenhouse gas concentrations, temperature, precipitation, albedo, etc. (see lesson 1).

WATCH THE VIDEO ↗

Each parameter depends on several others. The parameters (or variables) are linked by laws of physics and chemistry (see lesson 2).

$$R_{IR\ emission} = f(T_{surface}, T_{air}, H, m_{CO_2}, m_{H_2O}, m_{CH_4}, \ldots)$$

Tell students that they will explore the same regions as in lesson 1 (**WORKSHEET 1.1**). *Are there processes that happen within a region (internal processes)? What are the links between the different climatic regions? What are the global processes which affect our whole planet?* To answer these questions, the students use a climate model, here, via a board game.

PROCEDURE 45 MIN

1. Six students share a game board. There is a Game Master and 5 scientists (i.e. one of the 5 booklets, **WORKSHEET 3.3**).

2. Students read the rules of the game (**WORKSHEET 3.4**) and start playing rounds 1 and 2. Round 3 is designed for more advanced students [EXPERTS].

3. For the third round, note that there are small scales on the cards representing the level of consensus that climatologists attribute to the different feedbacks (low, medium, strong level). Discuss with your students the importance of degree of consensus associated with scientific knowledge.

TEACHER TIP
Most of the feedback arrows point to the same environment (Eath's atmosphere). This is because the processes taking place in each region can have an effect on the atmosphere.

WRAP-UP 10 MIN

Ask the students how this board game helped them understand the climate system. **The board game is a model,** a simplified representation of reality. It helps to better understand what has been observed in connection with climate change and the processes involved (see lesson 2).

The **interactions between different environments** can be made clearer by using an example. Emitting higher amounts of greenhouse gases into the atmosphere enhances the greenhouse effect, thus increasing the Earth's surface temperature, which in turn causes sea ice to melt, etc. These processes link the atmosphere to the cryosphere. This is discussed in 'Can we trust climate projections?' CLIM video, by Birgit Hassler, an atmospheric physicist.

WATCH THE VIDEO ↗

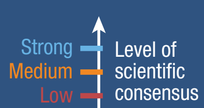
Round 3 can be used to illustrate the interactions between different environments. Ask more advanced students to explain positive and negative climate feedbacks. As mentioned in one of the booklets, the IPCC's 6th Assessment Report states that adding up all the climate feedbacks related to direct energy leads to a **net global negative feedback,** which ensures that **the Earth's surface temperature does not spiral out of control.**

You can also explain that reliable scientific information is always accompanied by a **level of confidence,** as can be seen in the IPCC reports. You can mention the IPCC as one of the most reliable sources of information on climate change.

BACKGROUND FOR TEACHERS

THE CONSENSUS OF THE SCIENTIFIC COMMUNITY

The IPCC assesses and compiles the latest scientific information on climate change, relaying the consensus of the scientific community. A scientific consensus is established on a body of scientific evidence that can be verified and is accepted by the scientific community (experts). It is valid for a given period based on current knowledge. There is, for example, a very broad consensus among climate experts that human activities are the causes of ongoing climate change. A scientific consensus is not proof of a scientific theory but rather **the result of converging lines of evidence** all pointing to the same conclusion. Scientific consensus is established gradually, as scientific research progresses.

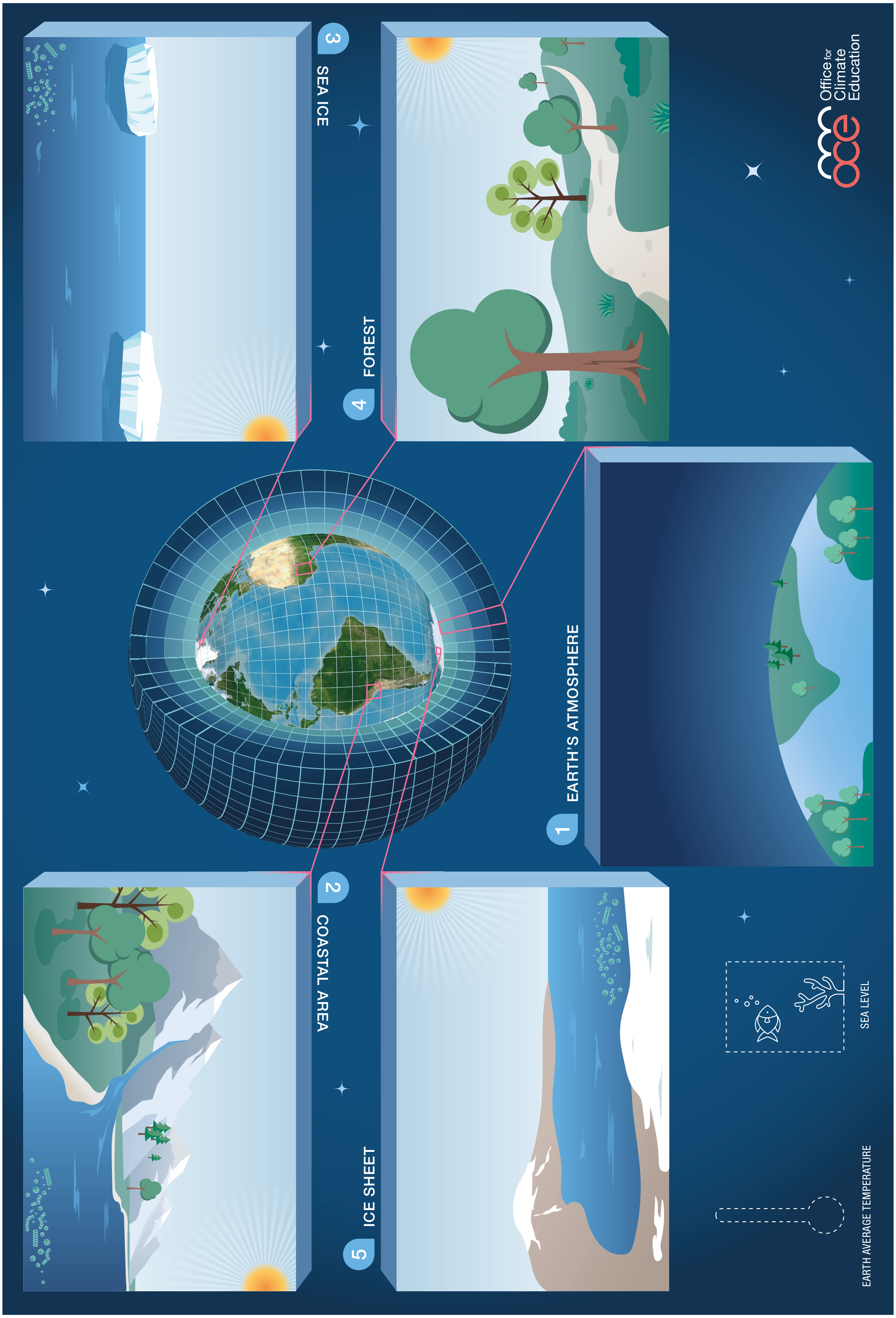


A scientific consensus is based on a high level of confidence (agreements between scientists, weight of evidence, etc).

A scientific consensus on a given subject **is not incompatible with:**

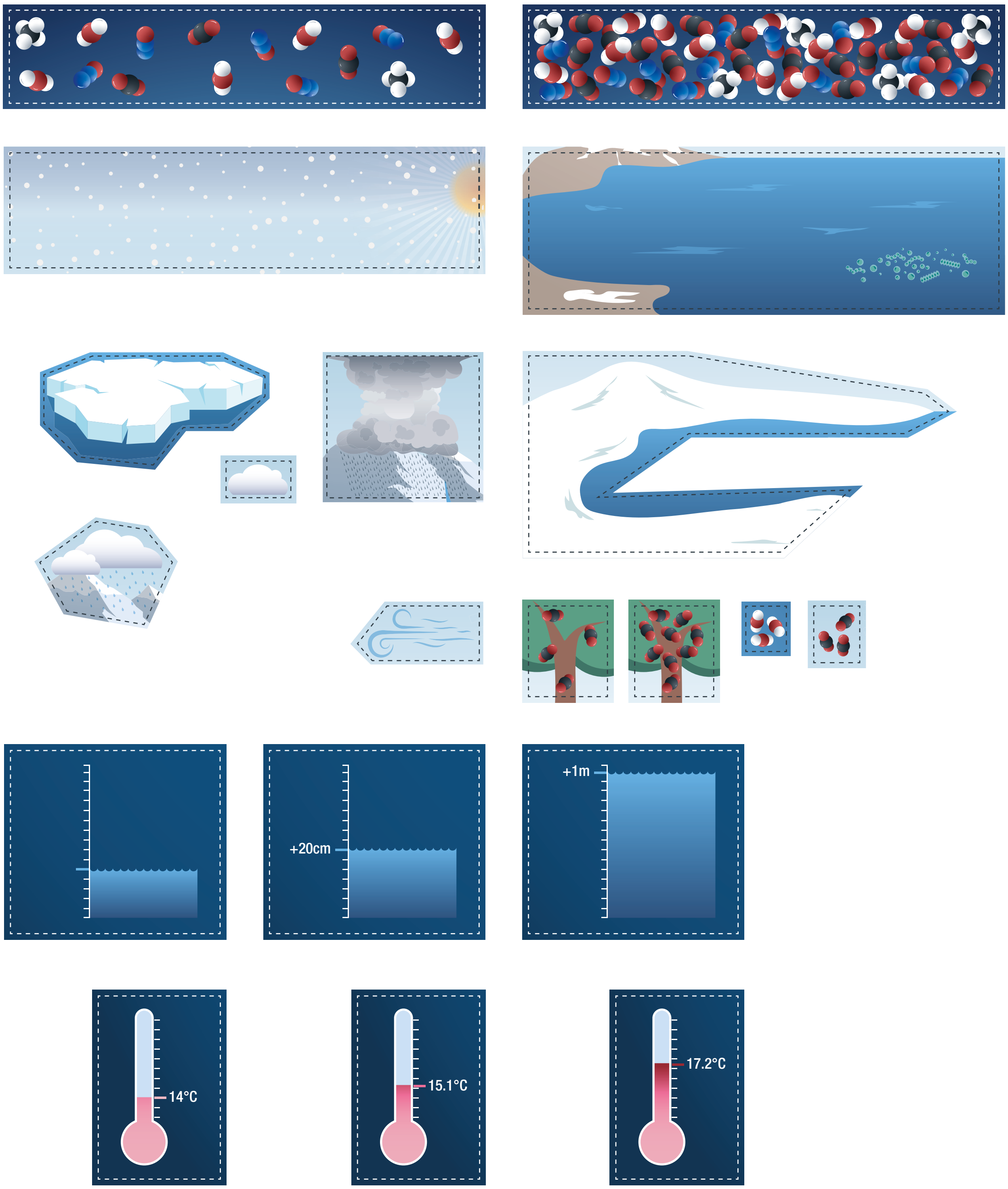
- Including different aspect of the subjects. For example, scientists currently disagree on the exact temperature rise in the event of a doubling of the atmospheric CO_2 concentration – the findings range from 2.5 to 4.5°C. But, contrary to what climate deniers say, this does not call into question the reality of human-induced climate change!
- The notion of uncertainty. Every scientific data is associated with uncertainty. Climate projections established by models are therefore always associated with uncertainties. There are two primary causes for uncertainty about the magnitude of climate change in the future:
  - → climate feedbacks (involving clouds, carbon uptake, ocean heat uptake, water vapour, sea ice, etc.);
  - → future human emissions (linked to climate policy, technology, politics, people, etc.).

WORKSHEET 3.1 GAME BOARD



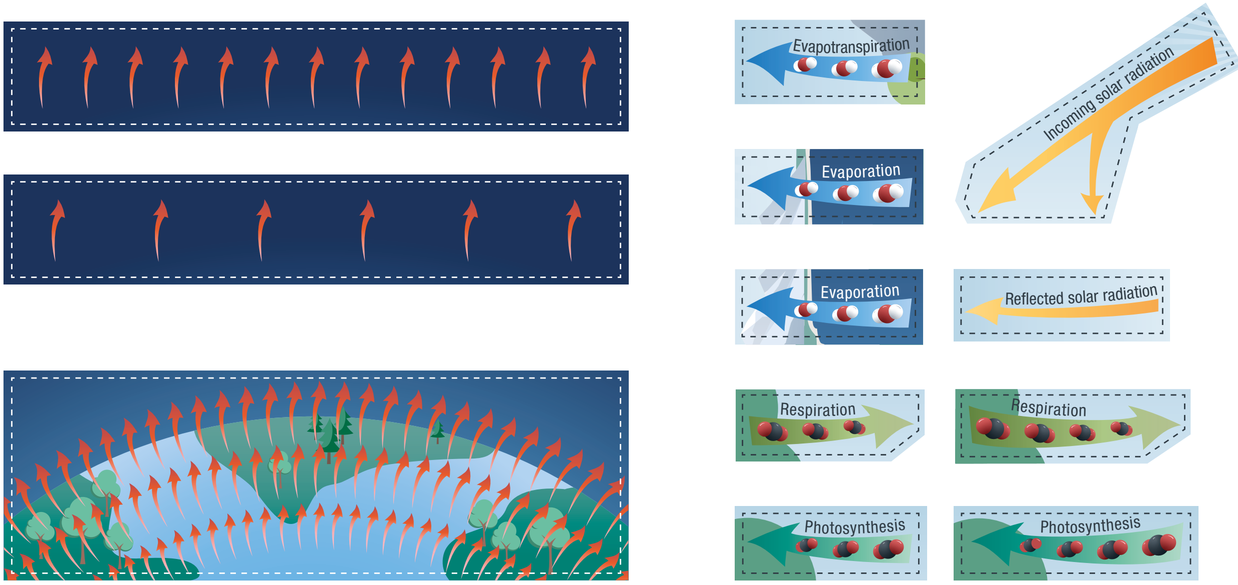
WORKSHEET 3.2 ITEMS

Cut out elements for the board game.



WORKSHEET 3.2 ITEMS

Cut out fluxes for the board game.



1 **Svante Arrhenius** (1859–1927) was a Swedish scientist. He was the first to make the connection between the increasing atmospheric CO_2 concentration and the increase in the Earth's surface temperature. He coined the expression 'greenhouse effect'.

PAGE 1

1 YOU ARE AN

ATMOSPHERIC SCIENTIST

PAGE 2

ROUND 1
BUILDING A MODEL

Adding the greenhouse effect to the model

The Earth's surface emits infrared radiation, carrying 'heat' to the atmosphere. The Earth's atmosphere naturally contains a mixture of greenhouse gases that trap part of the infrared radiation. This prevents all the infrared radiation from escaping into space. Therefore, the temperatures at the Earth's surface are quite cozy, allowing life to flourish.

—

Add 1 element
Add 2 fluxes

—

Question 1
What is the main consequence of the greenhouse effect?

PAGE 3

ROUND 1

—

Answer
The Earth's surface temperature increases.

—

Discussion between the 5 scientists
What would the Earth's surface temperature be without the greenhouse effect?

—

PAGE 4

ROUND 2
USING THE MODEL TO RUN AN EXPERIMENT

What does the model simulate?

Increase the amount of greenhouse gases in the atmosphere to mimic increased human-made greenhouse gas emissions.

Less infrared radiation is escaping from the atmosphere towards space. This leads to an increase in the Earth's surface temperature. Since the industrial revolution, the Earth's surface has warmed by almost 1°C.

—

Change 1 element
Change 1 flux

—

Question 2: What is the current level of global warming (i.e. how much higher is the average temperature on Earth compared with the preindustrial global temperature)?

PAGE 5

ROUND 2

—

Answer
The current level of global warming is +1.2°C compared to the preindustrial level.

—

PAGE 6

ROUND 3
UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS

Climate feedbacks

Global warming leads to more evaporation of water, thus increasing the water vapour concentration in the atmosphere. Since water vapour is a greenhouse gas, this enhances global warming. It is a very strong positive feedback.

—

Link at least 2 environments
with a red (reinforcement)
or purple (limitation) arrow

Strong — Level of scientific consensus

PAGE 7

ROUND 3

Climate feedbacks

All bodies emit thermal radiation. The radiation's intensity increases with the temperature of the body. Similarly, the Earth emits more radiation into space as its surface warms up. This leads to a lower surface temperature and hence limits global warming.

—

Strong — Level of scientific consensus

PAGE 8

WORKSHEET 3.3 BOOKLET 2

2 Emma Haziza, born in 1977, is an hydrologist. She is a specialist in natural hazards, particularly those related to fresh-water. In this sense, she's a climate change adaptation expert.

PAGE 1

2 YOU ARE A HYDROLOGIST

You are currently studying coastal areas, a very specific environment.

PAGE 2

ROUND 1
BUILDING A MODEL

Adding the water cycle to the model

Liquid water at the Earth's surface – over oceans, lakes, plants, etc. – evaporates into the atmosphere (through evaporation and evapotranspiration). The water vapour in the atmosphere is moved by winds. It condenses and forms little droplets that build up clouds. The droplets in the clouds grow leading to rain. This liquid water gets back to the Earth's surface and eventually flows into the lakes, rivers and oceans. This is the water cycle.

—

Add 4 elements
Add 2 fluxes

—

Question 1: Cite a few weather phenomena that come with rain?

PAGE 3

ROUND 1

—

Answer
Tropical cyclones, monsoon, thunderstorms, mid-latitude cyclones.

—

Discussion between the 5 scientists
Where on Earth are these events most likely to occur?

—

PAGE 4

ROUND 2
USING THE MODEL TO RUN AN EXPERIMENT

Increase the temperature of the Earth's surface to mimic global warming.

What does the model simulate?

It simulates a intensification of the water cycle, with more evaporation and more rain in some regions.

—

Change 1 element
Add 1 flux

—

Question 2
Some regions may experience both more droughts and more floods. True or False?

PAGE 5

ROUND 2

—

Answer
True! With climate change, precipitation patterns vary from one part of the world to another. But it also varies according to the time of year.

For example, certain regions like California may experience severe drought in summer, but torrential floods in autumn. Generally speaking, extreme events are more intense and more frequent with climate change.

—

PAGE 6

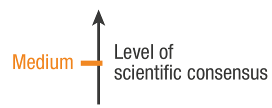
ROUND 3
UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS

Climate feedbacks

Around half of the climate models predict more precipitation in the Sahel zone in Africa. A greening of the Sahel would mean more photosynthetic activity, hence more CO_2 capture by plants. Since CO_2 is a greenhouse gas, this would mitigate climate change: It is a negative climate feedback.

—

Link at least 2 environments
with a red (reinforcement)
or purple (limitation) arrow



PAGE 7

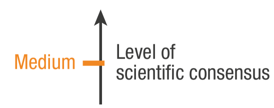
ROUND 3

Climate feedbacks

Global warming is altering the water cycle, changing, for example, the size and the type of clouds. Models indicate that in low latitudes (below 60°), high clouds will be even higher, reinforcing the greenhouse effect, whereas there will be fewer low clouds. The latter implies a lower albedo and an increase in the Earth's surface temperature. The sum of these two processes seems to increase the Earth's surface temperature. It is a positive climate feedback.

—

Link at least 2 environments
with a red (reinforcement)
or purple (limitation) arrow



PAGE 8

3 **Marie Tharp** (1920–2006) is a geologist and oceanographer from the United-States. She is known for her work on oceanographic cartography.

3 **YOU ARE AN**

OCEANOGRAPHER

You are currently studying sea ice on the ocean, a very specific environment.

ROUND 1
BUILDING A MODEL

Adding the sea ice albedo to the model

In the Arctic, the temperatures of the air and the ocean water are so low that sea ice is formed at the ocean's surface. Most of the solar radiation reaching the sea ice is reflected back to space because the ice is white – it has a high albedo. When the sea ice melts, it is replaced by the dark ocean which absorbs a lot of solar radiation.

—

Add 1 element
Add 2 fluxes

—

Question 1
What role does sea ice play in the climate system?

ROUND 1

—

Answer
Sea ice has a high albedo, thus reflecting most of the incoming solar radiation. This keeps the Earth's surface cool.

—

Discussion between the 5 scientists
If there was no Arctic sea ice, would the Earth's temperature be higher or lower than it is now?

—

ROUND 2
USING THE MODEL TO RUN AN EXPERIMENT

Increase the temperature of the Earth's surface to mimic global warming.

What does the model simulate?

The model simulates the melting of sea ice, infering a lower albedo (less solar radiation is reflected from the Earth's surface).

—

Remove 1 element
Remove 1 flux

—

Question 2
Can sea ice melting amplify the warming initially triggered in the model?

ROUND 2

—

Answer
Yes, less sea ice means less reflected solar radiation. The excess solar radiation is absorbed by the ocean, which becomes warmer, leading to more melting of sea ice, etc. This is a positive feedback loop.

—

ROUND 3
UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS

Climate feedbacks

When sea ice melts, the Earth's albedo decreases, and as a consequence less solar radiation is reflected back to space. This means: the Earth's surface absorbs more radiation and warms up. This causes even more sea ice to melt, enhancing global warming. This is called the polar amplification. It is a positive climate feedback.

—

Link at least 2 environments
with a red (reinforcement) or purple (limitation) arrow

Strong — Level of scientific consensus

ROUND 3

Climate feedbacks

The authors of the IPCC's 6th Assessment Report (AR6) estimated the sum of all climate feedbacks related to direct incoming solar radiation: feedbacks due to clouds, water vapour, albedo, thermal radiation, etc. Scientists concluded – with a medium level of confidence – that the sum of all these feedbacks results in a negative climate feedback. This would ensure that the Earth's surface temperature does not spiral out of control.

—

Medium — Level of scientific consensus

WORKSHEET 3.3 BOOKLET 4

4 **Agnes Arber** (1879–1960) was a British botanist and philosopher. She worked at a time when women were not allowed in the same laboratories as men.

PAGE 1

4 **YOU ARE A**

BOTANIST

You are currently studying tropical forests, a very specific environment.

PAGE 2

ROUND 1
BUILDING A MODEL

Adding the land carbon cycle to the model

In sunlight, plants grow through photosynthesis: they absorb carbon dioxide from the atmosphere and release oxygen. When plants breathe (which they do day and night), they release some carbon dioxide into the atmosphere (respiration), the rest being stored as carbon in the roots, trunk and leaves as well as in the soil. Native tropical forests, such as the Amazon rainforest, are large carbon sinks.

—

Add 2 elements
Add 2 fluxes

—

Question 1: Where does the carbon go when plants die?

PAGE 3

ROUND 1

—

Answer
It is released back into the atmosphere through decomposition (respiration) or fires (to clear land).

—

Discussion between the 5 scientists
What factors contribute to tree mortality, and thus to carbon release?

—

PAGE 4

ROUND 2
USING THE MODEL TO RUN AN EXPERIMENT

Increase the temperature of the Earth's surface to mimic global warming.

What does the model simulate?

In some regions, such as the Amazon, the model simulates more frequent droughts, slowing tree growth. Photosynthesis (and respiration) activity is reduced, and as a consequence less carbon is stored in the forest.

—

Change 1 element
Change 2 fluxes

—

Question 2: Does a higher surface temperature increase or decrease the efficiency of the forest carbon sink?

PAGE 5

ROUND 2

—

Answer
In some regions, such as the Amazon, the forest carbon sink efficiency declines with global warming.

—

PAGE 6

ROUND 3
UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS

Climate feedbacks

Projections indicate a change in precipitation patterns. For example, rainfall tends to be more abundant and frequent in Russian and Canadian forests. Coupled with higher temperatures, this leads to a growing vegetation cover. More vegetation can capture more CO_2. Since CO_2 is a greenhouse gas, this limits climate change. This is a negative climate feedback.

—

Link at least 2 environments
with a red (reinforcement) or purple (limitation) arrow

Medium — Level of scientific consensus

PAGE 7

ROUND 3

Climate feedbacks

Phytoplankton are primary producers: When exposed to light, they absorb CO_2 through photosynthesis – making phytoplankton a carbon sink. Some studies show that climate change is affecting phytoplankton: their activity is decreased by rising ocean temperatures and disruptions of ocean currents. The phytoplankton carbon sink is shrinking, leading to a higher atmospheric CO_2 concentration and a larger greenhouse effect. This is a positive climate feedback.

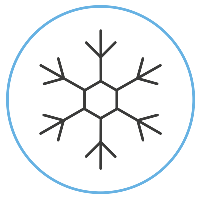
—

Medium — Level of scientific consensus

PAGE 8

5 **Louis Agassiz** (1807–1873) was an American glaciologist. He was the first to suggest the existence of past ice ages.

PAGE 1



5 **YOU ARE A**

GLACIOLOGIST

You are currently studying ice sheets, a very specific environment.

PAGE 2

ROUND 1
BUILDING A MODEL

Adding continental ice to the model

Antarctica is the largest continent covered with ice. The other big ice sheet on Earth is Greenland. Continental ice forms as snow accumulates and compresses on a land surface over a very long period.

—

Add 2 elements

—

Question 1
What is the difference between the ice in Antarctica and the ice in the Arctic?

PAGE 3

ROUND 1

—

Answer
Almost all of the ice in Antarctica is continental ice. It is compressed snow that covers a continent. In the Arctic, there is no continent: sea ice is formed from frozen water at the ocean's surface.

—

Discussion between the 5 scientists
Name other places on Earth (other than Antarctica) where continental ice can be found.

—

PAGE 4

ROUND 2
USING THE MODEL TO RUN AN EXPERIMENT

Increase the temperature of the Earth's surface to mimic global warming.

What does the model simulate?

The model simulates the melting of ice, leading to a sea level rise of between 50cm and 1m by 2100.

—

Remove 1 element
Add 2 elements

—

Question 2
Does the melting of sea ice in the Arctic also lead to sea level rise?

PAGE 5

—

Answer
No. You can do an easy experiment to prove this: put an ice cube into a glass of water – the ice cube melts, but the water level doesn't change. Similarly, the melting of sea ice does not contribute to rising sea levels.

—

ROUND 3
UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS

Climate feedbacks

Melting continental ice, from ice sheets or glaciers, reduces the Earth's albedo – less solar radiation is reflected back to space.

As a result, the Earth's surface absorbs more radiation and warms up. This enhances global warming. It is a positive feedback.

—

Link at least 2 environments
with a red (reinforcement)
or purple (limitation) arrow

Strong – Level of scientific consensus

PAGE 7

ROUND 3

Climate feedbacks

With climate change, temperatures are increasing, and droughts are becoming more frequent, leading to more wildfires. The burning of vegetation (organic matter) releases large amounts of aerosols into the upper atmosphere. These aerosols act as a shield: less solar radiation reaches the Earth's surface, mitigating climate change. This is a negative feedback.

—

Link at least 2 environments
with a red (reinforcement)
or purple (limitation) arrow

—

Medium – Level of scientific consensus

PAGE 8

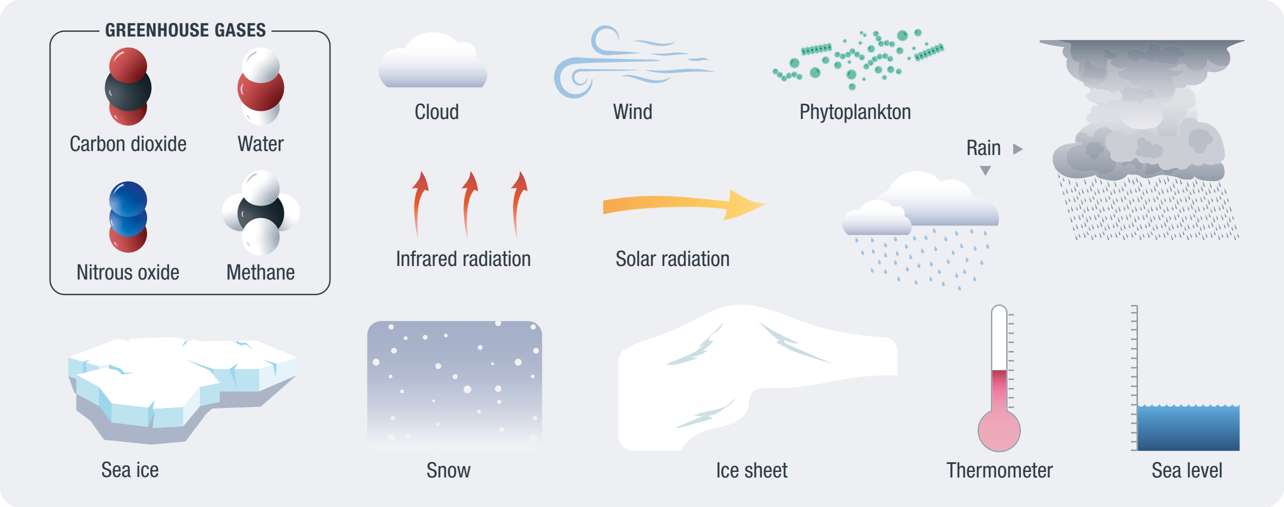
WORKSHEET 3.4

HOW TO PREPARE AND PLAY THE GAME

GAME PREPARATION: THE GAME MASTER

- Sets the thermometer to +14°C (the average temperature on Earth in the pre-industrial period).
- Sets the sea level at the lowest level (the pre-industrial sea level).
- Reads how to place the different items on the board, following the booklet.

LEGEND OF SOMES ITEMS



ROUND 1: BUILDING A MODEL

- The game master ensures that each stage of the game is rigorously followed by the scientists.
- The other five scientists take turns introducing themselves and reading the instructions aloud.
- This round is about 'unperturbed climate', the climate prior to the industrial period.
- The five scientists work together to build the different environments according to the instructions in the booklets and answer the questions.

Once all five models are built, it is time to add or remove 'elements' and/or 'fluxes' according to the instructions on the cards.

ROUND 2: USING THE MODEL TO RUN AN EXPERIMENT

- Round 2 represents a world with a 'perturbed climate' due to global warming.
- The game master sets the thermometer to the current average surface temperature of the Earth (+15.1°C).
- He/she sets the sea level at +20 cm (the current level compared to the pre-industrial sea level).
- The five scientists take turns reading aloud the instructions for round 2. Together, they modify the different environments according to the instructions (adding items, removing others, etc.) and answer the questions.
- Again, the game master ensures that each stage of the game is rigorously followed by the 5 scientists.

ROUND 3: UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS
for more advanced students

- Round 3 represents a world with a 'perturbed climate' due to global warming in the year 2100.
- The game master sets the thermometer at +17.2°C (without reinforcement of current policies, global warming is expected to rise 3.2°C in 2100, compared to the pre-industrial period).
- The scientists each take turns reading the cards aloud and following the instructions. Most of the time, they will have to link environments together via 'feedback' arrows. For each arrow, they need to choose the right colour that corresponds to the level of scientific consensus (light colours for medium consensus and dark colours for strong consensus).
- At the end of their turn, the scientist will explain the feedbacks that are being represented.
- The same arrows will be reused for each round.

ROUND 1: BUILDING A MODEL (unperturbed climate)
ROUND 2: USING THE MODEL TO RUN AN EXPERIMENT (perturbed climate: climate change)
ROUND 3: UNDERSTANDING THE INTERACTIONS BETWEEN ENVIRONMENTS (perturbed climate, but takes into account climate feedback: limitation or reinforcement of climate change)

1 SVANTE ARRHENIUS

PHYSICIST AND CHEMIST – EXPERTISE: THE EARTH'S ATMOSPHERE

ROUND 1

Add one element: a small amount of greenhouse gases.

Add two fluxes: IR radiation from the Earth's surface to the atmosphere + IR radiation from the atmosphere to space.

Discussion between the 5 scientists: What would the temperature at the Earth's surface be without the greenhouse effect?

Answer: Without greenhouse effect, less IR radiation is reflected back to the Earth's surface (= more IR radiation escapes directly into space). The temperature at the Earth's surface would therefore be lower (-18°C).

ROUND 2

Change one element: the small amount of greenhouse gases is replaced by a large amount of greenhouse gases.

Change one flux: the large flux of IR radiation escaping into space is replaced by a small flux of IR radiation escaping into space (the larger amount of greenhouse gases traps more IR radiation).

ROUND 3

Example of a positive feedback
Water evaporation increases → more water vapour (greenhouse gas) in the atmosphere → enhancement of the greenhouse effect → global warming. Place a reinforcement arrow pointing from environment 2 to 1.

Example of a negative feedback
Also called 'Planck feedback', it is powerful and has a high level of confidence from climatologists. Linking 2 environments is not possible here since it is an exchange between the atmosphere and space.

2 EMMA HAZIZA

HYDROLOGIST – EXPERTISE: COASTAL AREA

ROUND 1

Add four elements: water vapour, wind, cloud and rain cloud.

Add two fluxes: evaporation and evapotranspiration.

Discussion between the 5 scientists: Where are these events most likely to occur on Earth?

Answer: In tropical zones (more evaporation and evapotranspiration).

ROUND 2

Change one element: the rain cloud is replaced by a large rain cloud.

Add one flux: evaporation.

ROUND 3

Example of a negative feedback
The photosynthesis level in the Sahel region is modified. Place a limitation arrow pointing from environment 4 to environment 1.

Example of a positive feedback
More clouds due to an intensification of the water cycle. Place a reinforcement arrow pointing from environment 2 to environment 1.

3 MARIE THARP

GEOLOGIST AND OCEANIC CARTOGRAPHER – EXPERTISE: SEA ICE

ROUND 1

Add one element: sea ice.

Add two fluxes: incoming solar radiation and reflected solar radiation.

Discussion between the 5 scientists: Would the Earth's surface temperature be higher or lower if there was no Arctic sea ice?

Answer: Without sea ice, the ocean would absorb more radiation and the Earth's surface temperature would rise.

ROUND 2

Remove one element: sea ice.

Remove one flux: reflected solar radiation.

ROUND 3

Example of a positive feedback
Melting sea ice → albedo decreases → ocean gets warmer → more sea ice melts → global surface temperature of the Earth increases. Place a reinforcement arrow pointing from environment 3 to environment 1.

Example of a negative feedback
The sum of all the feedbacks is a negative climate feedback. This would ensure that the Earth's surface temperature does not spiral out of control. It is not relevant to link 2 environments here since it is a global feedback.

4 AGNES ARBER

BOTANIST – EXPERTISE: FOREST

ROUND 1

Add two elements: CO_2 into the atmosphere, lots of CO_2 stored in plants

Add two fluxes: strong photosynthesis, strong respiration.

Discussion between the 5 scientists: Which factors contribute to tree mortality, and thus to the release of carbon into the atmosphere?

Answer: Anything that limits plant growth (droughts, plant pests) or destroys forests (fires, deforestation) increases the amount of CO_2 in the atmosphere.

ROUND 2

Change one element: only a small amount of CO_2 is stored in plants.

Change two fluxes: replace strong photosynthesis by weak photosynthesis, and strong respiration by weak respiration.

ROUND 3

Example of a negative feedback
In Russia and Canada, vegetation cover is increasing (medium level of confidence) → the additional vegetation absorbs more CO_2 from the atmosphere. Place a limitation arrow pointing from environment 4 to environment 1.

Example of a positive feedback
Less phytoplankton in the ocean → less photosynthetic activity → ocean absorbs less CO_2 from the atmosphere → CO_2 concentration in the atmosphere increases → global warming. Place a reinforcement arrow pointing from environment 3 or 2 to environment 1 (ocean to atmosphere).

5 LOUIS AGASSIZ

BIOLOGIST AND GEOLOGIST – EXPERTISE: ICE SHEETS

ROUND 1

Add two elements: ice sheet and snowfall.

Discussion between the 5 scientists: Name other places on Earth (other than Antarctica) where continental ice can be found.

Answer: Greenland and Antarctica are the Earth's continental **ice sheets**. Continental ice is also found in mountain glaciers.

ROUND 2

Remove one element: ice sheet.

Add two elements: high sea level and ocean levels of up to 1m by 2100.

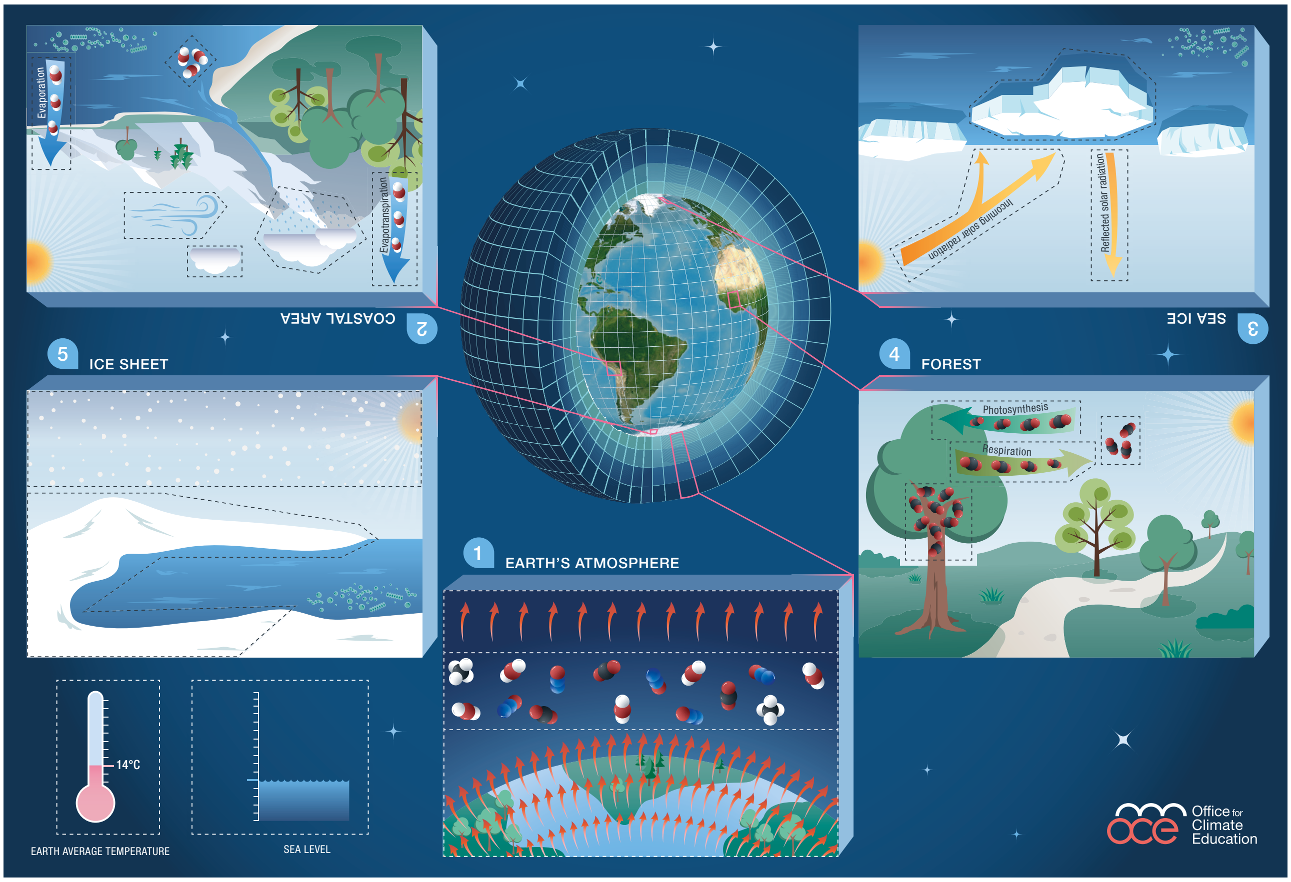
ROUND 3

Example of a positive feedback
Melting of continental ice (strong level of confidence) → sea level rises. Place a reinforcement arrow pointing from environment 5 to environment 3 or 2 (ice sheet to ocean).

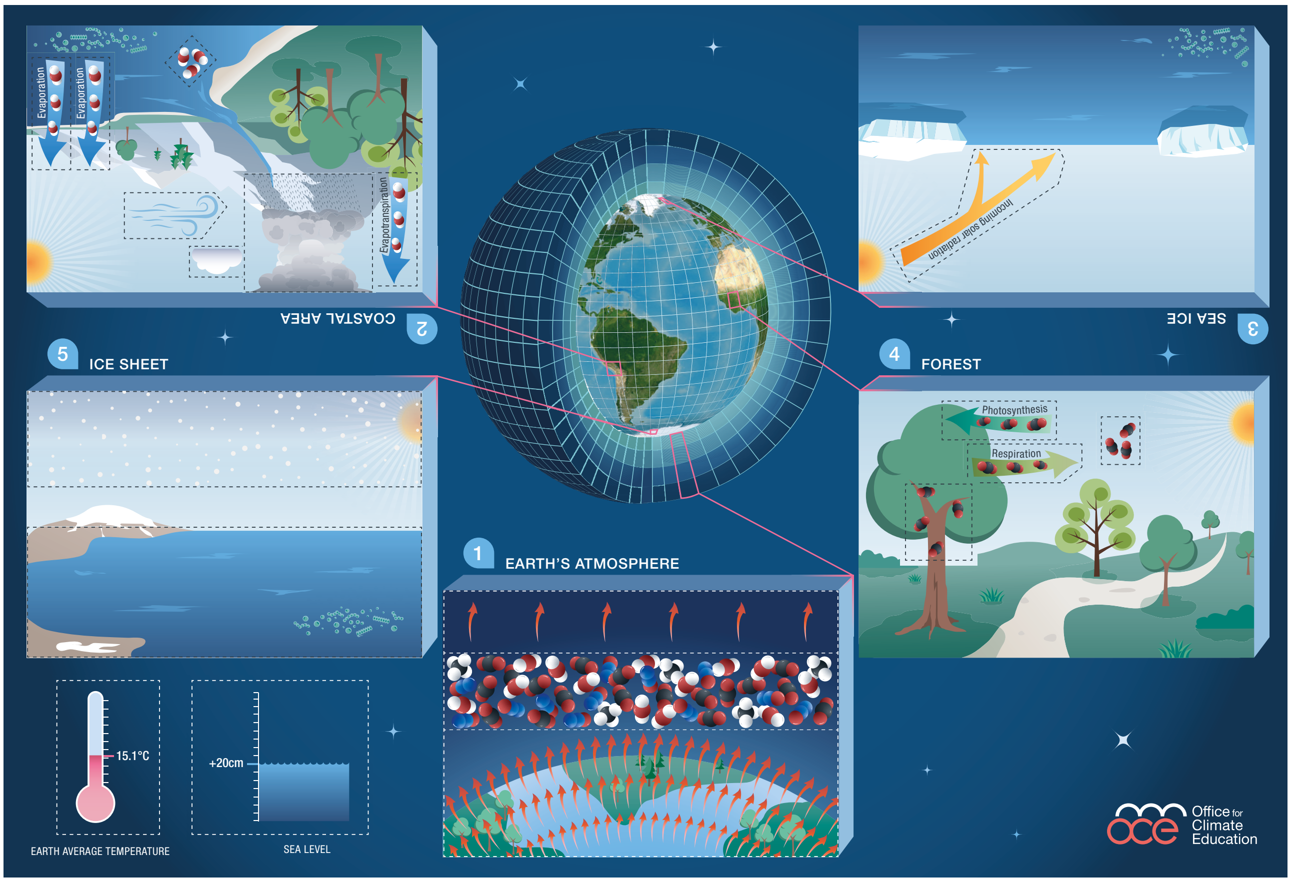
Example of a negative feedback
Megafires (medium level of confidence) → smoke particles shield the incident's solar radiation. Place a limitation arrow from the atmosphere towards the land.

WORKSHEET 3.5 CORRECTED VERSION – PAGE 3/3

CORRECTION: ROUND 1



CORRECTION: ROUND 2



LESSON 4 MODELS TO REPRESENT REALITY

MAIN SUBJECTS
Physics
Mathematics
Computer Science

DURATION
Preparation: 10 min
Activity: 1h (Curious)
1h30 (Expert)

AGE GROUP
15+ year-old students

TEACHING METHOD
Documentary analysis
Multimedia animation

LEARNING OUTCOMES
Students understand that models are simplified representations of reality. They are tools to understand and predict climate. Using models has many advantages, but it also has its limitations. They cannot represent the full complexity of reality. Using a physical model (a mock-up or analogy), students understand the differences between the real/physical world and the digital world.

TARGETED SUSTAINABILITY COMPETENCE
Domain 3 – Envisioning sustainable futures
Competency – 3.3 Exploratory thinking

CONCEPTS COVERED
Model, input, output, sampling

PREPARATION 10 MIN

- 2 thermometers, 2 lamps (or sunlight), 1 glass container.
- [EXPERTS ONLY]: computer with the file greenhouse.ipynb readily available, **WORKSHEET 4.1** (for each pair of students).

INTRODUCTION 20 MIN

Show pictures (or scale models) of three to five items: for instance a plastic dinosaur, a schematic of the water cycle, a weather forecast, a GPS device. *What do these have in common?* Guide them towards the word 'model'.

TEACHER TIP

GPS navigation uses a heuristic model. It calculates a good way to get from point A to point B, but not necessarily the best way (see the guide '123code' for more details).

What is a model? More specifically, what is it used for? Many possible answers:

FACILITATING AN OBSERVATION
- ~ Model of a representation of a living being (e.g. dinosaur, flower, etc.)
- ~ Scale model (solar system, lithospheric plates)
- ~ Grouping information in a diagram (flowchart, graph, pie chart)
- ~ Substitute for a standard living organism (drosophila in biology, swine in surgery)
- ~ Statistical analysis (poll, probabilities)

PRESENTING CLEARLY
- ~ Ontology (semantic web)
- ~ Data model (XML nomenclature)
- ~ Theoretical model (Mendel's laws of inheritance)
- ~ Conceptual model (the twins' paradox by Einstein)
- ~ Schematic (water cycle)

APPLYING THEORY FOR PREDICTIONS
- ~ Mathematical model (Malthusian population growth, consumer rational behaviour)
- ~ Heuristic model (GPS)
- ~ Computational model (weather forecast, flight simulator, neural network)

Plumage colour reconstruction model of the *Oviraptoridae Caudipteryx,* a dinausor.

Collectively, the class comes up with a **definition of a 'model': a simplified representation of reality that can be used to understand complex problems.** *Can a board game be a model?*

By debriefing the serious game in lesson 3, the students will find that the analogy is a model. Its components fall into three categories:

INPUTS
- IR, albedo, temperature, solar radiation, greenhouse gas concentration, evaporation, wind, respiration, photosynthesis, water (atmosphere, sea ice and continental ice, rain/snowfall), CO_2 (biosphere, atmosphere, lithosphere)
- Optional: permafrost, clouds, fires, thermal ocean expansion

OUTPUTS
- Outgoing IR emission, temperature, rain/snowfall, evaporation rate, sea level rise
- Updates of all input values

SAMPLING
- 5 cells (1 atmosphere, 1 Antarctica, 1 Arctic region, 1 forest, 1 hydrosphere)

The sampling category can lead to another discussion on the limits and limitations of models. Obviously, this model cannot be used for weather forecast, or even for regional climate projections. For instance, one cell (forest) can represent either the Amazon rainforest or a forest in Siberia: the former will develop into a semi-arid savannah and the latter into a livable breadbasket.

PROCEDURE 30 MIN (CURIOUS) TO 1HR (EXPERT)

Now, we can ask the following question: *Can a physical experiment be a model?* The students conduct the classic greenhouse effect experiment: they compare the temperature inside and outside of a greenhouse (the details of the experiment can be found in Ocean & Cryosphere, Lesson B1).

Discuss the experiment itself:

After Lesson 2, the students understand that the temperature increase observed in the experiment is not caused by the greenhouse effect. Instead, it is due to containment, where the warmer air is trapped in the greenhouse. Similar experiments could be conducted, replacing the glass container by a plastic container, or air by pure CO_2: in all cases, the temperature increases, but not due to greenhouse gases. The students understand the thought process of Svante Arrhenius, the Swedish chemist who coined the expression 'greenhouse effect' as an analogy.

Despite its limitations, this experiment is based on the use of a model, as can be demonstrated by filling the table:

INPUTS
- Container's material
- Air composition

OUTPUTS
- Temperature

SAMPLING
- 2 cells (1 control cell, 1 test cell)

ADDITIONAL ACTIVITY EXPERT ONLY, 30 MIN

The teacher hands out **WORKSHEET 4.1**. As a simple coding activity, the students will use and modify a Python/Jupyter digital model of the greenhouse effect on the computer. If needed, have **WORKSHEET 2.5** on hand.

The students answer the questions in the Python document:

1. Why are the variables ASR_obs and OLR_obs nearly equal? As seen in **WORKSHEET 2.5**, equilibrium is reached when the incoming solar flux is equal to the total outgoing (visible plus IR) flux. In the figure below (**WORKSHEET 4.1**), the magnitude of the incoming solar radiation is 340 W/m², and the magnitude of the outgoing radiation OLR_obs (infrared, or long waves radiation) is (100+240) W/m².

2. Compare two transmissivities (i.e. how radiation is transmitted): the students must keep *tau1* = 0.61 (the observed greenhouse effect) but they can choose any other value smaller than 0.61 for *tau2*. The smaller the *tau2,* the more the temperature increases, taking longer to reach equilibrium.

The students should clearly describe the components of the model. *Tau2* may represent the efficiency of the greenhouse effect (a small value means a strong greenhouse effect). Each variable represents one parameter, interaction, or physical entity. Two laws of physics (seen in lesson 2) are implemented in a very simplified manner:

$$T_{surface} = f(R_{sun}, R_{reflected}, R_{IR\ emission}, \ldots)$$

$$R_{IR\ emission} = f(T_{surface}, T_{air}, H, m_{CO_2}, m_{H_2O}, m_{CH_4}, \ldots)$$

Conclude that this digital/mathematical model can be used as a **predictive tool** (if tau2 is given, one can predict the value of the surface temperature).

WRAP-UP 10 MIN

The class can now compare the various models they have studied. Use a table like the one below, (let the students define the rows as they see fit) to analyse how finely/roughly reality is represented (e.g. for the sun: a lamp is used in one case and the value of the incident flux in the other case).

In every case, the students have observed that models may be used to reproduce the real world, either for pedagogical purposes (e.g. dinosaur model) or for analysis and prediction (e.g. weather forecast). The example of the 'classic greenhouse effect experiment' acts as a warning: **a model should never be over-interpreted, lest the conclusions drawn be completely off-track.** In the next lesson, the students will learn more about digital models.

Greenhouse experiment (analog model) in the classroom.

ASPECT	CARD GAME (ANALOG MODEL)	GREENHOUSE EXPERIMENT (ANALOG MODEL)	RADIATIVE EQUILIBRIUM PROGRAMMING (DIGITAL MODEL)
Solar radiation	Arrows	Lamp	Fixed mean annual value of 1,360 $W.m^{-2}$
Greenhouse gases	CO_2 fluxes	Solid container	Variable 'transmissivity of the atmosphere' *tau*
Dimensions	5 cells	1 test, 1 control	Constant radius of the Earth's atmosphere assuming spherical isotropy
etc.	...	...	...

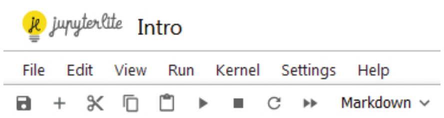
WORKSHEET 4.1

USING PYTHON / JUPYTER NOTEBOOK

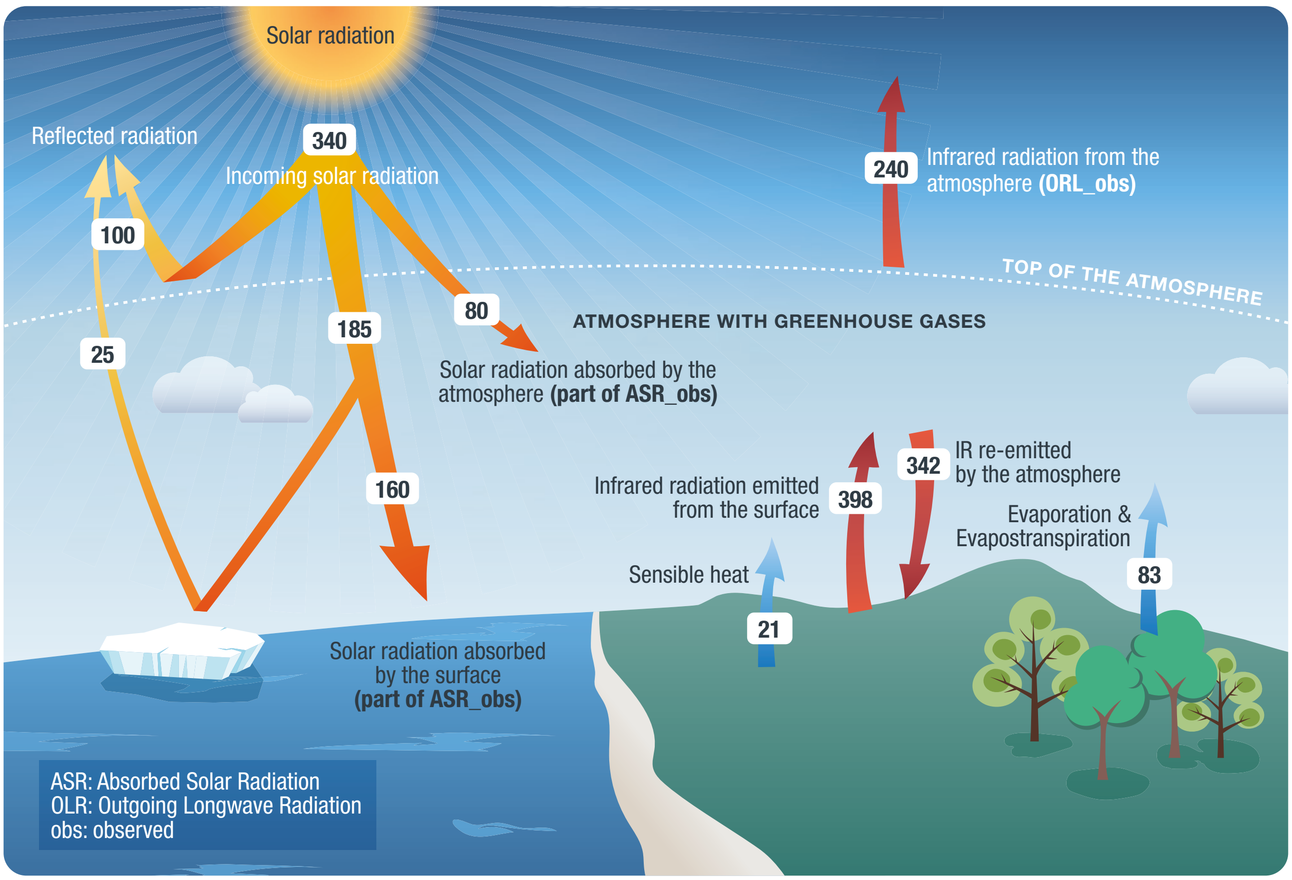
Open the *Jupyter Notebook* in your web browser: **https://jupyter.org > Try > Jupyter Notebook**.
(Direct link: https://jupyter.org/try-jupyter/notebooks/?path=notebooks/Intro.ipynb)

Jupyter Notebook is an environment that can manage two types of 'cells': blocks of *Markdown* text that can be formatted like in a regular text editor, and blocks of *Code* that interpret Python lines. In this very first page, you can see one *Markdown* cell entitled 'Introduction', a *Code* cell indexed '[1]:' with the Python syntax highlighted, then an automated graphic cell called by the former *Code* cell, and finally a second *Markdown* cell proposing further demos.

When browsing and clicking on the various cells, the dropdown menu at the top of the page will indicate the cell type (markdown, code, raw) that is selected. When you're selecting a *Code* cell, you can use the *Run* command (6th button from the left): this will compile and run the Python code from the first to the currently selected cell.



In order to load the notebook, click on the 'Jupyterlite' logo. This will open the page https://jupyter.org/try-jupyter/tree/ listing all the available files. Locate the file **'greenhouse.jpynb'**. If you can't find it, you may upload it manually from any location on your hard drive. Then double-click on the file name to open it. Now, follow the notebook, explore the code, and answer the questions. The following figure may help.



Schematic representation of the global mean energy budget of the Earth. The numbers indicate best estimates for the magnitudes of the globally averaged energy balance components in W/m^2, representing climate conditions at the beginning of the 21st century.

Sources: 2021 IPCC WG1 Figure 7.2 of IPCC AR6 WG1 Chapter 7 (p.934), and Météo-France. Adapted from a figure page 19 on https://www.statistiques.developpement-durable.gouv.fr/edition-numerique/chiffres-cles-du-climat-2023/pdf/chiffres-cles-du-climat-2023.pdf

LESSON 5 CLIMATE MODELS ARE EVOLVING

MAIN SUBJECTS
Physics
History
Mathematics
Computer science

DURATION
Preparation: 15 min
Activity: 2h

AGE GROUP
15+ year-old students

TEACHING METHOD
Documentary analysis

LEARNING OUTCOMES
Students learn that climate models evolve over time thanks to technical improvement and the integration of new climatic elements, resulting in increasingly accurate models.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2.3 Problem framing

CONCEPTS COVERED
Climate models, weather prediction, climate projection

PREPARATION 15 MIN

- Print out **WORKSHEET 5.1** (for each student).
- Computers or notepads for groups of 4 to 6 students.
- Videos:

'Evolution of video games'.

WATCH THE VIDEO ↗

You can choose to use a screenshot or **WORKSHEET 5.1**.

'What is a climate model?' CLIM video, by Roland Séférian, climatologist at the CNRM, Météo-France/CNRS, France.

WATCH THE VIDEO ↗

'Can we trust climate projections?' CLIM video, by Birgit Hassler, research scientist at the DLR Oberpfaffenhofen, Germany.

WATCH THE VIDEO ↗

> **TEACHER TIP**
> This activity is based on a comparison between computer games simulating a football (soccer) game and climate models simulating the climate. You can choose to introduce this activity with a live game of football with your students.

INTRODUCTION 15 MIN

Start with a discussion about video games and computing in general. Ask the students what they know about video games: *when were they invented and how have they evolved?*

In a way, a climate model is similar to a video game. In the following activity, we will compare video games (football) and climate models by analysing video games (videos and pictures).

PROCEDURE 1H30

Divide the students in groups of 4 to 6.

PART 1: VIDEO GAMES AS MODELS OF THE REAL WORLD 45 MIN

Watch the video 'Evolution of video games' and discuss. This video can be considered a model of a football game, which is created by the computer (hardware and software).

- Remind the students of the definition of a model.
- *Is this video game a good reproduction of a football game?*
  - list aspects that closely resemble real-world *football*;
  - list what is missing when compared to a real-life experience;
  - *do you think this model provides an enjoyable virtual football experience for the player of the video game?*
- *Would you say that playing a virtual football game helps to improve football playing skills in real life? Why?*

Watch the video again, focusing on the evolution of video games.
Discuss within the groups:

- Describe the evolution of video football games. List all the changes.
- Compare the first and last video game: *Which one would you rather play, and why?*
- Why are older video games less realistic than newer ones?

Now use **WORKSHEET 5.1.** Ask the students the same questions as before. You may wish to add the following:

- *What are the components of a climate model?*
- *How do modelers manage to represent the different elements of the climate system?*
- *How have climate models changed over time? Name two types of change.*
- *How do scientists incorporate human activity into their models?*

Class discussion and intermediate conclusion:
Discuss each group's answers as a class.
Video games are **models that represent the real world in a virtual setting/environment.** Game developers incorporate elements of playing live football into the software to produce a 'good' model of a football game. 'Good' means that the model adequately represents reality, and in the case of video games, the player has an enjoyable gaming experience.

In the past decades, video games have advanced alongside computer technology, integrating more details (e.g., spectators, commentators) which better simulate reality. However, while modern games are more realistic and pleasant to play, they will never be a true substitute for a live football game.

PART 2: CLIMATE MODELS 45 MIN

Divide each group into two subgroups of 2-3 students. Each subgroup watches one of the two CLIM videos and comes up with a set of four questions for a quiz about the content of the video. Then, they switch places: they watch the other video and answer the quiz.

If needed, you may give the students the following examples:
Quiz for the video 'What is a climate model?':

1. *What are the components of a climate model?*
2. *What is behind all these computer code lines?*
3. *How do modellers represent the different elements of the climate system?*
4. *How did climate models evolve over time? Name two types of changes.*

Quiz for the video 'Can we trust climate models?':

5. *What are the differences between weather predictions on TV and climate projections?*
6. *How can one determine the accuracy of a model?*
7. *Give an example of an uncertainty that is complex to include into a climate model?*
8. *What do scientists use to take into account human activity in the models?*

Class discussion and intermediate conclusion:
Ask the groups to discuss their answers with the whole class. Then, say a new discussion by asking:

To what extent can we say that a video game and a climate model are similar?

To build a climate model, scientists include the – necessary and sufficient – components of the Earth system into their computer program in order to adequately reproduce the Earth's climate. However, they are limited by their understanding of the climate system and available technology.

What are the similarities and differences in the evolution of climate models and video games?

Both have evolved over time, adding more elements to reproduce the real world as accurately as possible. Technical improvements help to increase both the resolution and accuracy of them.

What do climate scientists consider to be a 'good' model?

Climate models, nevertheless, are used to predict possible future scenarios and make projections, which is not what a video game does. For scientists, a 'good' model is a model that adequately reproduces reality in the scope defined by certain assumptions. For example, climate models are not designed to make precise weather predictions but can replicate long-term climate trends. This fact is one of the three builders of confidence for any numerical model (as explained by Birgit Hassler in the video). Other model assessments focus on the adequate reproduction of the variability of the mean climate, or regional patterns and their trends over a given historical period.

What are the limits of models or video games to reproduce the real world?

Integrating more detailed information into the program increases the accuracy of the model. However, this means increased computation time and computing power, which means higher costs. For video games, this may also 'slow down' the game and render it unplayable on old equipment. The amount of information that can be included also depends on available technology (i.e. a computer with a high-quality graphic card).

WRAP-UP 15 MIN

Climate models are computer models that simulate (parts of) the real world (e.g. the climate system), just as video games simulate a part of the real world (playing a football game).

The outcomes of climate models are statements about the real climate system. However, the accuracy and resolution of these statements depend on the quality of the model. Climate models have become increasingly accurate over time and continue to evolve with scientific and technological advancements. In the end, models are valuable tools to guide climatologists, researchers, policymakers and citizens to make informed decisions to mitigate climate change.

BACKGROUND FOR TEACHERS

HOW DO WE UNDERSTAND CLIMATE CHANGE NOW COMPARED TO WHEN THE IPCC STARTED?

The first IPCC report (1990) concluded that human-caused climate change would soon become evident but couldn't definitively confirm ongoing climate change at that time. Today, the evidence is overwhelming. With much more data, older records of past climates, and an increasingly ingenious use of models, we now have a better understanding of how the atmosphere interacts with the ocean, ice, snow, ecosystems, and land surfaces on Earth. Computer simulations of climate have improved drastically, incorporating many more natural processes, and providing more detailed projections of the future climate.

TO GO FURTHER

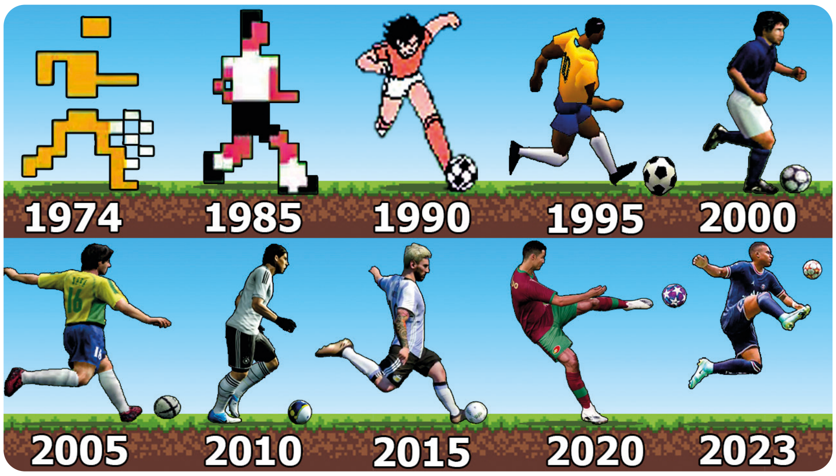
The grandfather of today's climate models:
https://earthobservatory.nasa.gov/blogs/earthmatters/2015/05/21/see-one-of-the-first-climate-models/

Sample elements of climate understanding, observations and models as assessed in the IPCC First Assessment Report (1990) and Sixth Assessment Report (2021). Many other advances since 1990, such as key aspects of theoretical understanding, geological records and attribution of change to human influence, are not included in this figure because they are not readily represented in this simple format.

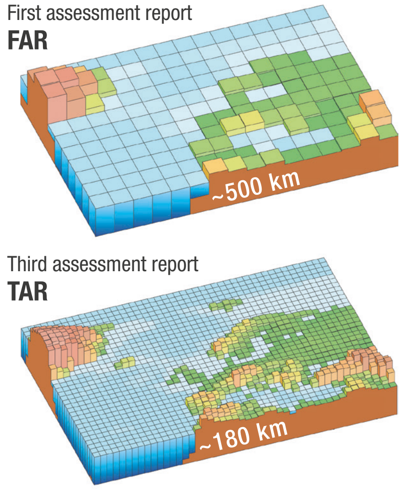
Adapted from IPCC AR6. Source: 2020, Frederikse et al., 2021 IPCC AR6 WG1 Chapter 1, Frequently Asked Questions (p.7). Available on the IPCC website (https://www.ipcc.ch/report/ar6/wg1/downloads/faqs/IPCC_AR6_WGI_FAQ_Chapter_01.pdf).

WORKSHEET 5.1

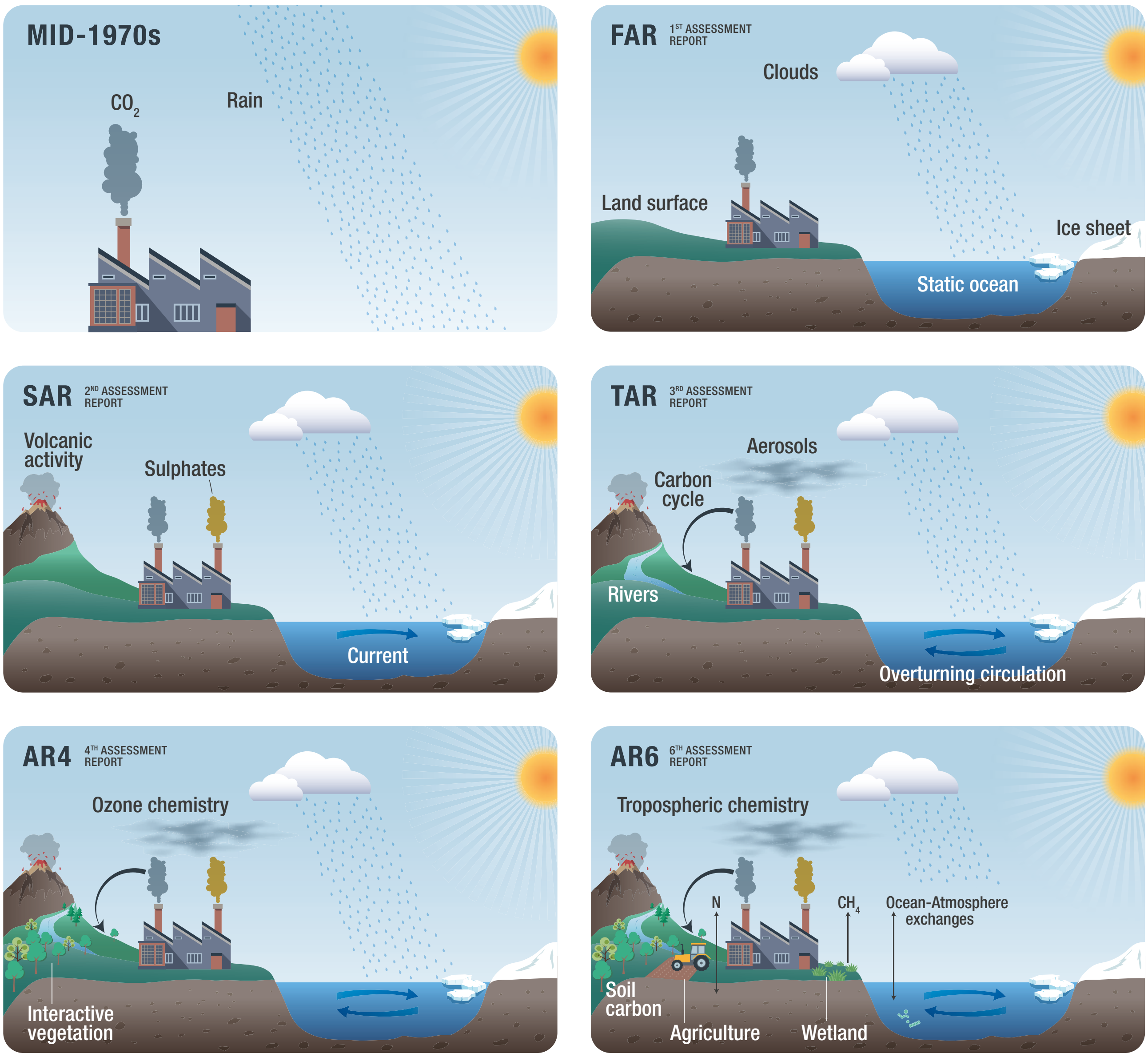
THE EVOLUTION OF
AVATAR REPRESENTATION IN VIDEO GAMES
OVER TIME



THE EVOLUTION OF
CLIMATE MODEL RESOLUTION
OVER TIME



THE EVOLUTION OF
RESOLUTION AND PARAMETERS TAKEN INTO ACCOUNT IN CLIMATE MODELS
OVER TIME



Source: 2007, adapted from Figures 1.2 and 1.4, IPCC AR4, The Physical Science Basis, available on the IPCC website (https://www.ipcc.ch/report/ar4/wg1/).

LESSON 6 VALIDATION OF NUMERICAL MODELS

MAIN SUBJECTS
Physics

DURATION
Preparation: 30 min
Activity: 1h30

AGE GROUP
15+ year-old students

TEACHING METHOD
Documentary analysis
Digital experiment

LEARNING OUTCOMES
Students discover how the reliability of numerical models can be assessed through the reproduction of present and past events, prediction of future events, etc.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2.1 Systems thinking

CONCEPTS COVERED
Radiation, absorption, emission, opacity, scenario, pathway, albedo, projection

PREPARATION 30 MIN

- Download and install the *SimClimat*. It is free educational software for climate simulations which helps introduce the concept of feedback and stability. There are many examples of how to use *SimClimat* for educational purposes, from the elementary school level to the university level. It is available in English and French, for Windows, Mac or smartphones via Google Play and Apple Store. The setup is quite straightforward, with no options to choose except the download folder.
- Print out **WORKSHEET 6.1** (one worksheet per pair of students).
- Print out **WORKSHEETS 6.2** or **6.3** (one pair of worksheets per pair of students).

The best way to carry out this activity is to have students work in pairs. In large-scale computer projects, ‘pair programming’ is very common: one person does the coding/programming while the other takes notes, checks for errors, contributes ideas and advice etc. Obviously, the roles should be switched regularly!

INTRODUCTION 10 MIN

Do a brief recap of the previous lessons: the interdependence of physical parameters (lesson 2), feedbacks (lesson 3), as well as inputs, sampling and outputs of numerical models (lesson 4).

How to check the trustworthiness (or ‘validity’) *of a numerical model?*

- Test the model against known data (this is the case we will deal with).
- Test each part of the model separately (also called ‘performing unitary tests’).

Each pair of students gets **WORKSHEET 6.1**.
Half of the pairs also get **WORKSHEETS 6.2** [CURIOUS], whereas the other half gets **WORKSHEETS 6.3** [EXPERT].

PROCEDURE 1H

> **TEACHER TIP**
> Using SimClimat in the classroom: a tutorial for teachers (You can subtitle this video in any language by modifying the settings).

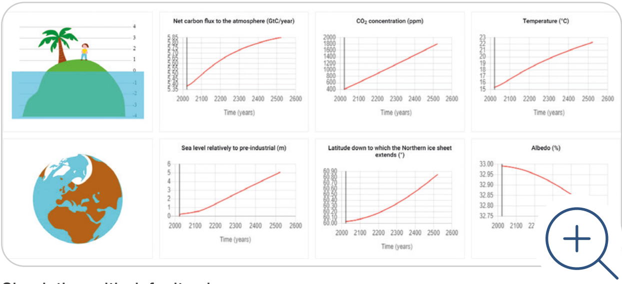
PART 1: GETTING STARTED WITH SIMCLIMAT [WHOLE CLASS] 10 MIN

For this part, use **WORKSHEET 6.1**.
The entire class follows the instructions to run their first simulation, with all values set to default. This enables the students to learn how the interface works. It is very intuitive:

1. Change the current language, access the documentation, and click on *Run simulation*.
2. Initial state of the simulation: date (from a drop-down menu) and duration (in years).
3. Aesthetic choices for the output graphs.
4. At the bottom of the screen, there are three tabs to change the input parameters:
   ~ Tab for astronomical parameters. For instance, click on *Earth-Sun distance*: two options are available (note that there is an ‘explanatory figure’, which will come handy for the definitions of precession or eccentricity).
   ~ Tab for CO_2 emissions.
   ~ Tab for climate feedbacks.

Run a first simulation – with all values set to default – by clicking on the yellow button.

> **TEACHER TIP**
> Screenshots of the solutions can be found on page 56.
> Each time a large preview is proposed to observe simulation results, it will be indicated as follows:
> VIEW LARGER



Simulation with default values.
Swipe to watch them all on small display screens.

VIEW LARGER
PAGE 56

Read and analyse each of the eight outputs. Note that the two pictures on the left illustrate the content of two of the diagrams. You may adjust some of the parameters:

- A slider at the bottom allows one to change the current date and animate the two pictures.
- There is a full reset button in the upper-left corner.
- With the toolbox in the upper-right corner, you may – from left to right – read the details of each simulation, save the session, save one of the simulations, export a simulation, save all outputs as pictures, or add a new simulation without erasing the current one(s). This last button will prove to be very practical.

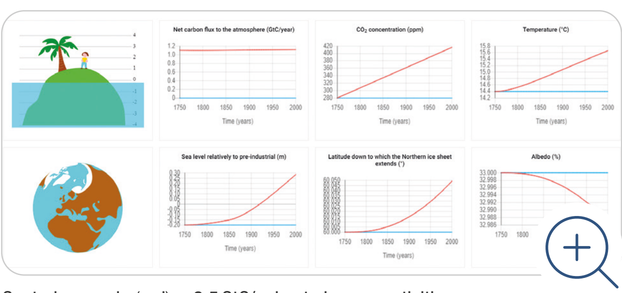
All together, students answer the questions listed on the **WORKSHEET 6.1**:

1. In 2100, global warming reaches +1.5°C, and sea level rise by 50 cm. This is consistent with the goals of the Paris Agreement.
   Warning: by default, the simulation ends in 2520!
2. The user can modify 17 input parameters (e.g. astronomical parameters, CO_2 emissions, climate feedbacks). The output of the simulation consists of six diagrams, for example: 'CO_2 concentration', 'net carbon flux', and 'albedo'.

Student pairs can now run various simulations. The teacher could ask them to prepare a short presentation to share their results during the group session at the end of the lesson.

PART 2 (GROUP 1): MODELLING CURRENT OBSERVATIONS [CURIOUS] 50 MIN

For this group, use **WORKSHEET 6.2**.



Control scenario (red): +2.5 GtC/y due to human activities
Simulation (blue): zero anthropogenic emissions

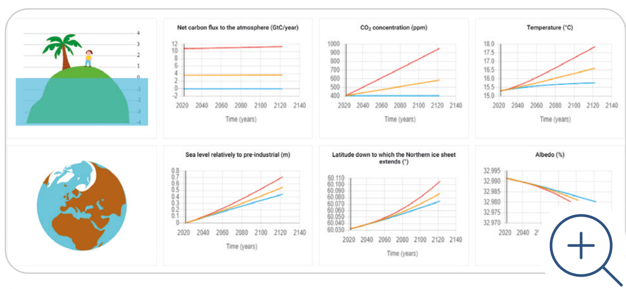
VIEW LARGER
PAGE 56

1. While the various reconstructions do not align precisely, they generally reproduce similar trends. All the reconstructions, as well as the direct measurements, show a suddenwarming of around 1°C over the past 150 years.
2. Input parameters, like CO_2 concentration, must be a single constant value. Between +0 GtC/year in 1750 before the Industrial Revolution and the +12 GtC/year current rate, *SimClimat* proposes a weighted average of +2.5 GtC/year.
3. With zero anthropogenic emissions, the various output parameters remain constant. This supports the fact that anthropogenic emissions are the major cause for rapid climate change since the late 19th century.

> **TEACHER TIP**
> How to convert emissions of CO_2 into emissions of C? Carbon (C) has an atomic mass of 12 and oxygen (O) has an atomic mass of 16. Thus, CO_2 has an atomic mass of 44. This means that one ton of carbon is equivalent to 3.67 tons of CO_2.
> For comparison: In 2021, total global emissions amounted to 37 Gt of CO_2 (source: Global Carbon Budget, 2023). This corresponds to: 37/3.67 = 10 Gt of carbon.

Conclusion: Starting from data recorded in 1750, *SimClimat* can reproduce the current measurement trend in 2000-2020, which builds a level of confidence in the model.

The second set of simulations explores the concept of **scenarios**: a given set of input parameters be it sensible, utopic or unrealistic. Each simulation using a given scenario will lead to results for the future – these cannot be proved wrong or true in advance and are thus called **projections**.



Control scenario (orange). Pessimistic scenario (red).
Optimistic scenario (blue)

VIEW LARGER
PAGE 56

Students answer the questions on the worksheet. The answers are:

4. The higher the anthropogenic emissions, the higher the rate of global warming. This is logical.
5. Due to the thermal inertia of the system, **the temperature continues to increase** before stalling. (This optimistic scenario differs from the pre-industrial simulation seen before, with 'zero anthropogenic emissions': between the two starting dates, anthropogenic GHG emissions were implicitly taken into account).
6. The pessimistic, control, and optimistic projections resemble the RCP8.5, RCP4.5, and RCP2.6 pathways adopted by the IPCC.

Conclusion: *SimClimat* can be used to roughly mimic the more complex models used by climate scientists. By defining likely **scenarios** for the future, *SimClimat* can give **projections** for the future climate.

PART 2 (GROUP 2): MODELLING ICE AGES [EXPERT]
50 MIN

For this group, use **WORKSHEETS 6.3**.

Document 4 shows the temperature trend in Antarctica reconstructed from the isotopic composition of ice cores in Vostok (Antarctica).
We observe a strong temperature variability, with warm periods every 100,000 years, known as interglacials, interspersed with periods that are colder (by around 10°C), known as glacial periods.

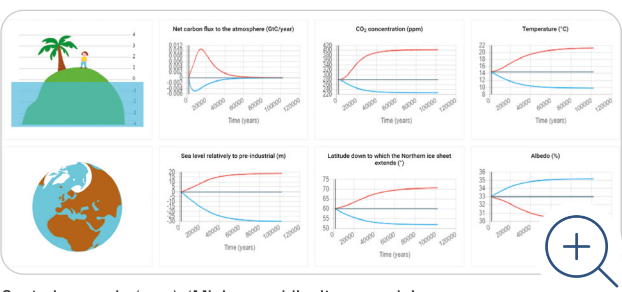
TEACHER TIP
Mathematically, the laws of physics can be computed even if the sign of the time variable *t* is negative. Thus, starting from the present day, and going backwards in time, a good model should be able to reproduce past data. However, *SimClimat* cannot go backwards in time.

Analysis of the Milankovic's cycles: the orbital parameters of the Earth are responsible for ice ages to occur approximately every 100,000 years (do not hesitate to use the 'explanatory figures' included within *SimClimat* to help students understand what orbital parameters are). The answers to the questions are:

1. We count 9 maxima in eccentricity, 20 maxima in obliquity, and 21 maxima in precession.
2. Respectively, 7 (i.e. 77.7%), 18 (90.0%), and 21 (56.7%) of these maxima do coincide with temperature maxima. As a consequence, we prefer focusing on obliquity.
3. Most frequently, there is a maximum in temperature when obliquity is at its maximum.

TEACHER TIP
Actually, whenever one orbital parameter is at its peak, there is an increase in temperature. But obliquity is the most obvious one here, and the easiest one to understand.

In the next experiment the temperature should increase when obliquity is at its maximum.

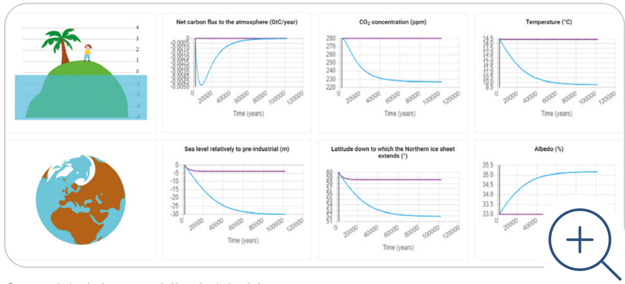


Control scenario (grey). 'Minimum obliquity scenario' (blue). 'Maximum obliquity scenario' (red).

VIEW LARGER PAGE 57

4. The control simulation is very stable.
5. Our hypothesis is confirmed: **when obliquity is at its maximum, temperature increases**, and **the lowest temperature occurs at minimum obliquity,** even though it takes millennia to reach equilibrium.
6. The coldest simulation, in blue, agrees on the temperature (-4.6°C vs -5°C), but underestimates the sea-level drop (-30m only vs -130m).
7. In the blue simulation (corresponding to a glaciation), the Earth's albedo increases and the atmospheric CO_2 concentration decreases.

The students first test the albedo. A constant albedo should lead to a constant temperature.

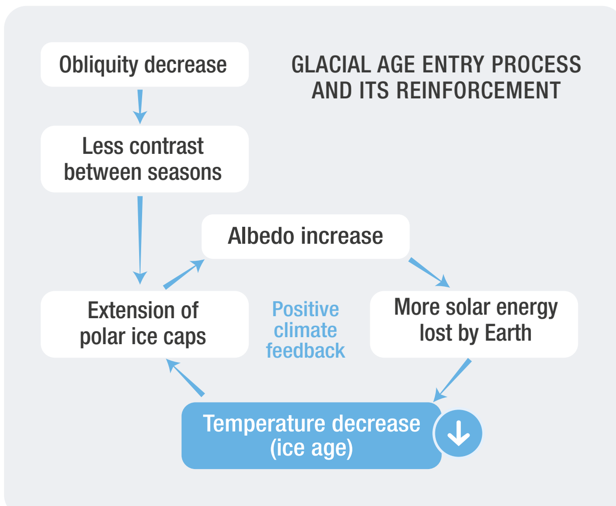


Control (minimum obliquity) in blue
Minimum-obliquity & constant-albedo simulation (purple)

VIEW LARGER PAGE 57

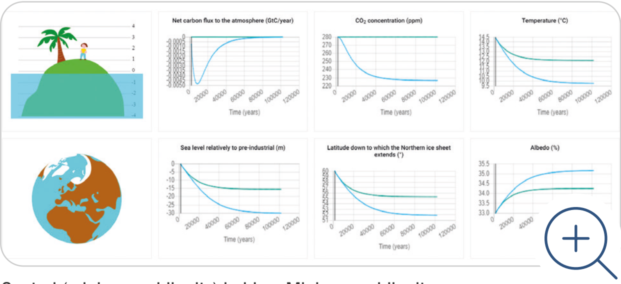
The answer to the corresponding question on the worksheet is:

8. Yes, **a constant albedo leads to a constant temperature.** As a consequence, in real life, there must be an albedo feedback that directly generates a cooling of the planet.



Note that the case 'Less contrast between seasons' also means 'cooler with longer summers and warmer with longer winters. Indeed, summers are rather cool and snow do not melt completely.'

Optionally, students can verify the oceanic carbon sink feedback: a constant solubilisation rate for CO_2 should lead to a constant temperature.

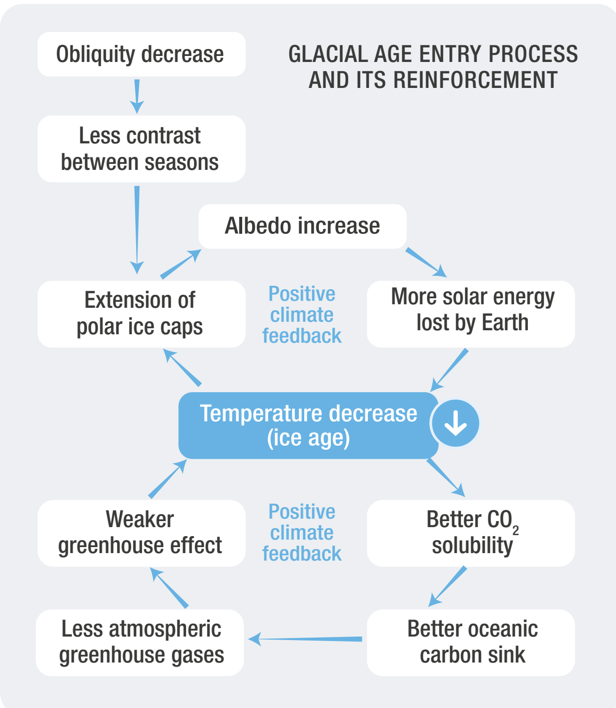


Control (minimum obliquity) in blue. Minimum-obliquity and constant-solubilisation simulation (green).

VIEW LARGER
PAGE 57

The students answer:

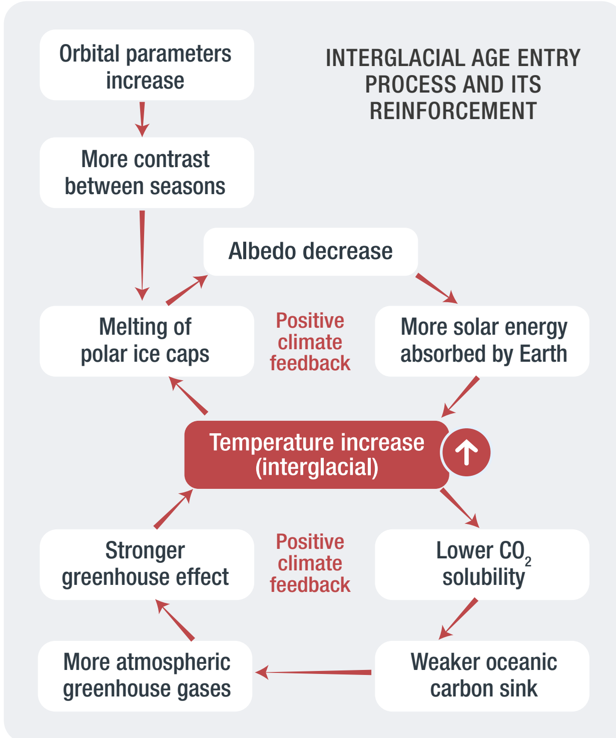
9. The temperature is not constant. A constant solubilisation rate hinders the glaciation process, but it does not stop it.



10. From these two experiments, we can conclude that the albedo feedback is predominant compared to the oceanic sink feedback. In real life, the albedo feedback triggers the beginning of a glaciation, which is slightly enhanced by the ocean carbon sink feedback.

Orally confirm that all of this is true as far as the other orbital parameters are concerned. (If there is time left, more advanced students may test another orbital parameter following the same method).

In addition, can the students imagine what the contrapositions of the two feedback loops are?



Conclusion: *SimClimat* does reproduce the trends of paleoclimates, which builds a level of confidence in the model.

WRAP-UP 20 MIN

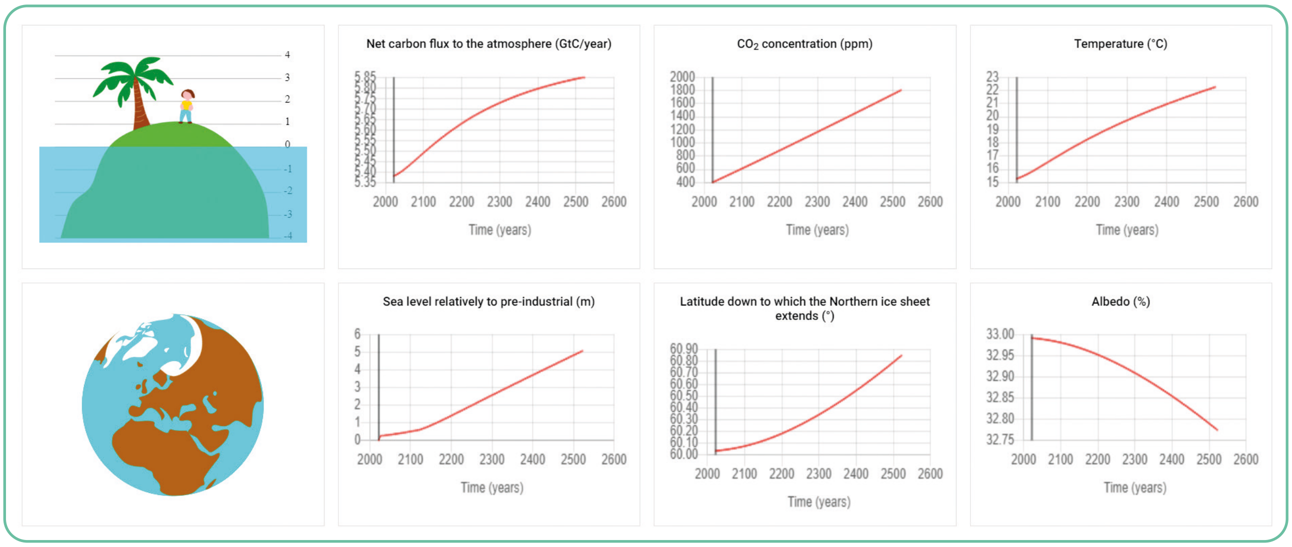
Each pair of students take turns explaining their findings to the class. SimClimat is in particular capable of reproducing present-day measurements, simulating paleoclimates, and simulating several positive feedbacks.

To check the validity of any model, one has to perform tests that are compared to 'real' climate data. The more tests it passes, **the stronger the confidence** in the model. However, uncertainties still exist! This is why IPCC reports use many models simultaneously – the global trends of parameters and the differences between the different models are both taken into account.

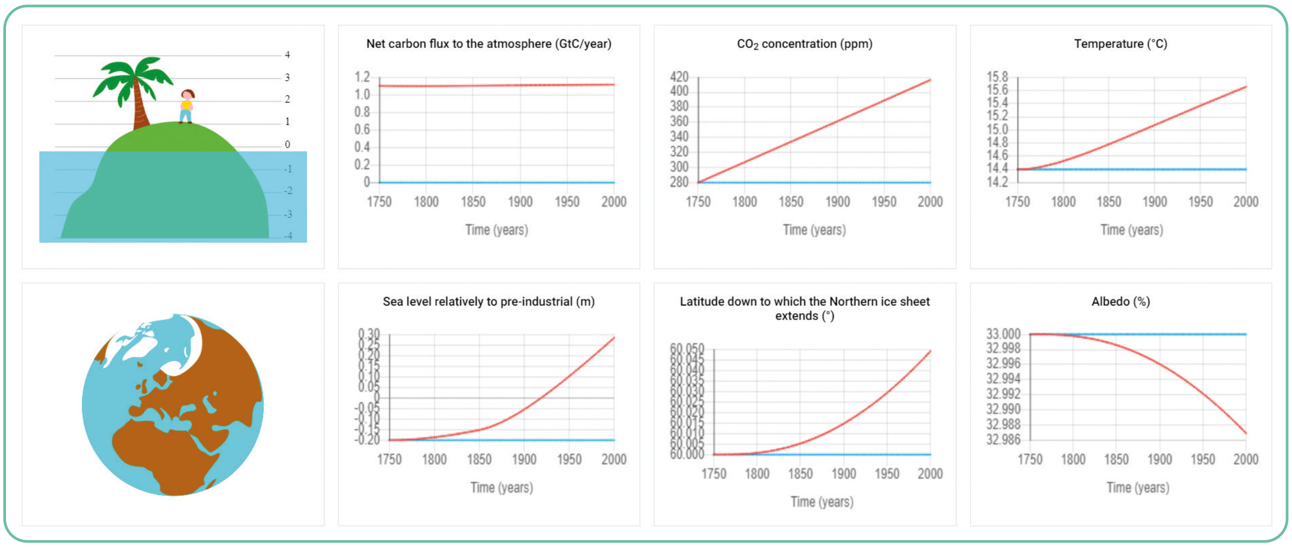
Summarise:

- Numerical climate models are **assessed** by their ability to reproduce well-documented facts:
  - historical and/or present-day measurements;
  - paleoclimates like ice ages and interglacials;
  - eventually, other planet's climate.
- **Confidence** is built when simulation data aligns with real data.
- A trustworthy model can be used in different ways:
  - A scenario is a given set of input parameters, chosen for historical, political, and ethical reasons.
  - While a simulation is one run of a model for one set of inputs, a projection is a particular simulation that cannot be compared to real data, because it explores a prediction of plausible future events.
  - IPCC compiles projections from many different models, gathering the most reliable trends for the future.

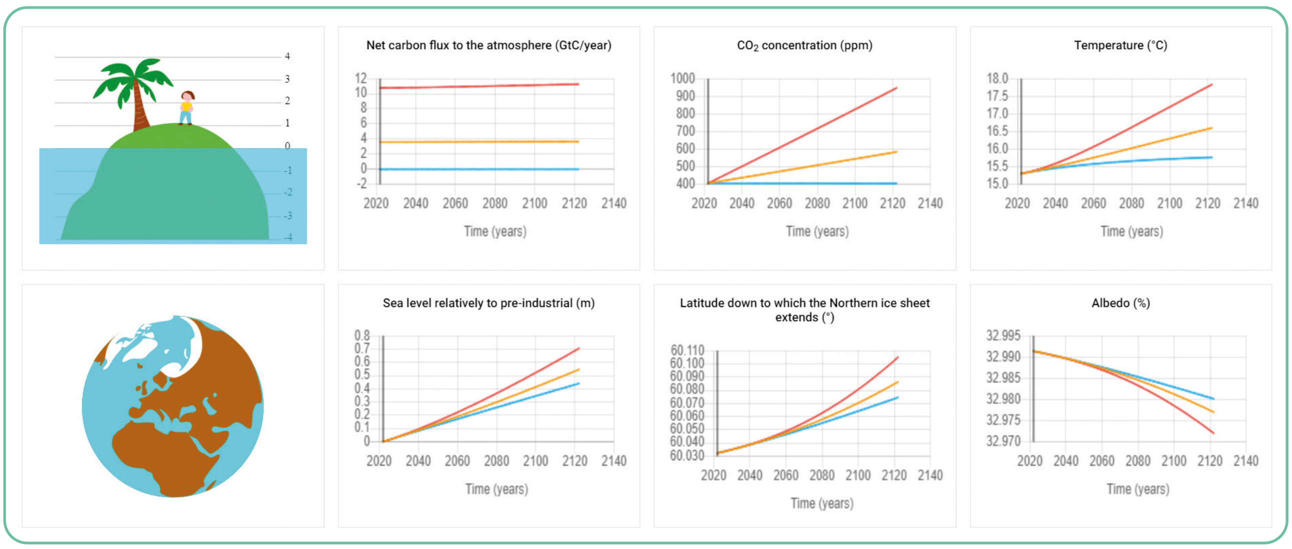
SIMCLIMAT: SCREENSHOTS OF THE SOLUTIONS



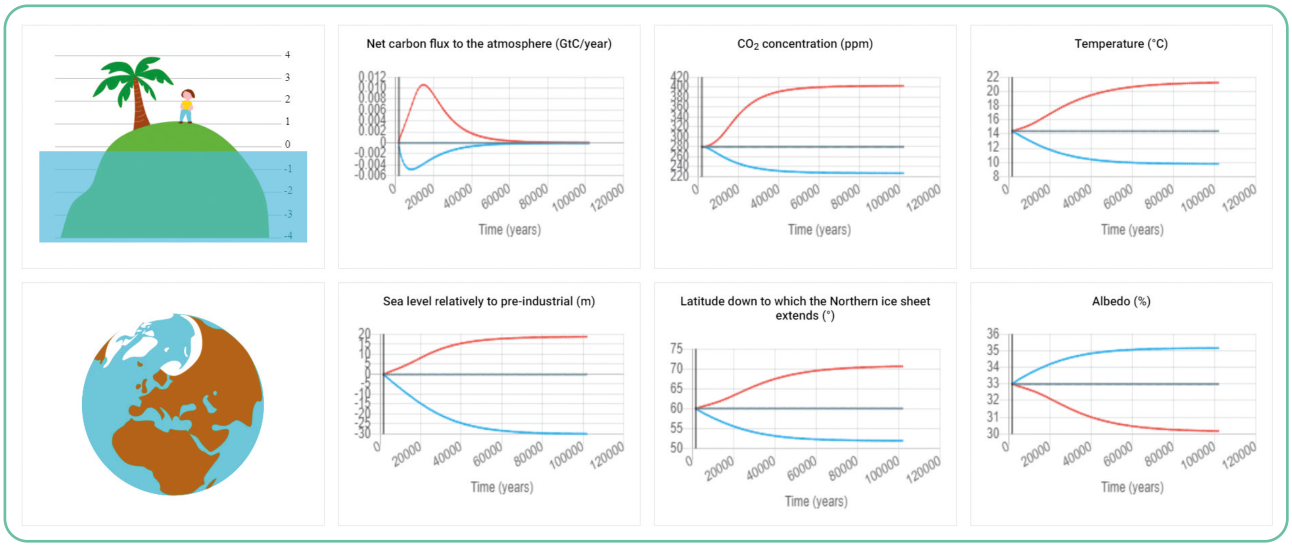
SimClimat simulation with default values. (Note: swipe to watch them all on small display screens).



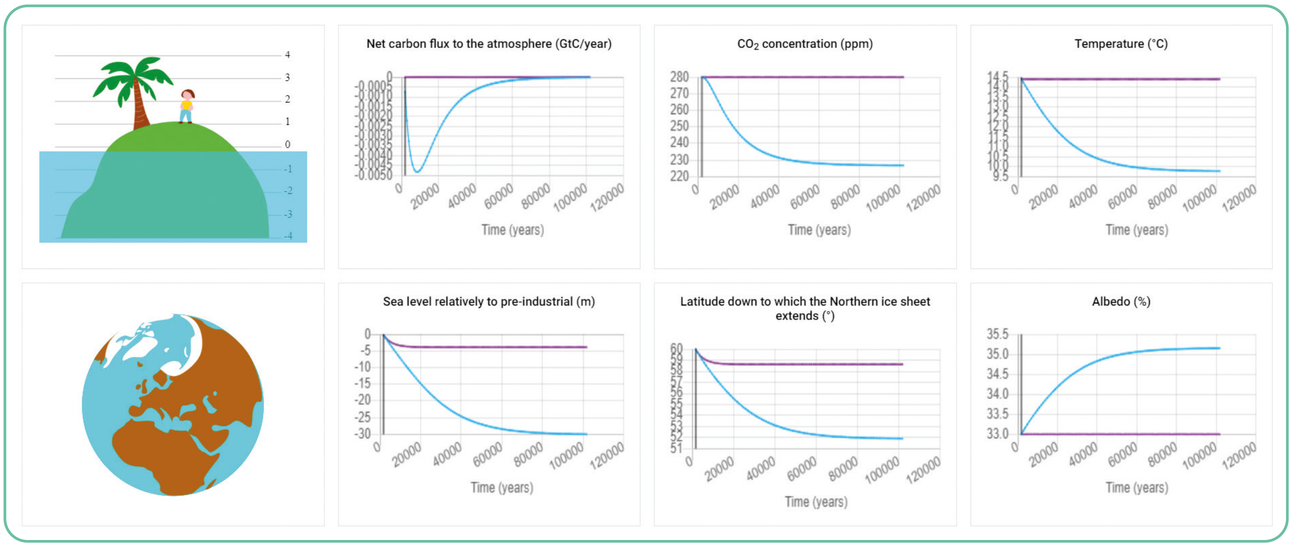
Reproducing current observations with SimClimat. Control scenario (red): +2.5 GtC/y due to human activities. Simulation (blue): zero anthropogenic emissions.



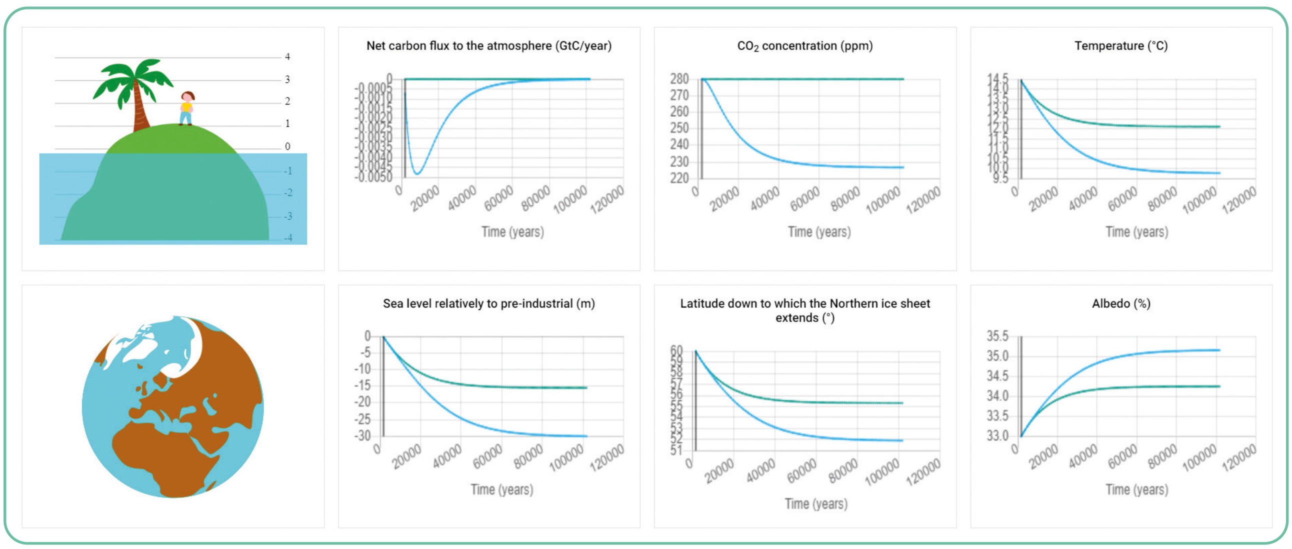
Using SimClimat for climate projections. Control scenario (orange). Pessimistic scenario (red). Optimistic scenario (blue).



Checking the influence of obliquity. Control scenario (grey). 'Minimum obliquity scenario' (blue). 'Maximum obliquity scenario' (red).



Probing the albedo feedback. Control (minimum obliquity) in blue. Minimum-obliquity & constant-albedo simulation (purple).

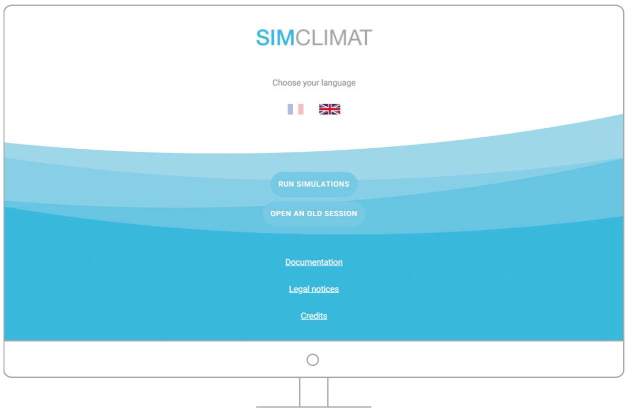


Probing the oceanic sink feedback. Control (minimum obliquity) in blue. Minimum-obliquity and CO_2-constant-solubilisation simulation (green).

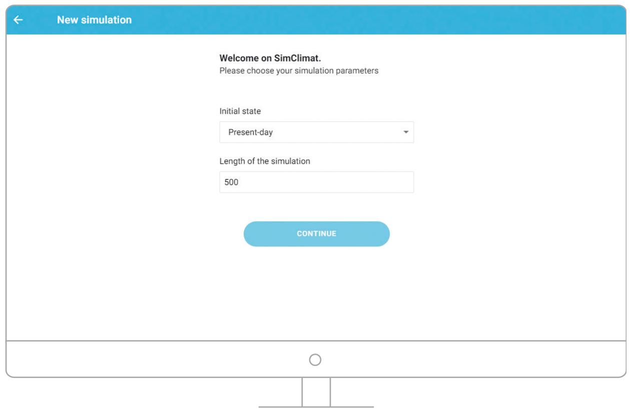
WORKSHEET 6.1

GETTING STARTED WITH SIMCLIMAT

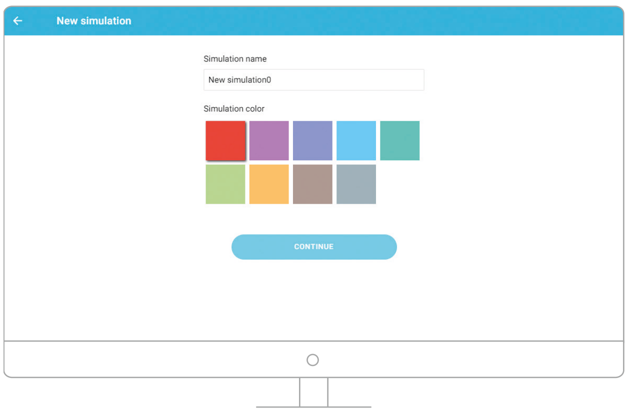
Launch *SimClimat* and run your first simulation with all the default values.



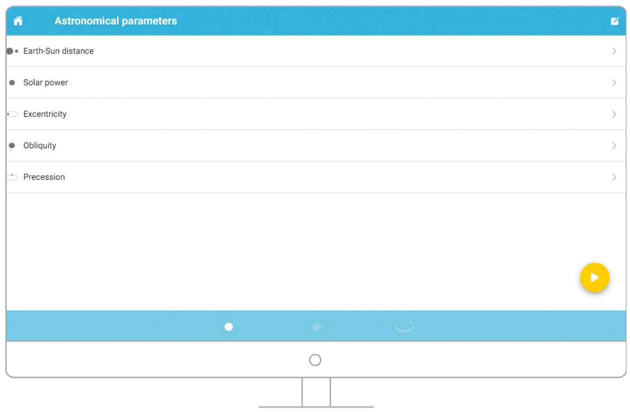
Landing page



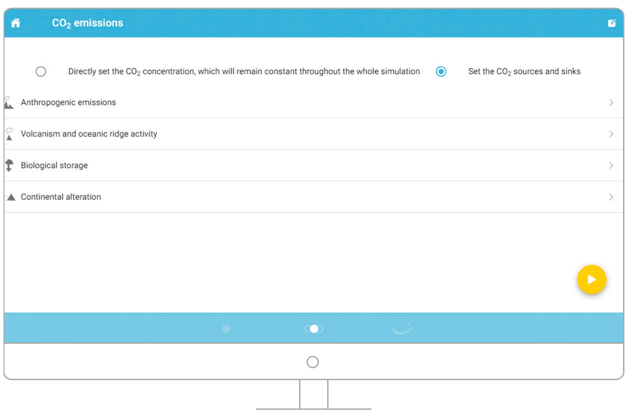
SCREEN 1
Initial date and simulation duration



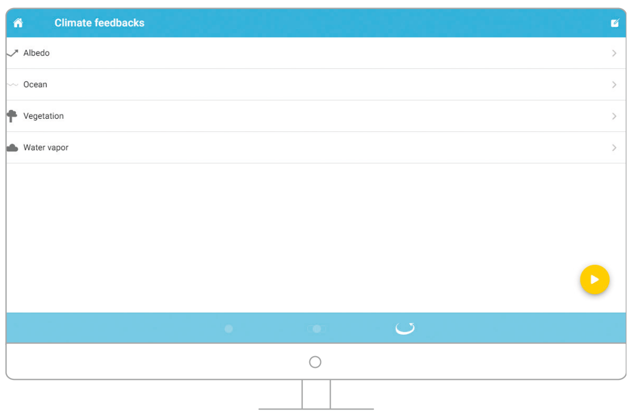
SCREEN 2
Colour and name of the simulation



SCREEN 3 - FIRST TAB
Astronomical parameters



SCREEN 3 - SECOND TAB
CO_2 emissions



SCREEN 3 - THIRD TAB
Climate feedbacks

Question 1. By default, *SimClimat* assumes anthropogenic CO_2 emissions of 12 Gt/year. Does this simulation illustrate what you've heard about the Earth's climate in 2100? (hint: use the slider to read all the graphs at the right date).

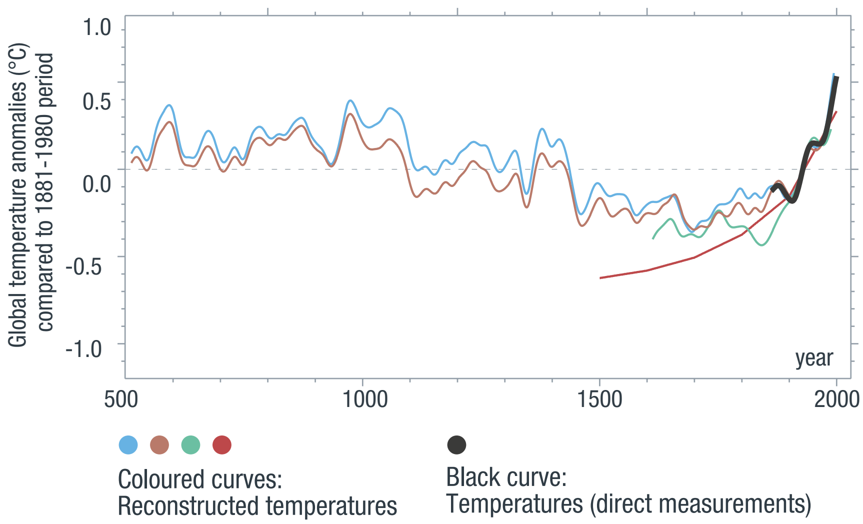
Question 2. *SimClimat* is a numerical model. Can you list all its inputs and outputs?

MODELLING CURRENT OBSERVATIONS

Question 1. From documents 1 and 2, describe how average temperatures have changed in the past. Explain the cause of this recent evolution.

Document 1. Trends in global temperature anomalies over the last 1,500 years, according to different paleoclimatic reconstructions

The document shows the evolution of global temperature anomalies over the last millennium, according to different reconstructions based on palaeoclimatic archives (tree rings, ice cores, historical harvest dates, etc.) and direct measurements **(black curve).**

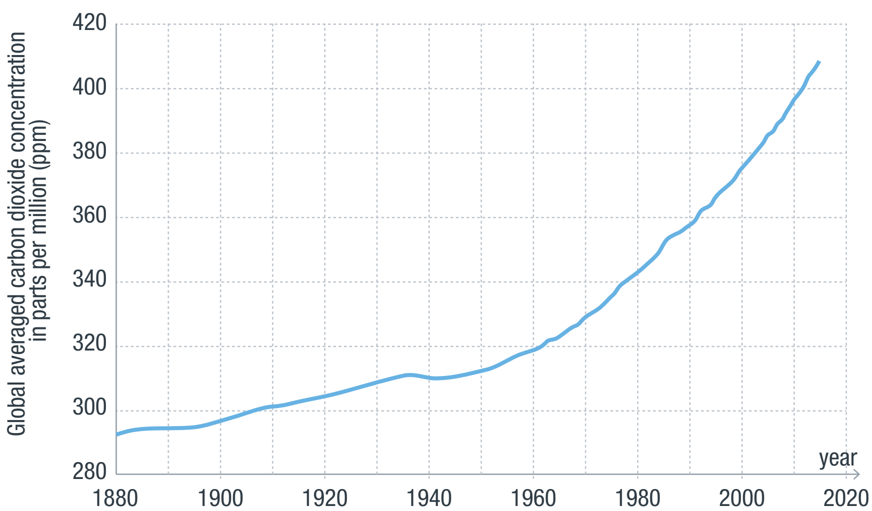


Source: 2007, IPCC AR5 WGI Chapter 5. Adapted from Figure 5.7.
(https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf).

Document 2. Evolution of the atmopsheric Carbon dioxide concentration since 1880

This dramatic increase is due to anthropogenic emissions, typically through the combustion of fossil fuels.

Climate change is mainly caused by this increase in CO_2 concentration.



Source: 2021, ESRL/ETHZ/NCEI. Adapted from the Figure ‘Atmospheric carbon dioxide and Earth’s surface temperature’.
Available on the NOAA Climate.gov website (https://www.climate.gov/media/13560)

→ Use SimClimat to run and compare the two simulations hereafter using the following scenarios:

EXPERIMENT #1	CONTROL SCENARIO	SIMULATION
Initial state	Pre-industrial	Pre-industrial
Length of simulation	250 years	250 years
Anthropogenic emissions	+2.5 GtC/y	+0.0 GtC/y

MODELLING CURRENT OBSERVATIONS

Question 2. Why did the control scenario use a +2.5 GtC/year value for the anthropogenic emissions when the present-day value is closer to 12 GtC/year[1]?

Question 3. Describe the climate in 2000 assuming zero anthropogenic emissions. What seems to be the major cause of rapid climate change in the last century?

SimClimat seems to be able to reproduce present-day measurements, but can it give us a glimpse of what the Earth's climate will be in the future? We start from the scientific consensus that the increase in global temperature is due to the increase of greenhouse gases emitted into the atmosphere by human activities. In the future, we could assume that CO_2 emissions will remain constant. Or, we can assume that emissions will continue to rise as a result of population growth and higher living standards around the world. Or, ideally, we can assume that, when facing the risks associated with global warming, governments will take drastic measures and CO_2 emissions will decrease.

→ Use SimClimat to run and compare the two simulations hereafter, using the following scenarios:

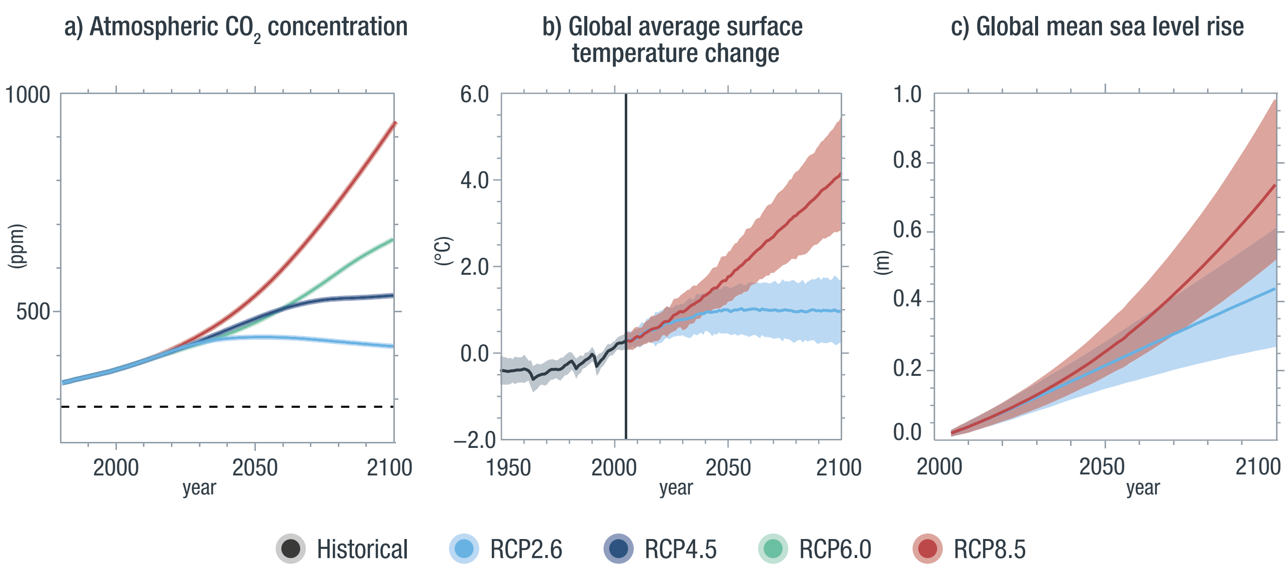
EXPERIMENT #2	CONTROL SCENARIO	PESSIMISTIC SCENARIO	OPTIMISTIC SCENARIO
Initial state	Present-day	Present-day	Present-day
Length of simulation	100 years	100 years	100 years
Anthropogenic emissions	+8.0 GtC/y	+24.0 GtC/y	+0.0 GtC/y

Question 4. Explain the evolution of the global temperature and its cause.

Question 5. Describe the temperature evolution in the optimistic scenario.

Question 6. The climate projections assessed in the IPCC reports are based on simulations using different climate models that are much more complex than *SimClimat*. Document 3 shows the global temperature change (b) and global sea level rise (c) projections for different atmospheric CO_2 concentration scenarios (a). Which scenario is the optimistic one? The pessimistic one? How do these compare to your *SimClimat* simulations?

Document 3. Projections made by the models participating in the Coupled Model Intercomparison Project (CMIP)



Adapted figures. Source: 2013, IPCC AR5 WG1 Fig SPM. Available on the IPCC website (https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_SPM_FINAL.pdf)

a) Four different scenarios for changes in atmospheric CO_2 concentration.
b) The bold lines indicate the anomaly of the mean surface temperature on Earth (difference with respect to the 1850-1900 value), simulated with the different climate models, for the RCP2.6 (blue) and RCP8.5 (red) scenarios. The envelope around the bold lines corresponds to all the values simulated by the different models.
c) As for (b) but for the sea level rise.

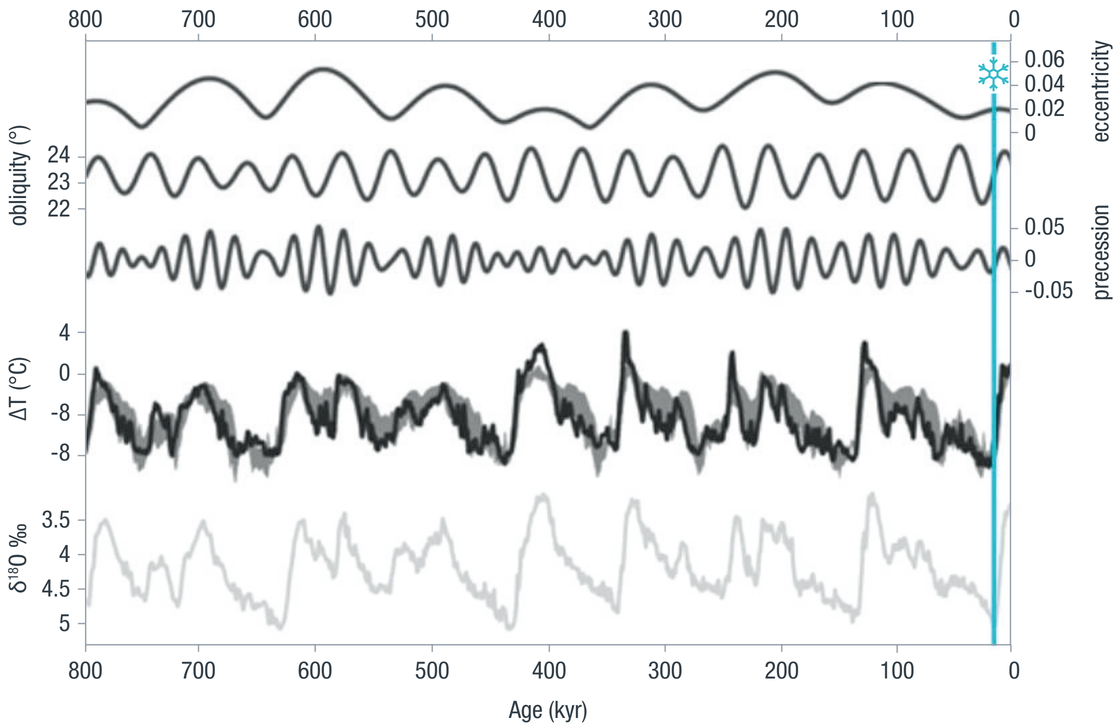
1 Source: Global Carbon Budget, 2023. https://globalcarbonbudget.org/download/933/?tmstv=1701441499

MODELLING ICE AGES

Currently, we are in an interglacial period that has lasted for the past 10,000 years, with the last glacial maximum occurring 21,000 years ago. Temperature reconstructions in other parts of the world, combined with sedimentary archives, show that during the last glacial maximum, the global temperature was 5°C lower than now, an ice cap covered the whole of Northern Europe, and sea levels were 130m lower than now.

Document 4. Isotopic composition measured in ice cores from Vostok, Antarctica

Temperature anomaly deduced from the isotopic composition of ice cores.
Variations of the Earth's orbit on geological time scales are defined by three orbital parameters: precession, obliquity, and eccentricity.
The light blue line corresponds to the last glacial maximum (21,000 years ago).



Source: 2013, IPCC AR5 WG1 Chapter5. Adapted from the Figure 5.3 p.400: 'Orbital parameters and proxy records over the past 800 kyr'.
Available on the IPCC website (https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_all_final.pdf)

Hypothesis: Regardless of atmospheric CO_2 concentration, could orbital parameters be the reason for the Earth's surface temperature variations?

Question 1. Find and list the local maxima of the eccentricity, obliquity, and precession curves.
Question 2. How many of these eccentricity maxima coincide with temperature maxima or minima? How about obliquity and precession maxima?
Question 3. Formulate your own hypothesis: 'Most frequently, there is a maximum in temperature when...'. Test your hypothesis with *SimClimat* in the following experiment.

MODELLING ICE AGES

→ Use SimClimat to run and compare the simulations hereafter, using the following scenarios:

EXPERIMENT #3	CONTROL SCENARIO	SCENARIO 'MIN OBLIQUITY'	SCENARIO 'MAX OBLIQUITY'
Initial state	Pre-industrial	Pre-industrial	Pre-industrial
Length of simulation	100,000 years	100,000 years	100,000 years
Obliquity	Present-day (23.5°)	Minimum (21.8°)	Maximum (24.4°)

Question 4. How stable is your control simulation?
Question 5. Is your hypothesis on the link between temperature and obliquity confirmed or refuted?
Question 6. In your 'coldest' scenario, how do sea level and ice cap coverage compare to the historical measurements quoted hereinabove?

Although the modification of orbital parameters can be the cause of ice ages, it does not change the total amount of solar energy received by the Earth annually. Follow-up question: What is induced by the orbital parameters that could subsequently start a glaciation period?

Question 7. In the board game you played in lesson 3, there was a card about 'Albedo climate feedback'. Would a high albedo limit or reinforce glaciation?

EXPERIMENT 4.

Hypothesis: Obliquity influences the amount of energy received by the polar caps in summer, and the subsequent melting. As albedo is the fraction of solar radiation reflected into space, the wider the ice cap, the higher the albedo and the less energy is kept by the Earth. Thus the albedo feedback could start a glaciation.

EXPERIMENT #4	CONTROL SCENARIO	SIMULATION
Initial state	Pre-industrial	Pre-industrial
Length of simulation	100,000 years	100,000 years
Obliquity	Minimum (21.8°)	Minimum (21.8°)
Albedo	Default (computed by *SimClimat* as a function of temperature, permitting the feedback)	Constant as its pre-industrial value (33%)

Question 8. Is your hypothesis confirmed or disproved?

EXPERIMENT 5 (OPTIONAL)

Hypothesis: The ocean can act as a carbon sink because CO_2 is dissolved in water. CO_2 dissolves more easily in cold water. Air bubbles found in Antarctic ice cores confirm that during ice ages, atmospheric CO_2 concentration is 100 ppm lower than during interglacials. Thus the oceanic sink feedback could start a glaciation.

EXPERIMENT #5	CONTROL SCENARIO	SIMULATION
Initial state	Pre-industrial	Pre-industrial
Length of simulation	100,000 years	100,000 years
Obliquity	Minimum (21.8°)	Minimum (21.8°)
Ocean carbon sink	Default (computed by *SimClimat* as a function of temperature)	Independent of temperature and remains as today

Question 9. Is your hypothesis confirmed or disproved?
Question 10. Which of these two is the dominant feedback?

LESSON 7 BUILDING SCENARIOS AND OBSERVING MODEL RESPONSES

MAIN SUBJECTS
Mathematics
Physics
Biology

DURATION
Preparation: 10 min
Activity: 1h

AGE GROUP
15+ year-old students

TEACHING METHOD
Documentary analysis
Creation and analysis of diagrams

LEARNING OUTCOMES
Students make choices and adjust parameters to build different scenarios. They look at projections to assess the impact of their choices. The scenarios they will build depend on choices made by farmers and the responses are based on biology. Similarly, IPCC scenarios are based on societal choices, and the climate responses are based on science.

TARGETED SUSTAINABILITY COMPETENCE
Domain 1 – Embodying sustainability values
Competency – 1.1 Valuing sustainability

CONCEPTS COVERED
Parameters, scenario, societal choices, climate simulation, climate projection

PREPARATION 10 MIN

- Computer and audio equipment to show in class the three videos:

'The Earth's climate system' CLIM video, by Fiona O'Connor (MET Office Science, United Kingdom).

WATCH THE VIDEO ↗

'Climate change: Pathways for Mitigation' CLIM video', by Joeri Rogelj (Imperial College London, United Kingdom).

WATCH THE VIDEO ↗

'The United Nations Climate Change Conferences' CLIM video, by Sofia Palazzo (Imperial College London, United Kingdom).

WATCH THE VIDEO ↗

- Print **WORKSHEETS 7.1** and **7.2** for each pair of students.
- Print **WORKSHEET 7.3** for each pair of students [TRAINEE].
- Use a computer and a digital version (e.g. LibreOffice or OpenOffice) of the table from **WORKSHEET 7.4** for each pair of students [CURIOUS].

INTRODUCTION 30 MIN

In sequence A, students saw that mankind is responsible for current climate change caused by large amounts of greenhouse gases emitted into the atmosphere since the Industrial Revolution.

Ask your students several questions about link between food and greenhouse gases emissions such as:

- *Where does your food come from? Your family's garden? The supermarket? A farm?*
- *What is a dairy farm?*
  Possible answers: A dairy farm produces milk. The cows eat grass (or are fed hay, soya, corn, etc. in the barn). The milk can be made into cheese, yogurt or butter, which can be sold at the farm.
- Explain the impact of farming activities on greenhouse gas emissions.

To help students answer these questions, you may watch 'The Earth's climate system' CLIM video. It explains how scientists take into account different parameters (water vapour, liquid water, methane concentration) to study the atmosphere's chemistry.

- *Describe the different types of farms in your country/in the world. What determines how farmers cultivate their land?*
  Expected answers: climate, soil quality, cow breeds used in the region, farming practices in the region, farmer's choices (financial margin, ecological conviction, cultural practices, etc.). Be sure to mention breeds and farming practices if they don't come up in the discussion.

PROCEDURE 40 MIN

1. Students will explore how cow milk is produced. They should read **WORKSHEET 7.1** and fill in the table.

2. Ask the students to put themselves in the shoes of a dairy farmer and to write a short text about their ideal farm. Some students may want to share their text with their peers. They should emphasise the values and opinions that guided their choices. For example, if a student wants their cows to graze in large meadows for most of the day, they were likely motivated by animal welfare and/or ecological concerns. Take note of local customs, culture and economic reasons, if they come up.

3. In this lesson, the farm is located next to a yogurt factory. Ask students to choose a dairy farming model to supply the factory. They should tick their choice on **WORKSHEET 7.2** (only one box to tick: each box already represents a set of parameters).

4. [TRAINEE] can answer the questions on **WORKSHEET 7.3**, whereas [CURIOUS] can work with **WORKSHEET 7.4**.

BACKGROUND FOR TEACHERS

TAKING INTO ACCOUNT ANIMAL WELFARE IN EDUCATION

The younger generation is more aware of animal welfare issues, thanks to social media reports (e.g., on slaughterhouses and mega-fires). This is reflected in changes in the way they consume, and in particular, their diets[1].

Animal welfare is increasingly taken into account in school curricula. However, agronomy teachers still tend to *'avoid controversial knowledge related to cattle emotions as they may conflict with the dominant values and practices of the livestock farming community'*[2].

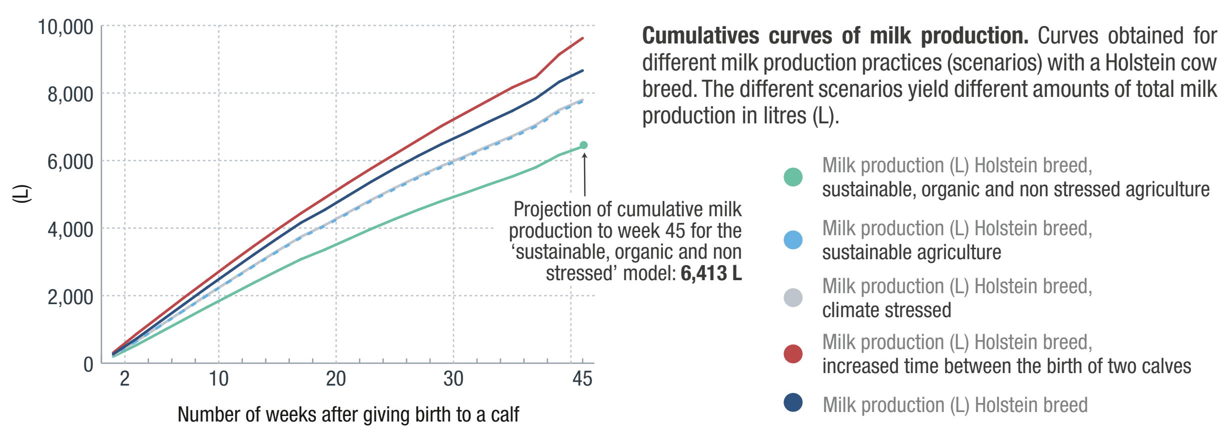
1 Source: 2022, Péraud-Puigségur, S., in: Annuel de la Recherche en Philosophie de l'Education, 2, 1 18, 'La grenouille, la vache et le koala. Que faire de la question animale à l'école de l'anthropocène?'
2 Source: 2028, Lipp, A., et Simonneaux, L., in RDST 18, 137 160, 'Savoirs et controverses liés au bien-être des bovins: Comment des enseignants de zootechnie les prennent-ils en compte?' (https://doi.org/10.4000/rdst.2072)

SOLUTION: WHAT DO STUDENTS OBSERVE IN THEIR DAIRY PRODUCTION?

Students will identify certain parameters that influence dairy the cow milk production (example of intensive agriculture in Paraguay).

They should adjust these parameters (more or less intensive farming, more or less ethical farming, more or less climate stressed) according to their opinions and values.

Finally, they will evaluate their choices by observing projections using different sets of parameters. The projections are based solely on observed data, not on a real model. The emphasis does not lie on the model – the model is considered a 'black box'. Students don't need to know how the milk quantities are calculated for the scenarios. They just need to identify the parameters that determine the different scenarios.



Cumulatives curves of milk production. Curves obtained for different milk production practices (scenarios) with a Holstein cow breed. The different scenarios yield different amounts of total milk production in litres (L).

WRAP-UP 10 MIN

Students have chosen to produce cow milk according to traditions, economic viability and/or ecological aspects. They have chosen a set of parameters (for example, Holstein breed, non-organic farming, climate stressed – which corresponds to the grey curve). By creating their own scenarios, they understand that they are framed by societal choices.

The students have studied the diagram with the **projected** milk production scenarios per cow after the birth of a calf. Some projections yield higher milk production than others (see the curve for intensive farming, for example). Scenarios represent a good analogy for climate scenarios and climate projections: **IPCC scenarios are based on societal choices, and the climate responses are based on science.**

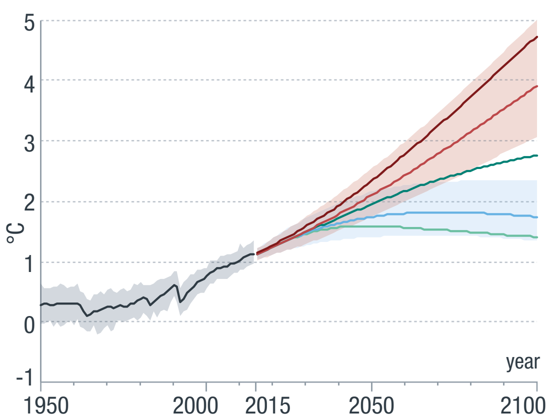
To illustrate possible societal choices and follow a more sustainable pathway, you may watch 'Climate change: Pathways for Mitigation' CLIM video,

BACKGROUND FOR TEACHERS

WHAT ARE IPCC PROJECTIONS?

Scenarios use a set of values for the main climate parameters. There are different hypotheses on how the greenhouse gas emissions (a key climate parameter) will evolve over the coming decades.

A **Shared-Socioeconomic Pathway (SSP)** is a scenario of projected global socio-economic changes that depend on societal choices. These scenarios cover all kinds of projections, from optimistic (drastic reduction of global greenhouse gas emissions) to pessimistic (further increase of greenhouse gas emissions). Five of these scenarios are presented below:



Measured temperature anomalies relative to the periode 1850-1900 (in black, up to today) **and five projections of temperature anomalies according to IPCC scenarios** (in colour, from today to 2100)

Measured temperatures

Projections: SSP1-1.9 SSP1-2.6 SSP2-4.5 SSP3-7.0 SSP5-8.5

Shades represent very *likely* range around the SSP1-2.6 and SSP3-7.0 projections.

Source: 2021, IPCC AR6. Adapted from the Figure SPM.8a 'Global surface temperature change relative to 1850-1900'. Available on the IPCC website (https://www.ipcc.ch/report/ar6/wg1/figures/summary-for-policymakers/figure-spm-8/).

Each scenario is labelled to identify both the level of greenhouse gas emissions and the Shared Socio-economic Pathway (SSP) used in the calculations. These scenarios are used as input data for climate models, which in turn calculate the corresponding change in climate.

Previously, **RCP trajectories for 'Representative Concentration Pathways'** were used to evaluate different scenarios of GHG emissions. However, unlike SSP scenarios, RCPs do not take into account socio-economic changes. Nevertheless, there are similarities between these two types of scenarios, as indicated in the table below.

SSP SCENARIO	CLOSEST RCP SCENARIO	COMMENT
SSP1-1.9	No equivalent RCP	Very optimistic
SSP1-2.6	RCP2.6	Optimistic
SSP2-4.5	RCP4.5	Business as usual
SSP3-7.0	Between RCP6.0 & RCP8.5	Pessimistic
SSP5-8.5	RCP8.5	Very pessimistic

Source: 2021, IPCC AR6 Cross-Chapter Box 1.4. Adapted from Table 1 'The SSP scenarios used in this Report'. Available on the IPCC website (https://www.ipcc.ch/report/ar6/wg1/figures/chapter-1/ccbox-1-4-figure-1).

The scenarios studied by the IPCC describe very different warmer worlds. SSP1, for example, assumes a world based on sustainable development – it is the most optimistic scenario. Guided by strong international cooperation, societies move towards a more sustainable path, with the emphasis shifting from economic growth to more inclusive development that respects the environment and human well-being. Inequalities are reduced, both between and within countries. Consumption is geared towards low material growth and the use of fewer resources and less energy.

Numerical models can be used to anticipate future climate changes. Climate models simulate the evolution of the climate of each scenario. For example, we can see that the SSP1 scenario is the only one that meets the objectives of the Paris Agreement, keeping global warming below 1.5°C. Using the interactive IPCC atlas, you can compare how the climate evolves between two scenarios, by looking at several variables of the mean climate (e.g., mean temperature, total precipitation) and climate extremes (e.g., number of days above 35°C).

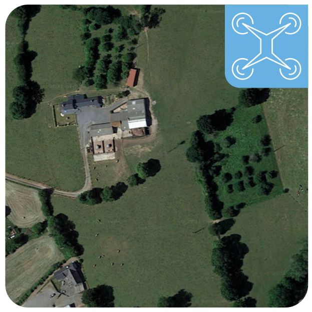
These climate trends are widely used and cited by the parties during the COPs. To illustrate this point, you may watch 'The United Nations Climate Change Conferences' CLIM video, by Sofia Palazzo (Imperial College London, United Kingdom).

WORKSHEET 7.1

THREE EXAMPLES OF COW FARMING

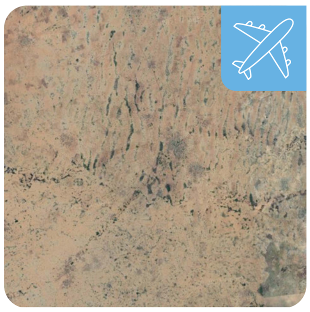
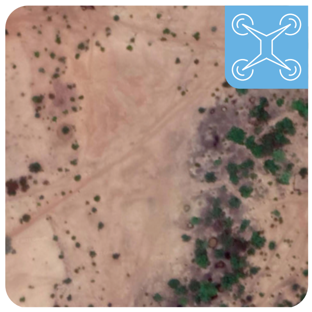
Plane view   Drone view   Pedestrian view

FRANCE: NORMANDY ‘BOCAGE’ LANDSCAPE


Normandy, in France, still has small-scale agriculture, with family-run farms. The meadows are small and delimited by hedges forming what is called the ‘bocage’. This landscape contains a very rich biodiversity, especially insects and birds, which benefit from many trees and shrubs. The traditional way of farming is to breed Normandy cows for milk (to make Camembert, for example), but also for meat. Cattle release methane into the atmosphere, which is a powerful greenhouse gas. In France, the cow breeds used are highly productive: Normandes and the dominant breed, Holstein. Certain breeds are raised specifically for meat production: Charolaise, Limousine and Corse.

BURKINA FASO: THE FULANIS’ ZEBUS


The Fulani people have large herds of zebus, a species related to cows. They get milk from the female cows and use the bulls for draught power. On special occasions, they eat the meat. Cattle release methane into the atmosphere, which is a powerful greenhouse gas. These animals graze across large, very arid areas and drink from big watering holes created by humans. Intense and increasingly frequent droughts linked to climate change are causing yield losses and herd mortality.

PARAGUAY: CATTLE FARMS



In Brazil and Paraguay, farmers cut down the forests to create space to raise cows. Cows live in dense groups within giant corrals to provide meat for the local population and for export outside South America. Cows are the main emitters of methane, a major greenhouse gas. Deforestation also contributes to climate change.

DIFFERENT TYPES OF COW FARMING IN THE WORLD

	LOCATION / CLIMATE	TYPE OF FARMING AND PRODUCTION	SIZE OF LAND NEEDED FOR FARMING (SMALL? LARGE?)
FRANCE **NORMANDE ‘BOCAGE’ LANDSCAPE**			
BURKINA FASO **THE FULANIS’ ZEBUS**			
PARAGUAY **CATTLE FARMS**			

WORKSHEET 7.2

PARAMETERS OF COW FARMING (ONLY ONE BOX TO TICK)

TYPE OF PARAMETERS

☐ FARMING MODEL **INTENSIVE, NO STRESS INDUCED BY CLIMATE CONDITIONS**

Intensive livestock farming is characterised by very high meat or milk production yields: animals are kept on a small surface, they receive treatments like antibiotics, are fed with high quality fodder and milked using automated machines. This kind of farming requires large amounts of energy and products (fuel, plant protection products, crop fertilisers). It has a huge impact on the environment.

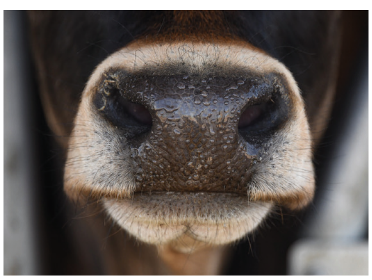
TYPE OF PARAMETERS

☐ FARMING MODEL **ORGANIC AGRICULTURE, NO STRESS INDUCED BY CLIMATE CONDITIONS**

Organic farming uses only organic fertilisers. Organic pest control (with predatory insects, for example) and polyculture are often employed. In organic farming, using synthetic substances is prohibited or strictly limited. Organic farming is more sustainable.

TYPE OF PARAMETERS

☐ FARMING MODEL **STRESS INDUCED BY CLIMATE CONDITIONS: HIGH-TEMPERATURE, HIGH-HUMIDITY**



Experimentally, it is possible to modify the temperature and humidity in the barn to generate stress in the cows. This stress simulates heat wave to see how it affects agricultural production.

TYPE OF PARAMETERS

☐ FARMING MODEL **EXTENDED LACTATION, NO STRESS INDUCED BY CLIMATE CONDITIONS**

For a cow to produce milk, she has to give birth to a calf. 40 to 50 weeks (on average) after giving birth to a calf, the cow doesn't produce any more milk and the dairy farmer doesn't earn any more money. Animal protection organisations and some farmers recommend allowing cows to rest between litters (this is known as **'extended lactation'**).

TYPE OF PARAMETERS

☐ FARMING MODEL **'SUSTAINABLE AGRICULTURE', NO STRESS INDUCED BY CLIMATE CONDITIONS**

These farms are close to an extensive model, but **'Sustainable farms'** are characterised by an economically, self-sufficient and autonomous production system based on grazing. Animals spend more time outdoors, with more grazing land available, which is treated with less fertilisers and chemical products than in conventional farming. This type of agriculture aims to protect and support biodiversity.

WORKSHEET 7.3

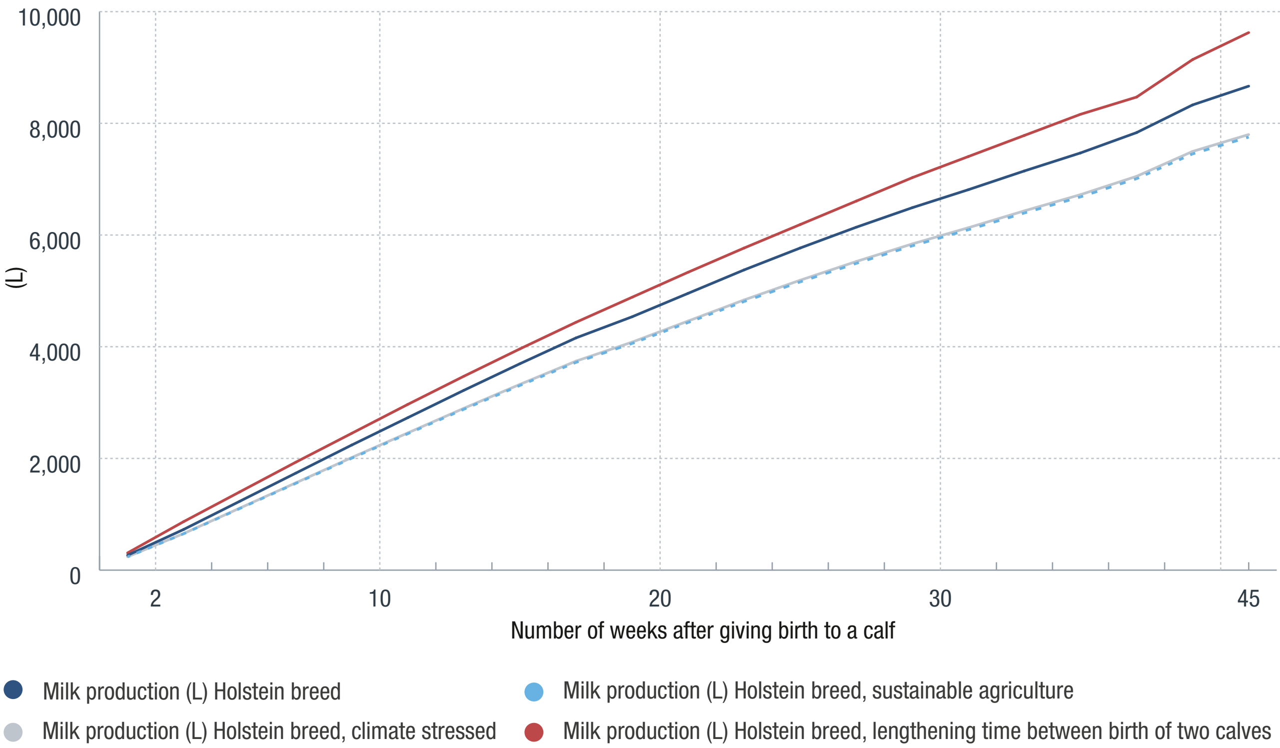
TRAINEE

CUMULATIVE CURVES OF MILK PRODUCTION SINCE CALF BIRTH

Question 1. Draw, in green, the curve corresponding to the cumulative milk production (L) from 'Holstein breed, sustainable and organic agriculture, **non stressed'.**

Question 2. Find the total production (in L) at the end of this period of milk production by a cow after giving birth to a calf: that is a projection (a milk production projection).

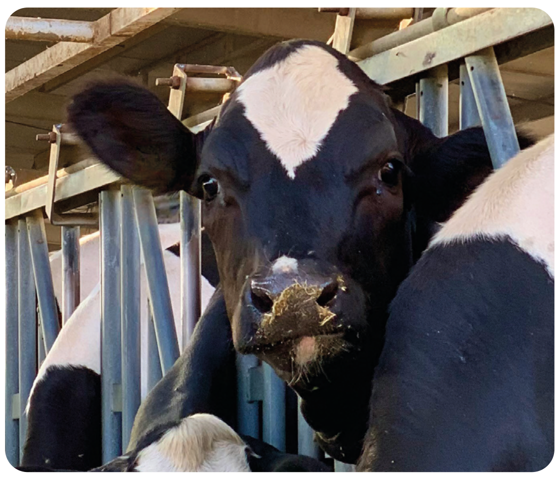
Question 3. Assess which scenario is the most productive (the one with the greatest projection). Assess your own scenario in comparison to others.



Number of weeks after giving birth to a calf																				
2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	42	45
Cumulative milk production (L) Holstein breed, sustainable and organic agriculture, **non stressed**																				
197	539	912	1,285	1,658	2,020	2,383	2,735	3,077	3,357	3,667	3,978	4,268	4,544	4,803	5,041	5,290	5,528	5,797	6,164	6,413

Data extracted from:
2013, Brocard et al., 'Conséquences techniques et économiques de l'allongement à 18 mois de l'intervalle entre vêlages chez les vaches laitières, 3R', (https://uploads-ssl.webflow.com/6135efc5e59d238060fe5710/61c346373c5fcc91cc3898c9_2021_Conduite_TVZ_allongement%20des%20lactations.pdf)

Additional data are extrapolated from the milk production decrease extracted from:
2019, L'observatoire technico-économique des systèmes bovins laitiers du réseau CIVAM, 'Comparaison des performances des exploitations d'élevage herbivore en Agriculture Durable avec celles du RICA' (https://www.civam.org/ressources/reseau-civam/agriculture-durable-thmatique/observatoire-technico-economique-des-systemes-bovins-laitiers-2021/)
2023, S. Mattalia et al., 'Quels sont les effets du réchauffement climatique sur les performances des vaches laitières?', (https://idele.fr/detail-article/quels-sont-les-effets-du-rechauffement-climatique-sur-les-performances-des-vaches-laitieres)


Holstein breed.

WORKSHEET 7.4

CURIOUS

CUMULATIVE MILK PRODUCTION AS FUNCTION OF DIFFERENT PARAMETERS

Question 1. Download the table and calculate the cumulative milk production since the birth of the calf. Record these values in a new table.
Question 2. Draw curves corresponding to each scenario. Give a title to your graph and for each scenario, determine the milk projection for week 45.
Question 3. Define a 'milk production projection'.
Question 4. Evaluate the scenario with the highest productivity (the one with the greatest projection). Assess your own scenario in comparison to the others.

Milk collected during every fortnight from one cow (in litres)

Number of weeks after giving birth to a calf	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	42	45
Milk production (L) Holstein breed	378	350	504	504	504	490	490	476	462	378	420	420	392	372	350	322	336	322	364	496	336
Milk production (L) Holstein breed, lengthening time between birth of two calves	378	490	532	532	518	518	504	490	476	448	448	434	420	420	420	378	378	378	308	672	483
Milk production (kg/d) Holstein breed, climate stressed	340	315	454	454	454	441	441	428	416	340	378	378	353	335	315	290	302	290	328	446	302
Milk production (kg/d) Holstein breed, sustainable agriculture	338	313	451	451	451	438	438	426	413	338	376	376	351	333	313	288	301	288	326	444	301
Milk production (kg/d) Holstein breed, sustainable and organic agriculture, **non stressed**	280	259	373	373	373	363	363	352	342	280	311	311	290	275	259	238	249	238	269	367	249

Data extracted from:
2013, Brocard et al., 'Conséquences techniques et économiques de l'allongement à 18 mois de l'intervalle entre vêlages chez les vaches laitières, 3R', (https://uploads-ssl.webflow.com/6135efc5e59d238060fe5710/61c346373c5fcc91cc3898c9_2021_Conduite_TVZ_allongement%20des%20lactations.pdf)

Additional data are extrapolated from the milk production decrease extracted from:
2019, L'observatoire technico-économique des systèmes bovins laitiers du réseau CIVAM, 'Comparaison des performances des exploitations d'élevage herbivore en Agriculture Durable avec celles du RICA' (https://www.civam.org/ressources/reseau-civam/agriculture-durable-thmatique/observatoire-technico-economique-des-systemes-bovins-laitiers-2021/)
2023, S. Mattalia et al., 'Quels sont les effets du réchauffement climatique sur les performances des vaches laitières?', (https://idele.fr/detail-article/quels-sont-les-effets-du-rechauffement-climatique-sur-les-performances-des-vaches-laitieres)

A cow and its calf.

SEQUENCE C – CLIMATE MODELS TO PREDICT FUTURE

LESSON 8 URBAN HEAT ISLANDS (UHI)

MAIN SUBJECTS
Physics
Natural Sciences
Geography

DURATION
Preparation: 10 min
Activities: 3h (2 x 1h30)
Wrap-up: 20 min

AGE GROUP
15+ year-old students

TEACHING METHOD
Documentary analysis
Multimedia animation

LEARNING OUTCOMES
Using a multimedia animation, students understand what urban heat islands are. They differentiate mitigation and adaptation scenarios, as well as their trade-offs and gains regarding the SDG's.

TARGETED SUSTAINABILITY COMPETENCE
Domain 2 – Embracing complexity in sustainability
Competency – 2.1 Systems thinking

CONCEPTS COVERED
UHI, adaptation, mitigation, SDGs, societal choices, climate projection, cooling solution, maladaptation

PREPARATION 10 MIN

This lesson will be divided into **2 activities of 1.5 hours each** to match the different parts of the multimedia animation. Both are linked, but you can focus on only one of them with your students.

The first activity aims to study the importance of models when predicting the evolution of climate at a global scale between 2020 and the end of the century, with the implementation of mitigation options to face climate change.

The second activity aims to zoom in on cities experiencing the urban heat island (UHI) effect in 2020 and the different solutions that can help limit this effect in 2020 (adaptation options) and confirm their lasting efficiency by the end of the century.

Common equipment for both activities: computer, internet connection or UHI multimedia animation set up on each computer, video projector.

INTRODUCTION

In sequence A, students saw that mankind is responsible for the current climate change caused by large amounts of greenhouse gases emitted into the atmosphere since the Industrial Revolution.

The main learning objectives addressed in this lesson are:

- Without any mitigation solutions the global temperature on Earth will continue to rise above the limit set by the Paris Agreement.
- The urban heat island effect (UHI) corresponds to a positive temperature anomaly measured in urban areas compared to the surrounding rural areas.
- Implementing adaptation solutions today can reduce the UHI effect.
- The implementation of solutions (mitigation, adaptation) to face the UHI effect can also limit the temperature increase by the end of the century; we talk about synergies.
- Some solutions that are implemented today for their efficiency can turn out to be less or no more efficient in the future; we talk about maladaptation.
- The UHI effect issue is closely connected to a number of Sustainable Development Goals (SDGs), and some solutions to face the UHI effect are in line with the achievement of several SDGs.

ACTIVITY 1 1H30

PART 1: GETTING STARTED WITH THE ANIMATION 25MIN

1. Students become familiar with the animation on their own to understand the goal and purpose of using it in the context of studying climate change. Guide them by asking them to think about the objectives of the animation.

2. Together, briefly recap what they did, why, and how to use the animation.

PART 2: LIMITING GLOBAL WARMING TO 1.5°C 55MIN

3. Students work in small groups of 2 or 3. Explain that they have one mission: to limit the temperature increase in 2100 under/at the Paris Agreement objective (around +1.5°C of warming with respect to the 1850-1900 era). Let them research the meaning of the logo next to the global thermometer on the internet. Ask them if the colour of the logo changed after implementing their solutions and what could be the meaning of this change of colour. (It is the logo of COP21 that is displayed as a signal next to the global thermometer: green when the Paris Agreement is achieved, red when the global temperature is too high).

4. Discussion: Each group can present its solution(s) and discuss their feasibility in terms of cost, cultural and ethical implications, and the scale of action (individual, local and/or collective), etc.

PART 3: CONCLUSION 10MIN

There are several ways to stay under +1.5°C.

5. Ask students what mitigation means and why it is important.

6. Ask students if it is possible to reach the Paris Agreement by making efforts in one sector only. Actually, the transformation of all sectors of our society is required (you can even introduce the term **'systemic transformation'**).

7. **Optional** (depending on remaining time): divide the classroom into two groups, one has to find the best combination to achieve the lowest temperature increase by 2100, and the other has to find the best combination to reach the highest temperature increase by 2100.

ACTIVITY 2 1H30

For this part, print out and use **WORKSHEETS 8.1** and **8.2** for each pair of students.

PART 1: SOLUTIONS TO FACE THE UHI EFFECT IN 2020 45MIN

1. Starting point: short offline brainstorming session altogether *1)* ***What is the UHI effect?*** From what they can guess or have heard on the television/internet, students should mention a difference of temperature between urban areas and the countryside. *Why are we interested in it?* and *2) How can we explain this anomaly of temperature in cities? Why is it warmer in urban areas?* **Students have to propose hypotheses to answer these questions.**

2. Then: Each group (2 students per group, one selecting and clicking on the options, the other checking the impact on the city and the temperature levels) chooses one city to begin with (it is up to you to impose the same city for every group or to let students pick the city of their choice).

Students first use the animation in 2020. They should observe a positive temperature anomaly in cities compared to countryside temperature).

- They focus on one or two cities.
- For each city, they have to implement and report various solutions in different sectors (building, agriculture, mobility, energy, urbanism and nature) to reduce the UHI effect represented by the temperature anomaly in the animation.
- Each group presents to the rest of the class the local context before testing their adaptation scenario in the chosen city(ies) and the different tested solutions that led to the reduction of the UHI effect (the presentation of some solutions that have no effect can also be of interest).

The class comes to the conclusion that there are some solutions that can be implemented to mitigate the UHI effect (in 2020).

3. Ask the groups to fill in the table in **WORKSHEET 8.1** and assess the feasibility of one solution they deem pertinent (economically, culturally, technically, etc.).

They must also make connections between these solutions to reduce the UHI effect and the relevant SDGs (available on this website: https://sdgs.un.org/goals or in the **WORKSHEET 8.2**).

PART 2: SOLUTIONS TO FACE THE UHI EFFECT IN 2100 45MIN

The idea in this second part is to look at the changes in 2100 in terms of both global warming and UHI.

1. Start by asking students what they think will be the evolution of both these parameters (countryside temperature and urban temperature anomaly) by the end of the century with the solutions they chose in 2020 (e.g. increase of T° and UHI, increase of T° and decrease of UHI, decrease of T° and UHI, etc.).

2. Students reset the animation (by clicking on the looping arrow), click on 2100, then zoom in on the city(ies) they already studied. In many cases, they will observe an increase in global temperature (represented by the countryside temperature) between 2020 and 2100 as a consequence of global warming with a constant UHI effect. That means that even if the UHI effect does not increase, urban areas are still warming because of climate change.

3. Then, they apply all the solutions they previously selected in the 2020 case study. They observe that the UHI is indeed decreasing, but two variations may arise: on one hand, sometimes the UHI effect does not decrease by the same amount as it did in the 2020 simulation; on the other hand, applying cooling solutions may also have an impact on the countryside temperature. We shall focus on the latter observation.

4. Finally, their objective is to find which cooling solutions have an impact (be it beneficial or aggravating) on climate change, while still decreasing the temperature in the city. Point out synergies to your students (like 'killing two birds with one stone').

5. Encourage students to make **connections between the solutions they found to reduce the temperature of the city and the relevant SDGs.**

In this last section, guide students through an example to illustrate that some efficient cooling solutions implemented in 2020 to reduce the UHI effect are no longer effective in 2100 and can sometimes even lead to an increase of the UHI effect.

In the multimedia animation, use the example of Moradabad, India, with the implementation of 'Green and Dry roofs' (go to building > roofs) in 2020 and 2100.

6. Ask them to fill in the following table collectively:

	BEFORE THE IMPLEMENTATION OF GREEN AND DRY ROOFS	**AFTER** THE IMPLEMENTATION OF GREEN AND DRY ROOFS	**EFFICIENCY ON THE UHI EFFECT**
TEMPERATURE ANOMALY IN THE CITY **IN 2020** (°C)	+2.84	+2.32	++
TEMPERATURE ANOMALY IN THE CITY **IN 2100** (°C)	+2,94	+2.89	+/-

This solution helps reduce the UHI effect, it represents an interesting and effective solution to face this phenomenon. However, if we look at the evolution of the temperature anomaly in the city by the end of the century, the temperature is barely lower than before the implementation of vegetation on roofs. This is a great example to discuss **maladaptation** (i.e. short-term solutions that lose effectiveness over time).

7. The implementation of most of the previously mentioned solutions helps achieve the SDGs. Fill in the table below to recap the different solutions implemented in the choosen city to reduce the UHI effect and/or global warming by 2100.

TEACHER TIP (QUESTION 6)

This maladaptation comes from the fact that climate change may certainly shift the local Chinese-type climate to a Semi-arid one; non-irrigated vegetation will then act like a bare soil surface by 2100. Adding an irrigation system is indeed more costly and technically even more complicated, and feels unnecessary in 2020 in humid climates, whereas photosynthesis will function as a heat sink regardless of the climate. (In fact, all plants can act as heat sinks when they use solar radiation to grow, instead of re-emitting infrared radiation like mineral surfaces. Trees are particularly effective in this regard, as they are more resilient in general to climate shifts, and are large enough to provide a second heat sink through evapotranspiration).

THE FOLLOWING TABLE IS JUST AN EXAMPLE OF HOW STUDENTS CAN FILL IT.

SOLUTION Solar Thermal Collectors on roofs

SCALE TO ACTION ☑ Individual ☑ Collective: City ☐ Collective: Country

HELPS TO LIMIT
- **IN 2020** ☑ Urban Heat Island Effect (adaptation) ☐ Global warming (mitigation)
- **BY 2100** ☑ Urban Heat Island Effect (adaptation) ☑ Global warming (mitigation)

SYNERGIES BETWEEN ADAPTATION AND MITIGATION ☑ Yes ☐ No

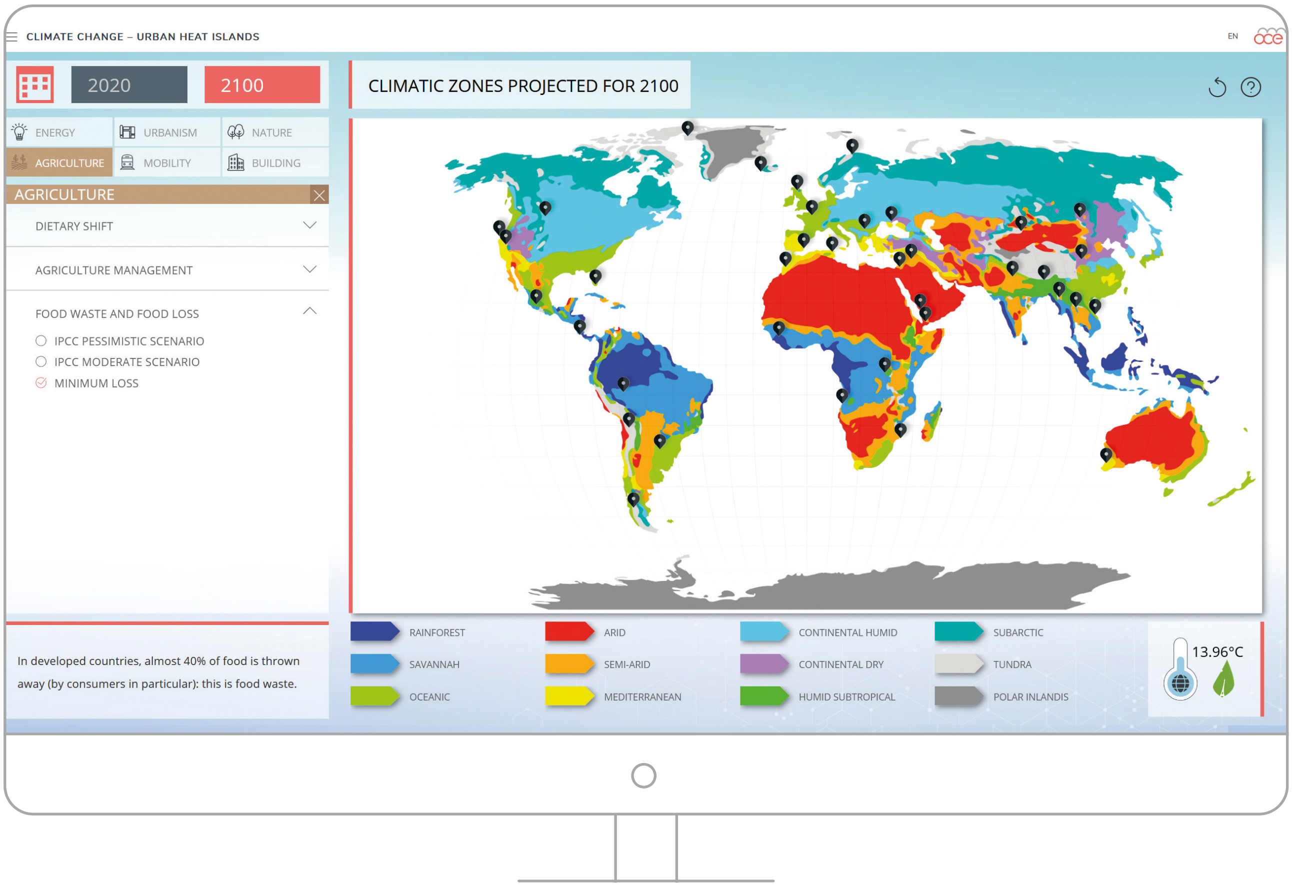
SDGS ACHIEVED THROUGH THIS SOLUTION

SDG N°: 7
TITLE: Affordable and clean energy

SDG N°: 11
TITLE: Sustainable cities and communities

SDG N°: ....
TITLE: ....

SCREENSHOTS OF THE MULTIMEDIA ANIMATION ON THE URBAN HEAT ISLAND.



Here, students are looking at a world climate map in 2100 and the average global temperature (13.96°C). They have chosen a range of mitigation solutions (including limited food waste and loss, as well as solutions in other sectors). Here we see the climate projection therefore: they have succeeded in limiting global warming by the end of the century to well below +1.5°C (the Paris Agreement has been reached: the little logo is green).

Moradabad, 2020. Here, students see an Indian city, Moradabad. They have chosen to plant the roofs to combat the urban heat island effect (adaptation solution: 'Green and Dry roofs').

Moradabad, 2100. Now, students see the result of the same adaptation solution in this city at the end of the century. They can see that planting green, dry roofs to combat the urban heat island effect is far less effective.

WRAP-UP 20 MIN

To conclude this activity, students can go to the 'Conclusion' part of the animation by clicking on the paper-like icon on the top right corner of the screen (it appears after your second visit to the global map). It will help them summarise what they have learned i.e.

1) Some solutions can be implemented worldwide to limit global warming, it will require **greater efforts in all sectors and at all levels** (individual and collective) but we can still manage to respect the upper limit of the Paris Agreement.

2) **Cooling solutions can be implemented** at a local level in 2020 to reduce the UHI effect in the short term; carefully selecting these solutions and modelling their efficiency in the future will help avoid maladaptations. In addition, some of these local solutions can also help reduce global warming by 2100: this is called 'synergy'.

BACKGROUND FOR TEACHERS

In this session, there are several learning objectives for students that encompass different scientific notions:

Without any **mitigation solutions,** the global temperature on Earth will continue to rise above the limit set by the Paris Agreement in 2015.
During the COP21 in 2015, 195 countries agreed to limit global warming below +1.5°C. The only way to stay below this limit is to reduce our greenhouse gases emissions and reach net-zero CO_2 emissions by 2050.

The **urban heat island effect (UHI) corresponds to a positive temperature anomaly** measured in urban areas compared to the surrounding rural areas.
Global warming is indeed not homogeneous worldwide. Warming is greater over land than over the ocean for example (because of thermal inertia). It also depends on the climatic zone (continental, oceanic, mountainous climates, etc.) and finally on the degree of urbanisation that could lead to varying degrees of the UHI effect.
This UHI effect corresponds to higher temperatures in urban areas compared to outlying rural ones. It mostly results from the higher population density that influences the heat production by human activities, and from the soil artificialisation that limits the vegetation cover. The UHI effect is independent of global warming, one of the first occurrences was in 1820 when it was discovered by Luke Howard in London. However, even if not directly related, global warming amplifies the UHI effect by increasing the global temperature and aggravating the dangerousness caused by the extra heat in cities. Since the urban population is expected to double by the end of the century, cooling solutions must be implemented to dampen the UHI. Yet, because of the complexity of the urban geometry at local, meso, and large scale, models need to be run to come up with projections on the efficiency of these aforementioned solutions.

The implementation of **adaptation solutions today can reduce the UHI effect.**
Adaptation solutions aim to reduce the impact of the UHI effect on population in urban areas and to cool cities by reducing the emission and/or the trap of heat (ex: planting trees, cool/green roofs, cooling centres, switching to electric transports, changing the way of planning and designing built environment, incorporation of vegetation, and so on.)

The implementation of **solutions to address the UHI effect can also limit the temperature increase by the end of the century,** we talk about **synergies.**
Adaptation solutions implemented to face the issue of the UHI effect in cities at a short time scale and at a local level can also limit the temperature increase in surrounding areas by 2100. These adaptation solutions are therefore also considered as mitigation solutions, in this case we can talk about synergies between adaptation and mitigation solutions.

Some solutions that are implemented today for their efficiency can turn out to be less or no longer efficient in the future, we talk about **maladaptation.**
Typically, green solutions (relying on the greening of artificial surfaces and/or the planting of trees) are highly dependent on the local climate. Not all tree essences will be able to survive future conditions if climate change modifies too deeply the local climate. As such, all cooling conditions should be assessed regarding their efficiency in the actual current climate **and** their potential efficiency in the plausible future climate.

The UHI effect issue is tightly connected to some Sustainable Development Goals (SDGs), and some solutions to face the UHI effect are in line with the achievement of these SDGs.
In 2015, United Nations members adopted 17 Sustainable Development Goals (SDGs) to take action in a global partnership aiming to end poverty, to improve health and education, to reduce inequality, etc. while also taking actions to face climate change. Some actions to reduce the UHI effect also follow some of the SDGs: e.g. encouraging vegetarian diet is in line with SDG 2 (zero hunger) and SDG 3 (good health and well-being); encouraging public transport development is in line with SDG 10 (reduced inequalities) and SDG 11 (sustainable cities and communities).

TO GO FURTHER (OPTIONAL)

The animation represents at a global scale the evolution of climate zones between now and in 2100, according to various scenarios.

You can work with your students on a specific activity on how the changes in climate zones may affect various ecosystems. For this, you may get inspired by activities from OCE's handbook (see lesson C2 or C4 in the 'The climate in our hands' series 'Climate Change and Land').

Make the students associate each climate zones with local adapted plants, animals species but also local human populations.

Ask them to reflect on the effect of such changes, to evaluate the impact of such time scale on various adaptation solutions for human populations and for ecosystems.

WORKSHEET 8.1

A SCENARIO FOR MY OWN CITY

→ Fill in these tables to recap the different solutions you implemented in the city of your choice in order to reduce the urban heat island (UHI) effect and/or global warming by 2100. The implementation of solutions to face the UHI effect can also limit the temperature increase by the end of the century, we talk about synergies (like ‘killing two birds with one stone’). Tick the ‘synergies’ box if this is the case. Finally, indicate the SDGs achieved through the implementation of this solution.

SOLUTION ....

SCALE TO ACTION	☐ Individual ☐ Collective: City ☐ Collective: Country		**SYNERGIES BETWEEN ADAPTATION AND MITIGATION**
HELPS TO LIMIT	**IN 2020**	☐ Urban Heat Island Effect (adaptation) ☐ Global warming (mitigation)	☐ Yes
	BY 2100	☐ Urban Heat Island Effect (adaptation) ☐ Global warming (mitigation)	☐ No

SDGS ACHIEVED THROUGH THIS SOLUTION

SDG N°: .... **TITLE:**	**SDG N°:** .... **TITLE:**	**SDG N°:** .... **TITLE:** ....
SDG N°: .... **TITLE:**	**SDG N°:** .... **TITLE:**	**SDG N°:** .... **TITLE:** ....

SOLUTION ....

SCALE TO ACTION	☐ Individual ☐ Collective: City ☐ Collective: Country		**SYNERGIES BETWEEN ADAPTATION AND MITIGATION**
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SDGS ACHIEVED THROUGH THIS SOLUTION

SDG N°: .... **TITLE:**	**SDG N°:** .... **TITLE:**	**SDG N°:** .... **TITLE:** ....
SDG N°: .... **TITLE:**	**SDG N°:** .... **TITLE:**	**SDG N°:** .... **TITLE:** ....

WORKSHEET 8.2

LIST OF THE 17 SUSTAINABLE DEVELOPMENT GOALS (SDGs)

13 CLIMATE ACTION

The fight against climate change is one aspect of Sustainable Development.

Approved in 2015 by the 193 member states of the United Nations, the 2030 Agenda for Sustainable Development sets targets to address international societal challenges.

These include the 17 Sustainable Development Goals (SDGs), which aim to ensure an ecological and inclusive transition while eradicating poverty and inequality.

The fight against climate change is specifically covered by SDG 13. The other SDGs all encourage the implementation of actions that will also contribute to the fight against climate change, with the aim of transforming society as a whole.

1 NO POVERTY
Reduce the vulnerability of the poorest populations to the consequences of climate change.

2 ZERO HUNGER
Develop low-carbon agriculture that is resilient to climate hazards to ensure food security.

3 GOOD HEALTH AND WELL-BEING
Reduce the spread of vector-borne diseases and those caused by pollution.

4 QUALITY EDUCATION
Introduce climate issues into the educational curricula of future generations.

5 GENDER EQUALITY
Promote the role of women in the fight against climate change and involve them in local political decision-making.

6 CLEAN WATER AND SANITATION
Reduce impacts on sanitation services and threats to water resources.

7 AFFORDABLE AND CLEAN ENERGY
Promote moderation, energy efficiency and the development of renewable energy.

8 DECENT WORK AND ECONOMIC GROWTH
Begin the transition to a low-carbon economy based on sustainable growth and job creation.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE
Promote industrial transformation through low-carbon technological innovation.

10 REDUCED INEQUALITIES
Include equity and justice in the fight against climate change.

11 SUSTAINABLE CITIES AND COMMUNITIES
Promote the development of low-carbon, resilient cities that encourage the use of public transport.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Adopt modest consumption habits and promote a climate-friendly circular economy.

13 CLIMATE ACTION
Take urgent action to combat climate change and its consequences.

14 LIFE BELOW WATER
Protect the oceans to strengthen their role as carbon sinks and climate regulators.

15 LIFE ON LAND
Preserve forest ecosystems and their biodiversity and increase soil carbon storage.

16 PEACE, JUSTICE AND STRONG INSTITUTIONS
Mitigate climate change to reduce the number of climate refugees and curb geopolitical tensions.

17 PARTNERSHIPS FOR THE GOALS
Mobilize governments, businesses and civil society to achieve the objectives of the Paris Climate Agreement.

LESSON 9 FUTURES LITERACY

MAIN SUBJECTS
Literature
Visual arts
Theater
Natural Sciences

DURATION
Preparation: 10 min
Activity: 2h

AGE GROUP
15+ year-old students

TEACHING METHOD
Storytelling exercise
Creative activity

LEARNING OUTCOMES
Students revisit the concept of scenarios they have encountered in previous lessons. They imagine stories of possible futures. They can translate their stories into art, an exhibition, a novel, etc. It is a good opportunity to project themselves into a positive world under climate stress.

TARGETED SUSTAINABILITY COMPETENCE
Domain 3 – Envisioning sustainable futures
Competency – 3.1 Futures literacy

CONCEPTS COVERED
Scenario, societal choices, climate projections, urban heat island effect, adaptation, mitigation

PREPARATION 10 MIN

- Computer and projector equipment to show the **WORKSHEET 9.1**.
- Print out **WORKSHEET 9.2** for each group of students.
- Visual arts materials (pens, paints, pencils, or computer equipment of your choice).
- Refer to **WORKSHEET 8.1** filled during the previous lesson.

INTRODUCTION 30 MIN

As an introduction, ask the students what the temperature will be in 2100. After what they have learned, they will probably answer that there are different possible projections, depending on the scenario decided on by society (lesson 7). The current path is as follows: current climate change is leading to a rise in global temperatures over the next few decades.

Present **WORKSHEET 9.1**, a sketch by students illustrating life in a city in 2042. Ask students to identify some of adaptation or mitigation choices that have been made in this city to combat climate change. You can remind them of the multimedia animation they used in lesson 8.
Expected answers: *'we can see environmentally-friendly mobility (no cars), lots of trees, urban farms, etc'*.

Ask students for some clues that the inhabitants are experiencing a heatwave.
Expected answers: *'The inhabitants are sweating, their faces are red'*. The students should imagine the lives of these climate-stressed inhabitants.

PROCEDURE 1H20

PART 1: INSPIRING BY AN ARTISTIC PRODUCTION 40 MIN

1. Hand out **WORKSHEET 9.2** and ask the students to read the testimonies of three residents. They will match each testimony to the corresponding resident in **WORKSHEET 9.1**.

2. Ask the students to imagine a new character living in this city. They should describe a day in his/her life, how he/she interacts with his environment and other people. They can invent caracteristics of the character (such as age, name and so on). You can work on your students' artistic skills (drawing), literary skills or theatrical skills (character interpretation). Whatever your or your students' choice, you can use the following grid to assess their work.

BACKGROUND FOR TEACHERS

FUTURE STORYTELLING EXERCISE TO OVERCOME ECOANXIETY
Numerous international studies show that eco-anxiety is increasingly affecting young people, as early as nursery school. This affect is linked to the anticipated rapid and dramatic changes in one's environment and catastrophic consequences of extreme events, often associated with a fear of the future. Considering this affective dimension is crucial for successful school education. The authors recommend that, to deal with eco-anxiety, educators themselves should be aware of their own emotions about climate change[1]. It is also important to remind students that all emotions, positive, negative or even neutral (indifference, weariness,...) are legitimate and deserve to be expressed. Creative projects (artistic ones, work on future narratives) thus have a rightful place in climate change education[2].

1 Source: 2012, Ojala, M. et al.
2 Source: 2019, Jorgenson Simon N. et al.

	TAKING INTO CONSIDERATION THE CLIMATE CONSTRAINT	FUTURES LITERACY EXERCISE IS POSITIVE	QUALITY AND CONSTRUCTION OF THE STUDENTS' PRODUCTION
Very inadequate	The characters don't live in a world that has changed.	The story is depressing and sad!	Off-topic production.
Inadequate	A few indicators point to a warmer world.	The characters manage to adapt to climate change, but in their own way (e.g. air conditioning).	Unfinished work but some elements are acceptable.
Acceptable	Several indicators point to a warmer world.	The characters interact with each others and have ideas and energy to fight climate change.	Inventive, structured work.
Very good	A world under climate stress is very well integrate.	The inhabitants are united, imaginative and have modified their city to drastically limit the consequences of climate change.	Highly mastered production.

Students imagine their future on the theme of 'Holidays in 2042', a futures literacy activity. What will holidays in 2042 look like under climate constraints? Here, students imagine different aspects of their life in 2042. (Productions: OCE in partnership with DSAA, or graphic design at Jacques Prévert High School in Boulogne Billancourt).

PART 2: STORYTELLING EXERCISE IN A CITY IN 2100 40 MIN

1. Retrieve **WORKSHEET 8.1** and ask the students to realise a new narrative (preferably on a different medium from part one). This time, they imagine a future in 2100 for one city they studied the last lesson:

- Students work in pairs and write their story.
- They tell the story of a typical day in their city (how they get around, what they eat, where they work, their connection to nature).
- In pairs, they check whether SDGs and/or synergies are effectively included in the story.

2. To make the most of your pupils' work, encourage them to share their stories outside the classroom: blog, school newspaper, open days, etc.

WRAP-UP 10 MIN

Ask students to present their productions and let the class discuss the relevance of the different measures. Some difficulties may appear when trying to classify these measures as some may be relevant for adaptation but not for mitigation (air conditioning for example). Adaptation will benefit us in the short term, while mitigation will be fundamental in the long term. Both must be considered together.

Conclude by telling the students that there are solutions to the problems of climate change. This lesson shows that they can be implemented at different levels (individual, family, school, city).

To illustrate other levels (country, region, world), you may watch 'The United Nations Climate Change Conferences' CLIM video, by Sofia Palazzo (Imperial College London, United Kingdom). She explains that at COPs, the various governments agree on effective measures to combat climate change. Many people, communities and organizations around the world are already implementing adaptation and mitigation measures.

WATCH THE VIDEO ↗

The world is changing, but humanity has the capacity and ongoing potential to make societal choices to adapt to it. Envisioning alternative futures by imagining and developing positive scenarios is one way of overcoming eco-anxiety and empowering students.

LIVING IN THE CITY OF 2042, UNDER CLIMATE STRESS (STUDENT ART PRODUCTION)

Artistic production (risography) and texts are made by students: Julia and Alice, Master DSAA, High School Jacques Prévert, Boulogne Billancourt, France. © OCE.

WORKSHEET 9.2

TESTIMONY OF 3 INHABITANTS OF THIS CITY (ARTISTIC PRODUCTIONS BY STUDENTS)

Linda

I have just left our apartment three minutes ago. I'm on my way on my bicycle to meet my friends Akim, Sarah and Lucy in the park. However, my mother has just sent a message: she needs me to help her in our greenhouse. The zucchinis are ripe and need to be harvested. I quickly drive my bike to the greenhouse – which only takes 15 minutes on the brand new bicycle path; there's no traffic light to stop me. This year, I quit my annual bike rental subscription since I bought a bike at the flea market. It is still working perfectly well, after I changed the chain and mended the flat tyres. Today, I'll bring Akim a second-hand game boy that I have found in the 'give-away' box at the gym.

Enrique

I'm heading towards the community laundromat of our building. I haven't used an individual washing machine since I moved in in 2035. It's simple: we pay a small fee to compensate for the ecological footprint caused by running the washing machine. We can book slots in order to avoid queueing. I like to meet and chat with various people at the laundromat. I have a special deal with my neighbour Imany: I take care of her laundry, and in exchange I get some of her excellent home-grown tomatoes. Since drinking water is become more and more scarce, the washing machines use rain water that is collected in big barrels. And to flush the toilet, we use greywater.

Imany

I have been picking tomatoes in our vertical garden that is adjacent to our apartment. I'll give some of the tasty yellow cherry tomatoes to my friend Enrique who is doing my laundry today. I want to make ketchup with the ripest of my freshly harvested oxheart tomatoes. My friend Linda will come and help me. In our vertical farm, every party has its own little garden where they can grow vegetables and fruit. I always cook with very fresh ingredients thanks to the short distance between our garden and our kitchen. Besides, it's really nice to meet and chat with the other residents of our building while gardening. Often, we give each other tips on how to get rid of lice, for example, or we exchange our harvest surplus. The other day, I traded radishes against strawberries.

GLOSSARY

ADAPTATION
The process of adjusting to current or expected climate change impacts. In human systems, the aim of adaptation is to reduce risks, increase resilience or seize beneficial opportunities. In natural systems, human intervention may facilitate adjustments to expected climate change impacts.

CLIMATE
Climate is defined as the average weather conditions over long timescales in a given region.

CLIMATE CHANGE
Generic term encompassing several global phenomena, including: changes in temperature, precipitation, melting ice (glaciers and pack ice), extreme events, sea level rise, and so on. The term is most used to describe the current human-induced climate change that started around 1850 due to an increase in the global average temperature.

CLIMATE PROJECTION
Simulation of a future climate based on a scenario.

CLIMATE SIMULATION
Experimentation with a digital model.

CONFIDENCE (LEVEL OF CONFIDENCE)
In the IPCC report, the level of confidence refers to the degree of certainty in the validity of a finding, based on the type, amount, quality, and consistency of evidence and the degree of agreement among experts. The level of confidence is indicated by a qualitative scale ranging from very low to very high, with corresponding probabilities ranging from less than 10% to over 90%. The level of confidence is used to communicate the degree of uncertainty associated with a particular finding or statement.

CONSENSUS
A scientific consensus is based on a high level of confidence (agreements between scientists, weight of evidence, etc). A scientific consensus on a given subject is not incompatible with all aspects of the subject or the notion of uncertainty (see page 31).

COOLING SOLUTION
Nature-based, technical-based, or behavioural-based transformation of the city aiming at a diminution of the Urban Heat Island effect (UHI).

DIGITAL MODEL
Simplified representation of reality that uses mathematics and computer science.

EXTREME EVENTS
Rare meteorological events with a strong negative impact on human society and ecosystems (e.g. tornadoes, landslides, major fires, droughts, or heatwaves). Climate change is increasing the frequency and amplitude of some extreme events worldwide (extreme cold events are reduced however).

FEEDBACK
Process by which the consequence can modify its own causes. Positive feedback will amplify the consequence. Negative climate feedback will limit it.

GREENHOUSE EFFECT
Solar radiation crosses the atmosphere, is absorbed by the Earth's surface and warms it. The absorbed solar radiation is transformed into infrared radiation (heat). Some of this infrared radiation is 'trapped' on its escape towards space by greenhouse gases in the atmosphere and is sent back towards the Earth's surface – heating it up even more. This is called the greenhouse effect.

GREENHOUSE GASES (GHG)
Greenhouse gases cause the greenhouse effect. Greenhouse gases are mainly water vapour, carbon dioxide, methane, nitrous oxide and ozone.

INPUT ON A MODEL
Data entered in the model.

INTERACTIONS
The Earth's envelopes (atmosphere, hydrosphere, etc.) continually exchange matter and energy. These fluxes help redistribute the uneven incoming solar energy. There are also interactions between different terrestrial environments (the melting of the Antarctic ice cap has repercussions on global ocean and on European coasts for example).

MALADAPTATION
Solutions that are implemented today for their efficiency which turn out to be less or no longer efficent in the future.

MITIGATION
Human intervention to reduce global warming by reducing GHG emissions or by enhancing GHG sinks.

MODEL
Simplified representation of reality. Using models has many advantages, but it also has its limitations. It can not represent the full complexity of reality. Climate models are analogies for reality to make predictions/projections. Climate models are evolving thanks to the integration of new parameters and improvements in computers and technical power, leading to greater resolution and accuracy. There are different types of models: an 'analog model' is a simplified representation of reality using physical objects, and a 'digital model' is a simplified representation of reality using numeric data (the accuracy and resolution determine the quality of the model).

OUTPUT OF A MODEL
Data produced by a numerical model when running a simulation.

PALEOCLIMATE
Description of the climate of past eras.

PARAMETERS
Measurable values used to characterise a system (e.g. for characterising the atmosphere system: level of CO_2 in ppm). Climatologists must study a set of parameters simultaneously.

PERTURBED CLIMATE
Since the industrial revolution (1850-1900), the Earth's climate has been changing rapidly due to increased human activity.

PROJECTION
The simulation of a given scenario. Climate projections show the potential future evolution of a quantity or set of quantities, calculated by a model. They are based on physics and are used to quantify global and regional climate change, and its impact on phenomena such as monsoons.

PARIS AGREEMENT

An international agreement on climate change, approved in 2015 during the COP21 in Paris and signed by 196 countries. The main goal is to limit the increase of global temperature to 1.5°C by the end of the century.

RELIABILITY

Not all sources of information are trustworthy; they should always be checked. The Intergovernmental Panel on Climate Change (IPCC) assesses and compiles the latest scientific information on climate change and relays the consensus of the scientific community, making it one of the most reliable sources of information on climate change.

REPRESENTATIVE CONCENTRATION PATHWAY (RCP)

Trajectories for 'Representative Concentration Pathways' were used to evaluate different scenarios of GHG emissions. However, unlike SSPs scenarios, RCPs do not take into account socio-economic changes. Nevertheless, there are similarities between these two types of scenarios. RCPs were used in the previous IPCC report (e.g. AR5).

SAMPLING

Reduction of continuous information to a finite set of values.

SCENARIO

Selection of inputs based on social/ethical reasons. A climate scenario is a plausible and often simplified representation of the future climate. IPCC scenarios are based on societal choices.

SHARED-SOCIOECONOMIC PATHWAY (SSP)

Scenario of projected global socio-economic changes that depend on societal choices. These scenarios cover all kinds of projections, from very optimistic (SSP1-1.9: drastic reduction of global greenhouse gas emissions) to pessimistic (SSP5-8.5: further increase of greenhouse gas emissions). These scenarios are used as input data for climate models, which in turn calculate the corresponding change in climate. SSPs are used in the latest IPCC report (AR6).

SIMULATION

One run of a digital model.

SOCIETAL CHOICES

Possibilities for the evolution of a society. This evolution is based, among other things, on demographic changes, future energy choices, the type of development, or the application of environmental policies.

SUSTAINABLE DEVELOPMENT GOALS (SDGs)

Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs. The SDGs have different objectives across sectors to support sustainable development.

SYNERGIES

Implementing solutions (mitigation, adaptation) to face the UHI effect can also limit the temperature increase by the end of the century.

TEMPERATURE ANOMALY

Difference between an observed or simulated temperature and a specific reference.

UNCERTAINTY

Every scientific data is associated with uncertainty. Climate projections established by models are therefore always associated with uncertainties. There are two primary causes for uncertainty about the magnitude of climate change in the future:

- climate feedbacks (involving clouds, carbon uptake, ocean heat uptake, water vapour, sea ice, etc.);
- future human emissions (linked to climate policy, technology, politics, people, etc.).

UNPERTURBED CLIMATE

The unperturbed climate is considered here to be the climate prior to the pre-industrial period. Climate has varied a great deal over long time scales, but has been relatively more stable over the last 10,000 years.

URBAN HEAT ISLAND (UHI) EFFECT

An urban area has a higher average temperature than its rural surroundings owing to greater absorption, retention and generation of heat by buildings, pavement and human activity.

VALIDATION

Act of proving the accuracy of a model.

WEATHER

State of the atmosphere (including - but not limited to - temperature, humidity, wind, and precipitation) at a particular time and place.

WEATHER PREDICTION

Forecasts for the weather on a given date. Climate projections, on the other hand, calculate the average weather conditions over much longer timescales (decades, centuries, millenia) in a given region. However, both forecasts and projections use models.

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