Copernicus Climate Change Programme: User Learning Service Content

Florian Dierickx

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Chapter 1

Disclaimer

The information in this document is gathered from the Copernicus Climate Change Programme User Learning Service. More specifically, it is content from the following chapters/lessons:

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Chapter 2

Introduction to Copernicus Climate Change Service

Copernicus = a public service framework to allow full, free and open access to all environmental monitoring data for scientist, policy makers, entrepreneurs and citizens:

- Satellite observations
- In-situ observations
- Model (assimilated) data
- Past, present and future

2.1 Available tools & setup

Status October 2018:

- **CDS** beta version: data sets added
- **CDS toolbox** beta version
- **CDS CB** operational
- **SIS** proof of concepts
- **EQC** in development
- **ULS** beta version

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Figure 2.1: copernicus

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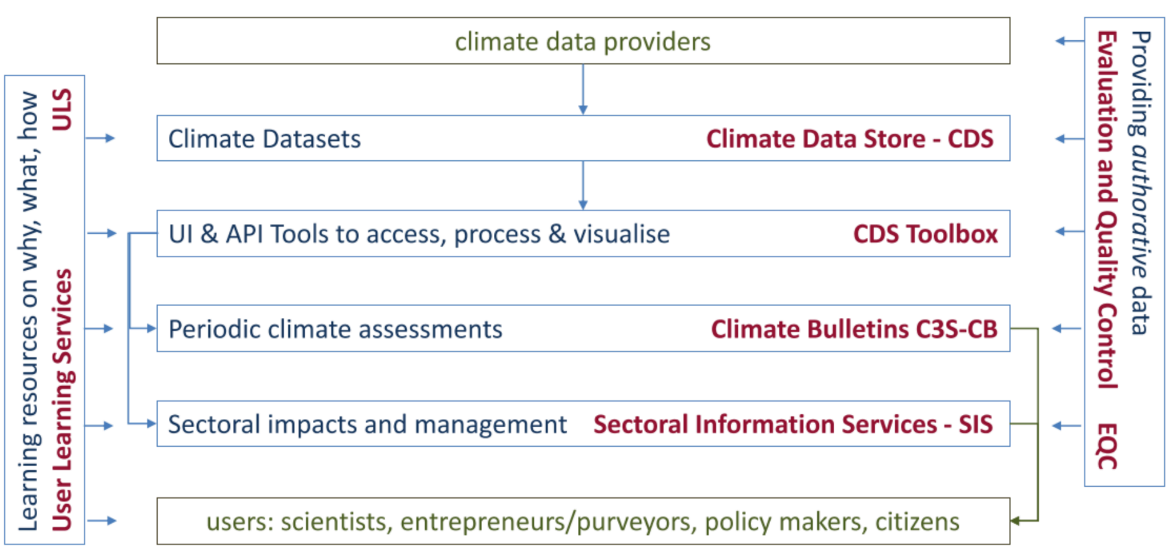

Figure 2.2: tools

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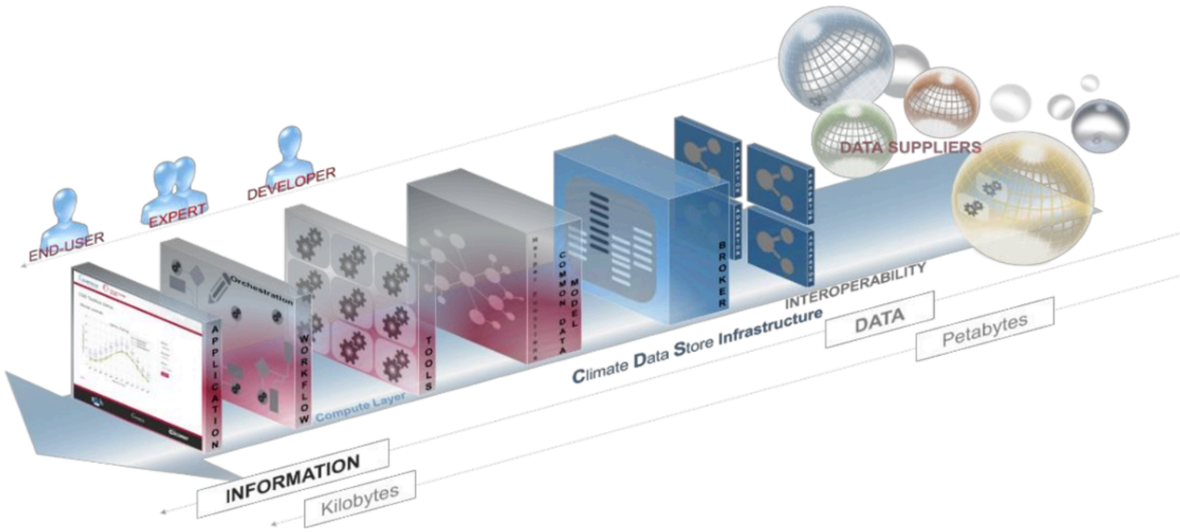

Figure 2.3: processing

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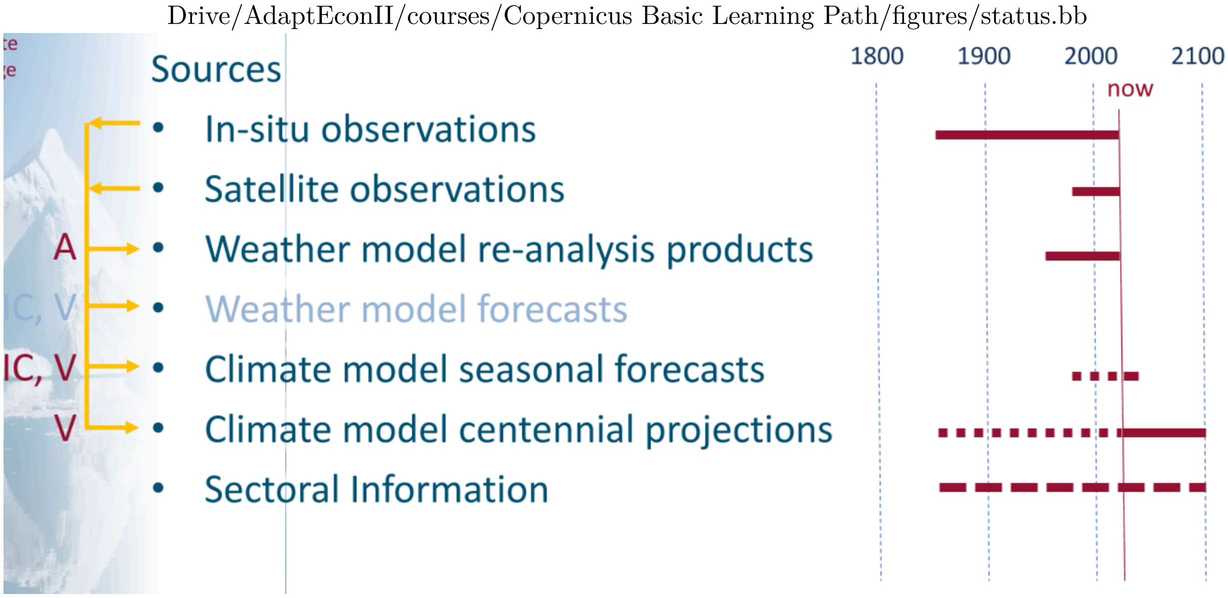
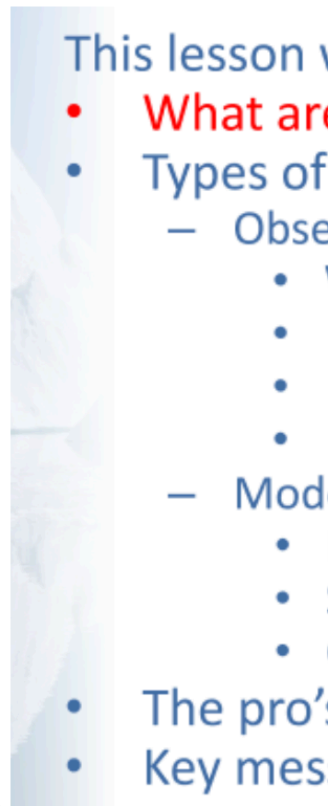


Figure 2.4: status

Chapter 3

Data Resources Introduction



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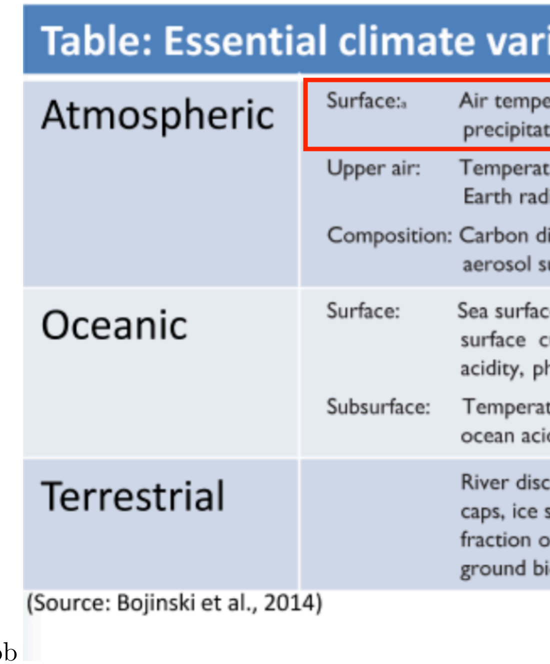
3.1 What are essential Climate Variables?

The Global Climate Observing System (GCOS) has developed 50 measurable Earth System Parameters : the Essential Climate Variables (ECVs). ECV = physical, chemical or biological variable or a group of linked variables that critically contribute to the characterization of Earth's climate. ECVs are selected based on relevance, feasibility and cost effectiveness. See below figure for all ECVs: atmospheric (surface, upper air and composition), oceanic (surface and subsurface) and terrestrial. This lesson will focus mainly on atmospheric surface climate variables, as they are most often used in (sectorial) impact studies:

- Air temperature
- Wind speed and direction

- Water vapour
- Pressure
- Precipitation
- Surface radiation budget



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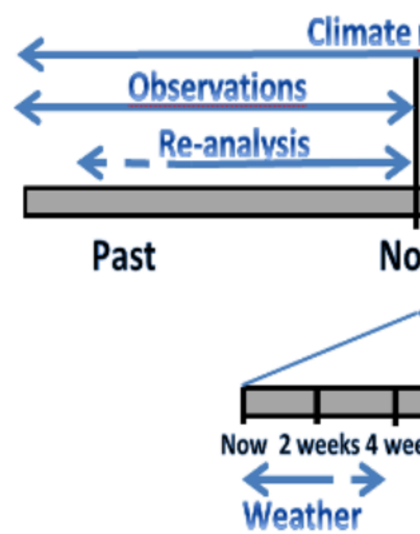
3.2 Types of climate data resources

Various data sources can be used, categorised based on the period (past - future) and timescale (weeks, years) for which they provide data:



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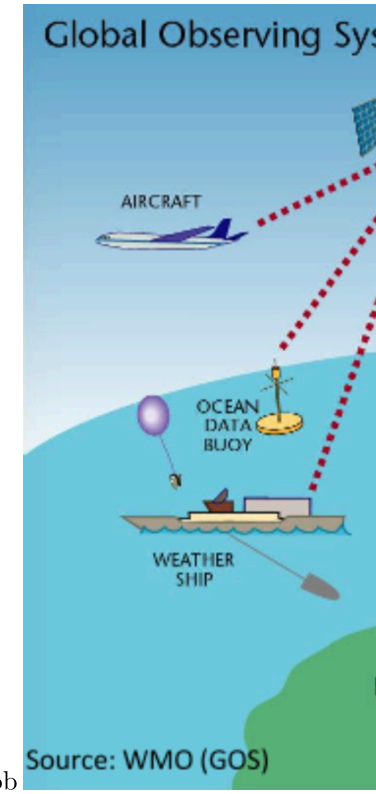
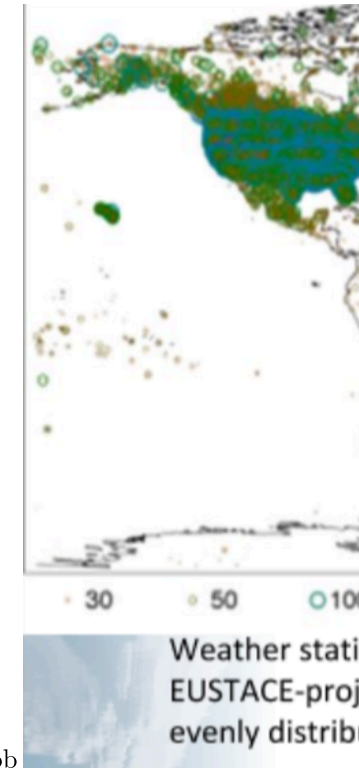
3.2.1 Observations

Observations ony provide information on the past and current climate. Besides the traditional observation stations on land there are many more direct and indirect observation methods:

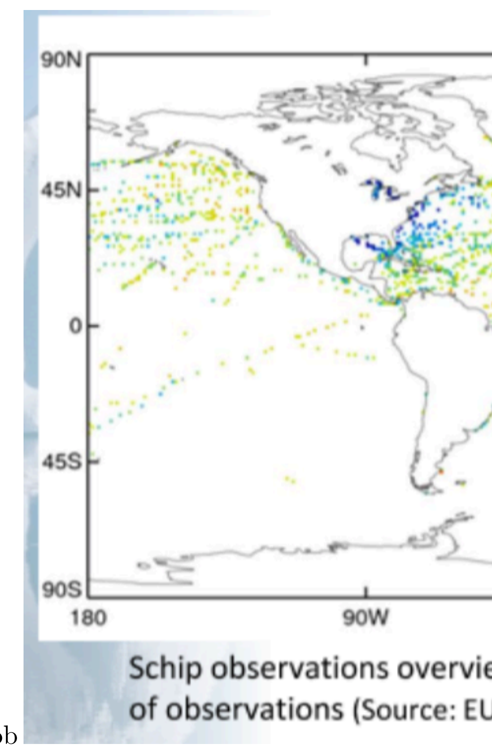
Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/observation-methods.bb 

3.2.1.1 DIRECT (in-situ) observations

- **Weather stations**: there are thousands of weather or meteorological stations measuring at or near the Earth's surface meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature and relative humidity. These are observations at one location, or "in situ". The number of stations is not evenly distributed over the Earth (see figure below). The WMO formulated standards for these stations (eg: T measured at 2 m height, no high vegetation around the station, …). For more info see WMO - best practices.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/weather-stations.bb 

- Over the oceans the Global Observing System (GOS) relies - in addition to satellites - on **ships**, **moored and drifted buoys** and **stationary platforms**. The number of observing ships is around 4000, 1000 of them report observations every day.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/ships.bb 

3.2.1.2 INDIRECT Observations

As there are no records of climate from direct measurements before the 1600s, other sources are used to estimate and investigate the climate further back in time:

- **Tree-rings** and **ice-cores**: used to infer changes in temperature and precipitation
- **Depth profiles of temperature in oil-drilling boreholes** can be used to estimate the changes in air temperature over recent centuries
- **Corals** can be used to estimate oceanic temperature and sea-level changes

None of these indirect, or 'proxy' methods are as precise as direct instrumental measurements. Also, there are few proxy datasets, so it is very difficult to obtain reliable estimates of past global temperatures. However, long-term temperature trends derived from borehole and other independent proxy data are in reasonable agreement, confirming the climate in the past two thousand years, was not as warm as it has been in recent decades.

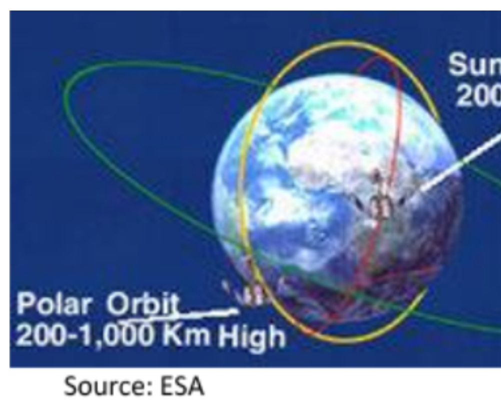
3.2.1.2.1 Satellites

Satellites are normally equipped with visible and infra-red imagers and sounders from which one can derive many meteorological parametres. Several over the polar-orbiting satellites are equipped with sounder instruments that can provide **vertical profiles of temperature and humidity in the atmosphere in cloud-free areas**. Geostationary satellites can be used to measure e.g. **wind velocity** in the tropics by tracking clouds and water vapour. Recent developments have made it possible to derive temperature and humidity information directly from satellite information.

Gridded observation products available at C3S

Types of satellites:

- **Geostationary satellite**: earth-orbiting satellite placed at an altitude of around 35800 km directly over the equator, that revolves in the same direction the earth rotates (west to east), and therefore constantly observes the same path of the earth.
- **Polar orbiting satellite**: closely parallels the earth's meridian lines, thus having a highly inclined orbit close to 90°. It passes over the north and south poles each round. As the earth rotates to the east beneath the satellite, each pass monitors and area to the west of the previous pass. These strips can be pieced together to produce a picture of a larger area.



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3.2.1.2.2 Radar and Lidar

Weather radars have been used in the detection of precipitation rates since the 1950s. The first figure below shows and example of a rainfall radar image. In principle the method is based on sending out a radar pulse and measuring the return signal. The signal has to be translated into a precipitation rate with the help of in situ measurements (see second figure).

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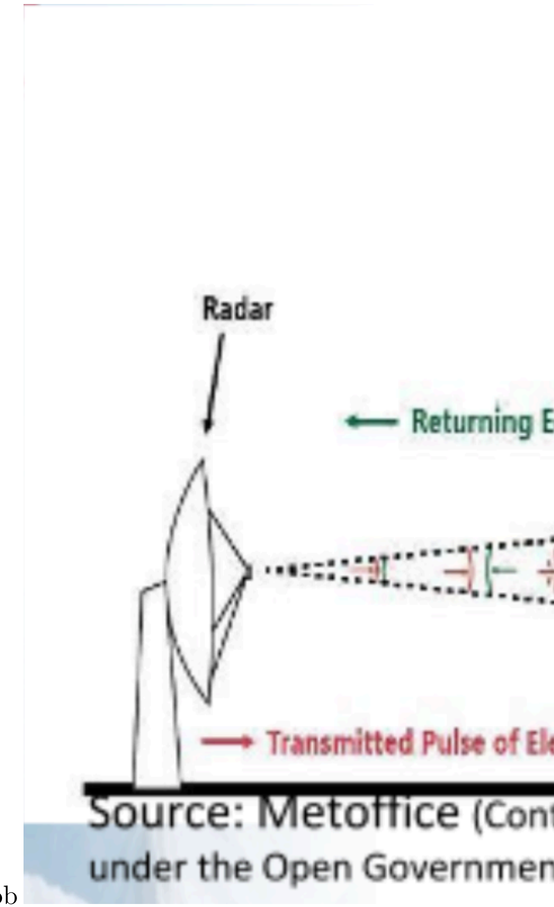
Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/radar.bb 

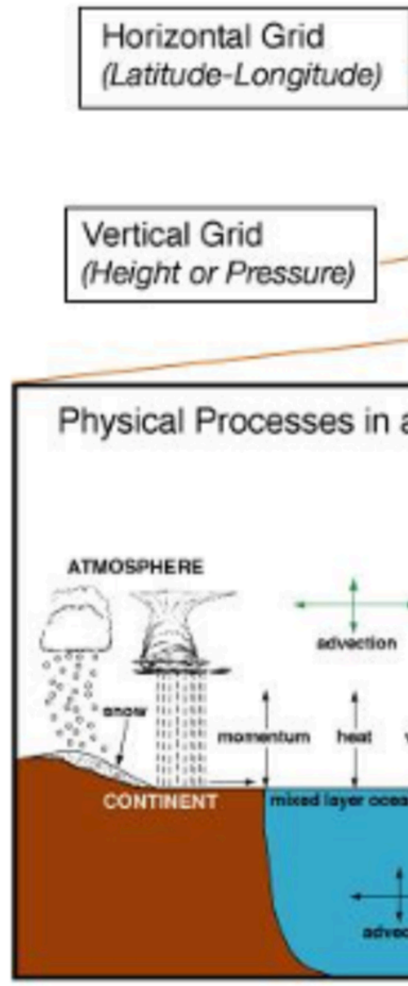
Dual polalized or doppler radars can measure wind and rainfall. They enable more accurate determination of precipitation types and sizes. This makes it easier to see whether the precipitation consists only of rain or also contains snow or hail (see video explanation).

Instead of using a radar pulse, Lidar (Light Detection And Ranging) is using laser light to study atmospheric properties from the ground up to the top of the atmosphere. Such instruments have been used to study, among others, atmospheric gases, aerosols, clouds, wind and temperature.

3.2.2 Models

For more information about model selection, see the dedicated chapter below

A **climate model** is a numerical representation of the climate system based on physical, chemical and biological properties of its components, its interactions and feedback processes.



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Climate models are systems of differential equations based on the basic laws of physics, fluid motion and chemistry. To "run" a model, scientists divide the planet into a 3-dimensional grid, apply the basic equations, and evaluate the results. The models calculate winds, heat transfer, radiation, relative humidity, and surface hydrology within each grid and evaluate interactions with neighboring points (IPCC, 2007). See also video explanation from the UK MetOffice and an introduction to climate modeling from Climate Literacy.

3.2.2.0.1 Difference between weather and climate models

- **Weather** consists of the **short-term (minutes to months) changes** in the atmosphere. Weather is described in terms of temperature, humidity, precipitation, cloudiness, brightness, visibility, wind, and atmospheric pressure, as in high and low pressure. In most places weather changes from minute-to-minute, hour-to-hour, day-to-day, and season-to-season. Weather is predictable up to about 2 weeks ahead in the mid-latitudes and in the tropics somewhat longer.
- **Climate** is the description of the long-term pattern of weather in a particular area. Climate is the average weather for a particular region and time period, and the probability of extremes. Usually a period of **30 years** is used to describe the climate. **Examples of described climate variables** are

precipitation, temperature, humidity, sunshine, wind velocity, phenomena such as fog, frost and hail storms. Also vegetation changes, changes in glaciers/icecaps etc. can be described.

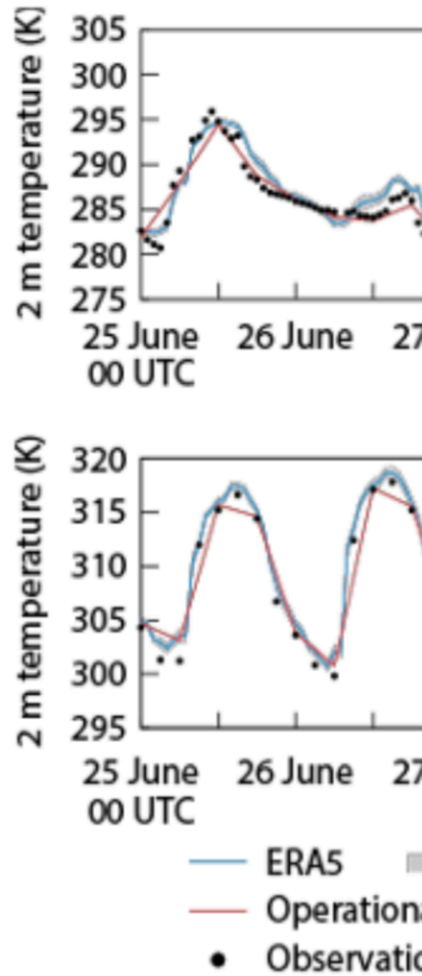
Weather and climate models both follow the basic laws of physics, fluid motion and chemistry. However, they differ in some aspects:

- **Weather model**: predicts in most cases til about 15 days into the future, while a climate model can integrate forward in time for hundreds of years. In a weather model, we care about **when and where a storm or front occurs**. In a climate model we care about the statistics (averages and probabilities of extremes). Since the weather of tomorrow depends strongly on the weather of today, the **initial conditions for the simualtion of the weather are very important** (**initial value problem**)
  - Model-based weather forecasts are generally less reliable beyond a week, because the atmosphere is an inherently chaotic system. Small changes in observed conditions, which are fed to the model regularly, can produce completely different weather forecasts a week into the future, because the atmosphere is very dynamic.
- In **climate models** you get climate variables for each day, but you don't really care on which day and exact location you get a certain value for this variable as long as the **long term statistics** are correct for this location. This does not depend on the initial conditions of the simulation, but it depends on the parameters in the model itself (boundary value problem).
  - Climate models aren't trying to predict what is going to happen at a specific place and point in time. They cannot produce a forecast for, say, the 15th of March 2077, or even not for tomorrow! Instead, climate models are used to determine **how the average and extreme conditions will change**. Will it be on average warmer or cooler, wetter or drier, in England over the next 50 years? This is information we need if we're going to construct e.g. bridges or the water management system for the next decades.

3.2.2.1 Re-analysis

A **climate reanalysis** gives a *numerical description of the recent climate*, produced by combing models with observations (assimulation of observations in a climate model). It contains estimates of atmospheric parameters such as air temperature, pressure and wind at different altitidues, and surface parameters such as rainfall and soil moisture content. In the **global re-analysis** *estimates are produced for all locations on earth, and they span a long time period that can extend back by decades or more.*

Weather and climate (reanalysis) models vary in their **use of data assimilation**. **Weather models** *assimilate observations only in the starting conditions of the forecast.* **Climate reanalysis models** *assimilate observations in the starting conditions as well, but also during the whole period simulated.* This can only be done for the past climate where we do have observations.



Example of reanalyses (sour
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observed values. Upper: nea
Sahara Desert

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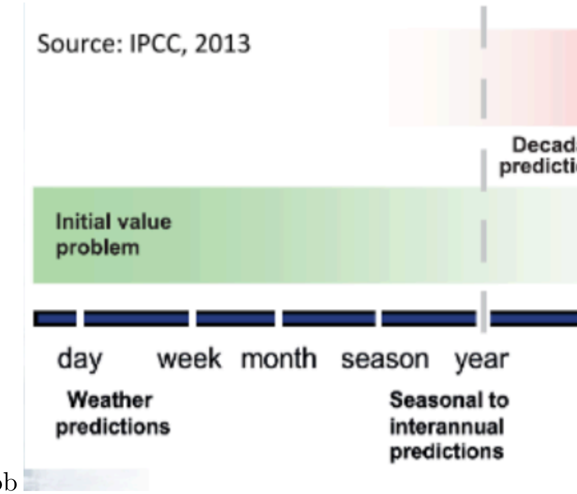
For more information on re-analysis data and models that can be used in Europe, see the [dedicated chapter][regional reanalysis for Europe]

3.2.2.2 Seasonal to decadal predicitons (S2D)

Weather forecasts or predictions generally give information for up to two weeks ahead. Many sectors in society would like to know what the weather will be in one month, a year or a decade. E.g. will the coming season be dryer or warming than average? This is where S2D predictions come in. In S2D predictions, both **initial values and boundary conditions are important**.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/s2d.bb 

At lead times of weeks to months, **predictions are typically initial value problems**. “Climate” predictions such as seasonal outlooks, El Niño forecasts and seasonal hurricane outlooks fall into this category. The initial value is represented by the initial states of the climate system, including ocean heat content, and surface snow and ice cover. In this case, **short-term evolution from an initial state is analysed with constant boundary conditions**. Also, probability can be verified in time to provide meaningful feedback.

With **projections**, one looks typically at **changing statistics in response to changing boundary values**. In this case, the probability of projections cannot be given.

What will happen in the near future, up to a decade or two ahead, is the combination of natural variability and human-induced climate change. The next few years may be relatively cold, although the long term trend is increasing temperature. The next season may be extremely dry in a region, although the long term trend can be an increase in rainfall.

Example of a seasonal forecast: August 2018

The figure below shows how much colder or warmer the average temperature is expected to be for September-November 2018 compared to the period 1993-2016 based on several models. Whether one can rely on this forecast depends on the skill, which means whether we know that the forecast has added value of the longer term averages. For some regions this forecast has higher skill than for other regions. In the tropical regions there is a higher skill due to El Niño/La Niña.

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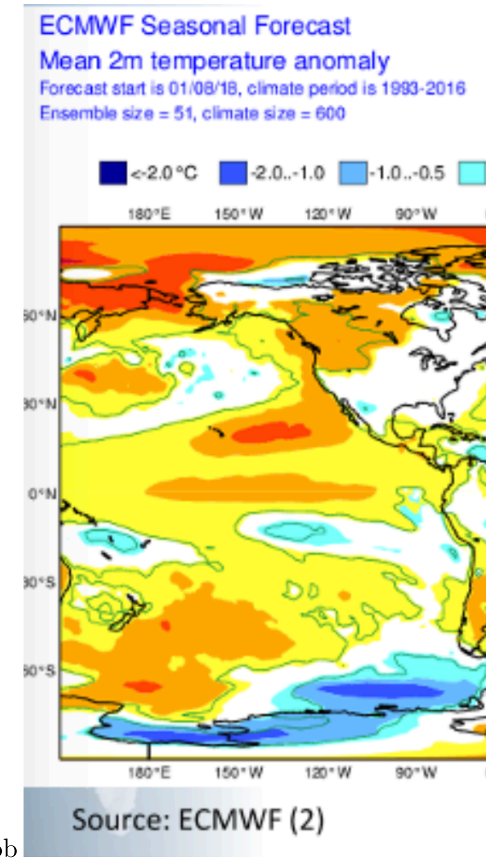


3.2.2.3 Types of climate models

Climate models are often used to make projections for the future based on certain amounts of emissions (**Representative Concentration Pathways**, RCPs).

Among many different types of climate models, there are:

- Models that simulate the climate of the whole world (**Global** Climate / Circulation Model = **GCM**, **Earth** System Model = **ESM**)
- Models that simulate the climate only for a part of the world (**Regional** Climate Model = **RCM**)
- Models with more or less complexity/coupling. Some models only include the atmosphere (**Atmospheric** models), some models couple the ocean and atmosphere (**coupled** models). Earth System models couple even more systems.

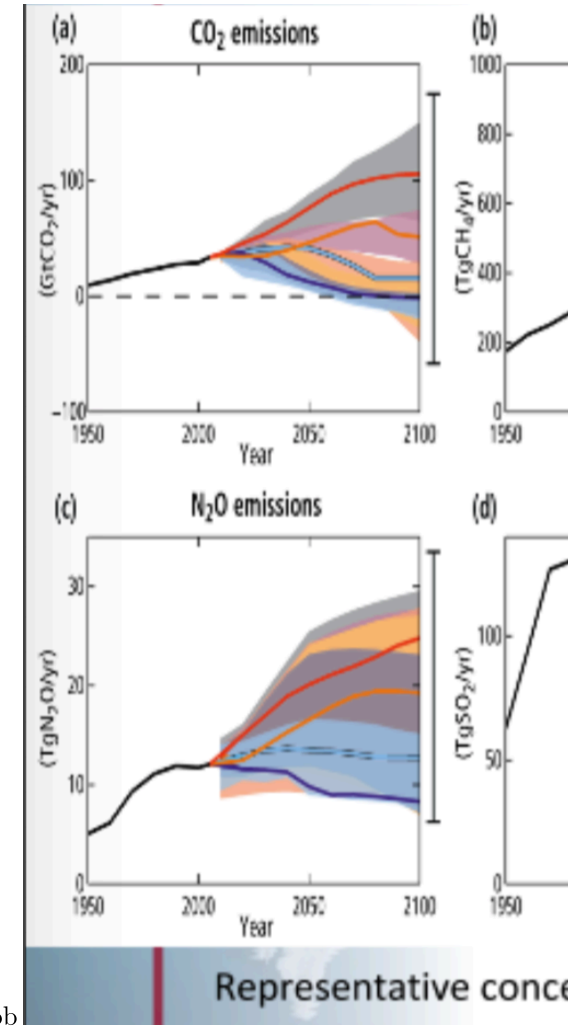
There are more types of models which are used for specific climate research such as cloud studies on exchange of energy, humidity, etc. between the different air layers.

3.2.2.4 Emissions scenarios and RCPs

Emission scenarios are descriptions of how greenhouse gas emissions could evolve on various hypotheses. Emission scenarios are translated into GreenHouse Gas (GHG) concentration scenarios. These are used as direct input in climate models.

Currently 4 Representative Concentration Pathways (RCPs) are used. They are named after a possible range of radiative forcing values in the year **2100** relative to pre-industrial values (+**2.6**, +**4.5**, +**6.0** and +**8.5** W/m^2). The RCPs are consistent with a wide range of possible changes in future anthropogenic (i.e. human) GHG emissions, and aim to represent their atmospheric concentrations:

- **RCP2.6** corresponds to very ambitous climate policy, which probably leads to a temperature change of about 2 degrees Celcius compared to the pre-industrial era.
- **RCP8.5** represents a scenario where few measures are taken and few technological breakthroughs are used.



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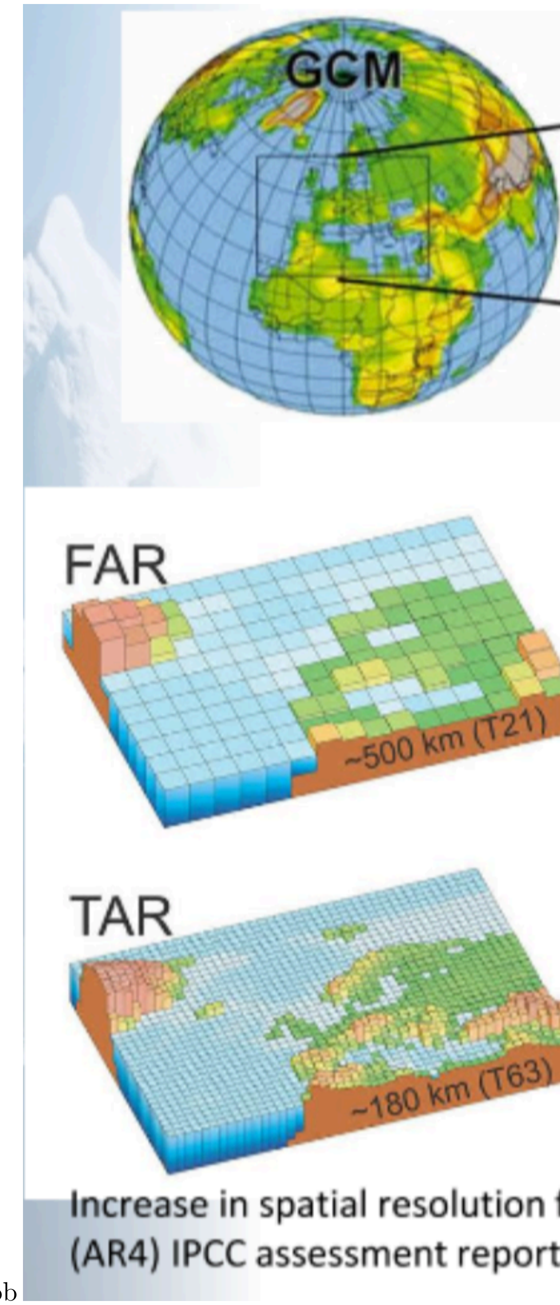
3.2.2.5 Global and Regional Climate Models

A **Global Climate Model** (**GCM**) is a numerical model representing physical processes in the atmopshere, ocean, cryosphere and land surface simulating the response of the global climate system to increasing GHG concentrations. GCMs depict the climate using a 3D grid over the globe. Different GCMs may simulate quite different responses to the same GHG emission scenarios, simply because of the way certain processes and feedbacks are modelled.

Regional Climate Models (**RCMs**) do a similar job as GCMs, but for a limited area of the Earth. Because they cover a smaller area, RCMs can generally be run more quickly (less computational power required) and at a higher spatial resolution than GCMs.

RCMs use information from GCMs at their boundaries (***nested regional climate modelling technique***). The driving data at the boundaries are derived from GCMs and can include GHG and aerosol forcing. 'Regional' in RCMs refers to regions as large as Europe or a large part of Europe. Currently many RCMs for Europe have a spatial resolution of about 25 x 25 km but also many simulations at 12 by 12 km are available. RCMs are used as a **downscaling technique** (from a coarser resolution of global models to higher resolution)



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3.2.2.6 Climate Model Bias

Models are always a simplification of reality and therefore they will never represent reality exactly. In re-analyses we observed small differences between observations and model results. In climate models the differences may become clearly larger (also in S2D predictions biases will occur and will become larger with increasing time horizon).

Definition

Climate model bias are the *differences in statistics of the observations for the reference period and the climate model simulation for the same period*. It is determined by **comparing the climate model output for a past period with observational data for that same period**. This is illustrated in the figure below .

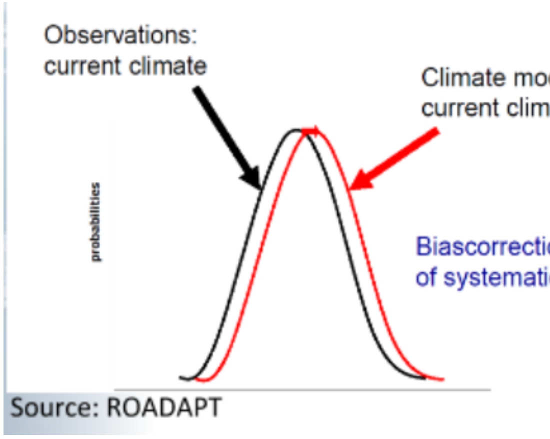
Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/bias.bb 

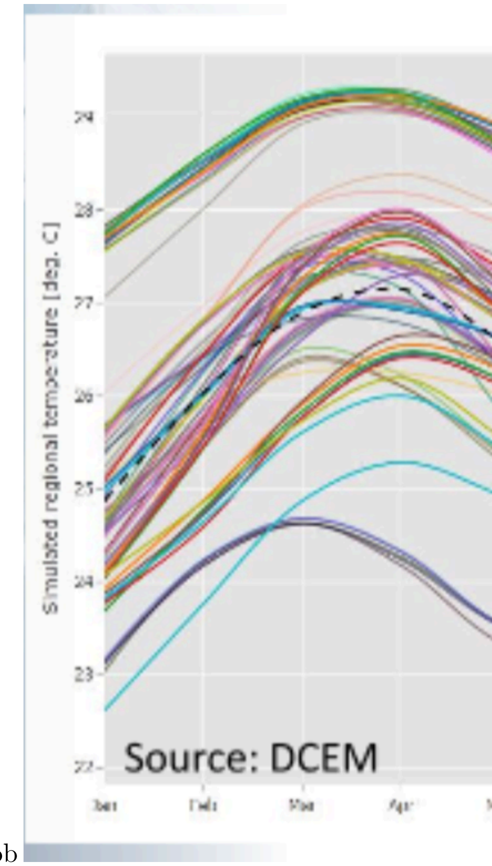
Figure of schematic representation of climate model bias: the systematic difference between model output and observations. The figure presents on the x-axis the daily temperatures in e.g. the month of July in the period 1981-2010 on a certain location. On the Y-axis the probability is shown. As can be see in the figure in the climate model, there is a systematic difference (higher temperature) between model output (red) and observations (black).

Model skill

Example applications: comparison of annual and seasonal climatological averages for relevant climate variables such as probability of extremes, variability, trends, etc.. **The smaller the bias, the higher the model skill** to simulate the observed climate correctly. The skill is often used as a measure of quality.

Biases are compared by comparing the statistics of observational records for a certain period (often 30 years) with the simulated climate for the same period in the past (for projections). Biases can not be determined by comparing e.g. the weather on certain dates or in certain years in the past.

In the below figure, the annual cycle of the average temperature of West Africa for the period 1981-2010 from a large number of RCMs is compared with the annual cycle from the ERA-Interim re-analysis data (dotted black line; used as alternative for observations). Some models simulate the temperatures fairly well, whereas others have large biases.



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Reasons for climate model bias

Some possible reasons are:

- **Simplified physics** and thermodynamic processes
- The way relations are described in **numerical schemes** (**parametrization**)
- **Incomplete knowledge** of climate system processes
- Limited **spatial resolution** in the climate model (horizontal and vertical)

Climate models produce **area-average data**, whereas many observations are **point measurements**. In order to determine the skill, climate model data should be compared with area-average data. This is especially important for climate variables where large spatial differences are observed within a grid cell, e.g. precipitation. For this reason, **re-analysis data is often used to determine the skill of climate models**.

The **quality of climate data for the future** cannot be assessed in a direct way, since no observational data set is available for the future. It is generally **assumed that the bias/skill for the future is the same as for the past/current climate**. When the skill is good for the current climate, we generally have more confidence in the results for the future.

3.2.2.7 Ensembles

Ensembles are a *collection of model simulations characterizing a climate in the past, a prediction or a projection.* Differences in initial conditions and model formulation or parameters result in somewhat different evolutions of the modelled system, and may give information on **uncertainty** associated with:

- **type of model and initial conditions**, in the case of climate **forecasts**
- **type of model and scenario** and **internally generated climate variability**, in the case of climate **projections**

Ensembles are usually made to **characterize uncertainties** (or **variability**). They need to be big enough to describe the relevant uncertainties or natural variability. The following uncertainties can be studied with the help of ensembles:

- **Initial conditions**: espacially important for forecasting and prediction. The initial conditions are slightly changed and the same model is run again (***single-model initial condition ensemble***). E.g. for the weather forecasting at ECMWF, 51 runs are made twice a day to determine the impact of the weather on the forecast. Having an initial condition ensemble can help to identify natural variability in the system. These ensembles are especially important for forecasting and predictions.

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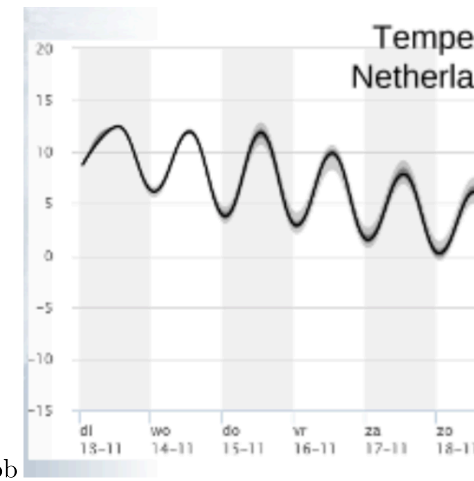

- **Model descriptions of the physical processes** (called '***perturbed physics ensembles***'): an ensemble of runs can be made with somewhat different parameter values in the **same model**, or even with different ways of describing various processes (including different resolutions, **different climate models**). Therefore, also a multi-model ensemble can be made.

- **Forcings** (emission scenarios): various RCPs are used as input for the climate projections. They represent the uncertainties about the future developments of socio-economic and technological developments (resulting in different emissions).

See below figure for an **example** of how ensembles are used to **characterize and quantify various uncertainties**. The grey lines present simulations with different climate models for the past. This helps to **characterize the natural variability** of the past and current climate. E.g. the red lines present the projections of different climate models for the highest RCP scenario. This helps characterizing the **uncertainty about the climate** (also called model uncertainty). The differences between the different colors (different RCPs) are used to characterize the **uncertainty due to socio-economic and technological developments** (also called scenario uncertainties).

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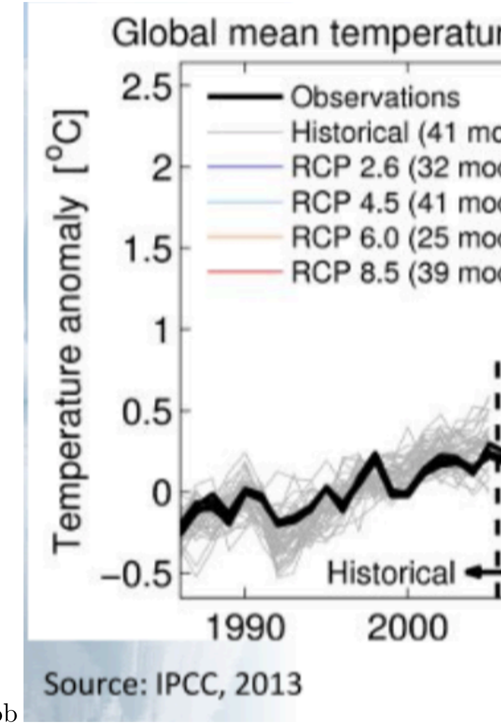


3.3 Pro's and con's of different data sources

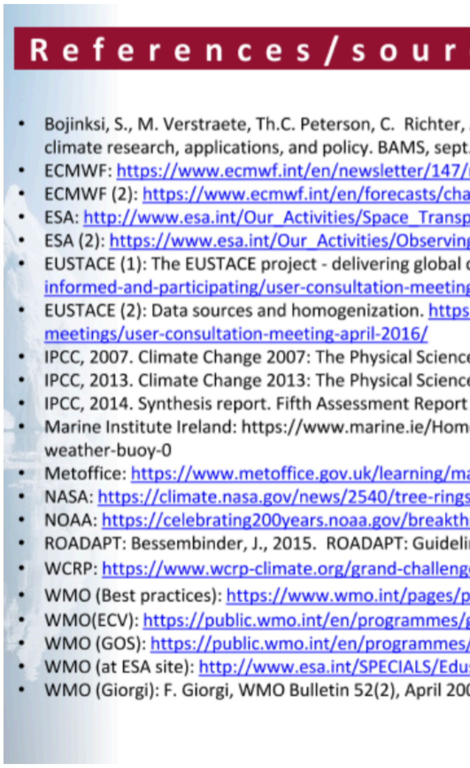
3.3.1 Advantages and disadvantages of different measurement types

	In situ stations (weather stations at land)	Data measurements at sea	Satellite data (radar and lidar)
Advantages	- **Long time series**. Some starting in 1850, from 1950 many more stations- **Direct** measurements of the ECVs	- Important for weather models, since they provide **information for regions with a low density of observations- Direct** measurement of ECVs	- **High spatial coverage** (also data for regions without ground stations) and high spatial resolution.- Data almost **directly available**
Disadvantages	- **No equal distribution** over the earth- Time series often contain '**inhomogenieties**': apparent changes in climate due to e.g. the use of better instruments or changes in the environment.	- Ships and drifting buoys do **not** have a **fixed** location- **No long time series** at fixed locations	- **No long time series** yet (from about the end of the 90s)- The satellite signal has to be translated into the desired climate variable: this introduces additional **uncertainties** and ground observations are needed to make this translation.- Systematic **disturbances** in the signal due to the atmosphere

3.3.2 Advantages and disadvantages of different types of data

	Reanalysis data	S2D Data	Climate model data
Advantages	- Provide also **estimates for climate variables where and when there were no observations**- Provide area-average data, and therefore can be used to **determine the skill of climate model projections/simulations** and S2D predictions.	- Data for the **near future** (seasons to decade).- Because of the use of ensembles this data can also be used for **characterizing the natural variability** more accurately then with observations only.	- Provide data for past and future (and look much further into the future then S2D).- Because of the use of ensembles this data can also be used for **characterizing the natural variability** and to **determine the probability of extremes more accurately** than with observations only.
Disadvantages	- Many reanalysis data have a rather **coarse spatial resolution**- May also contain some **biases**, espacially where there are few observations that could be assimilated.	- **Poor skill** of S2D models in large part of Europe- Can contain **biases**, especially when forecasting for a longer period ahead.	- Presence of **biases** (various methods have been developed to correct for those)- Often **relatively low spatial resolution** ("downscaling" techniques have been used to get a higher spatial resolution)

3.4 References

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/references1.bb 

Chapter 4

Climate data from models

Introductory video by Rob Groenland from KNMI Netherlands.

For more information about model selection, see the dedicated chapter below

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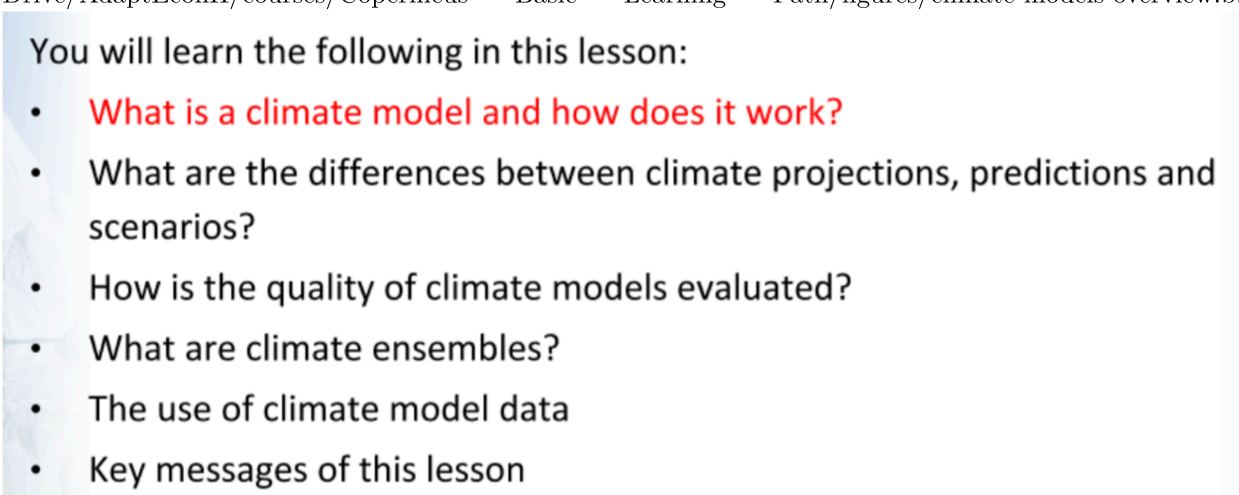
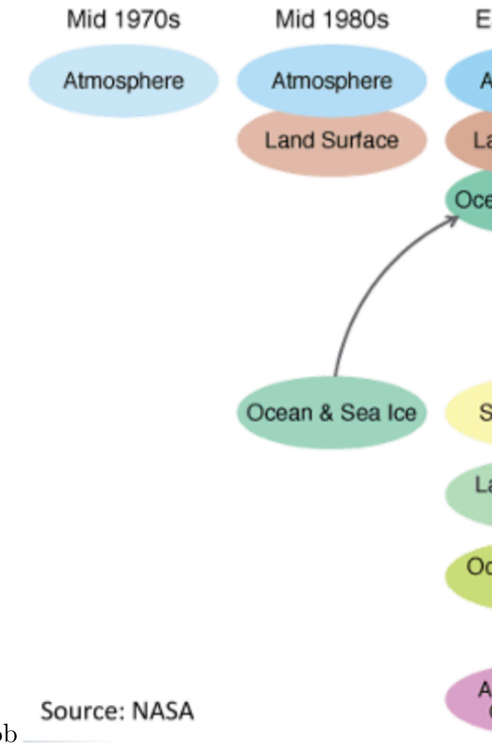


4.1 What is a climate model?

- For a basic explanation of **climate models**, see the section on climate models in lesson 1.
- For an explanation of the **difference between weather and climate (models),** see the dedicated section in lesson 1.
- For a basic overview of **types of climate models**, see the dedicated section in lesson 1.
- For a basic overview of **definitions and differences between global and regional climate models**, see the dedicated section in lesson 1.

4.1.1 Complexity of climate models

For decades scientists have been using mathematical models to help us learn more about the Earth's climate. Over time these models have increased in complexity, as separate components ahve been merged to form coupled systems. The figures below shows the evolution of such systems (first figure from NASA, second figure from IPCC, 2007)



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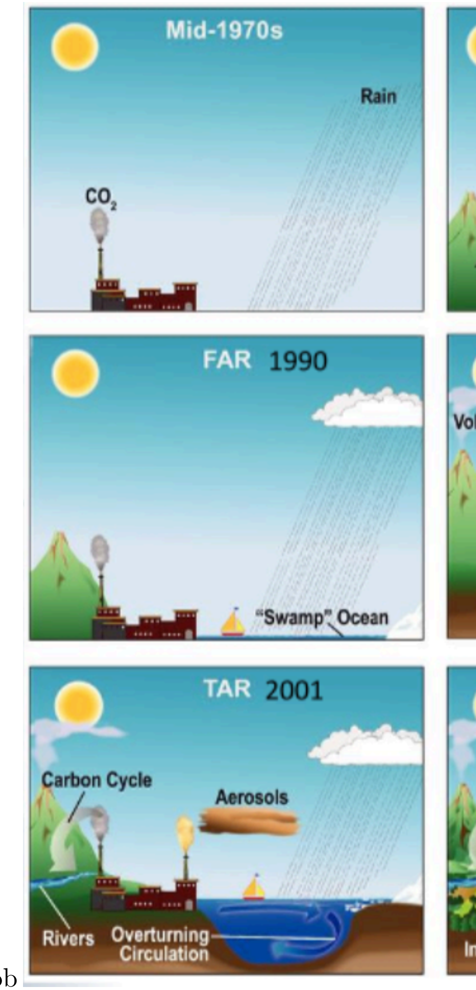
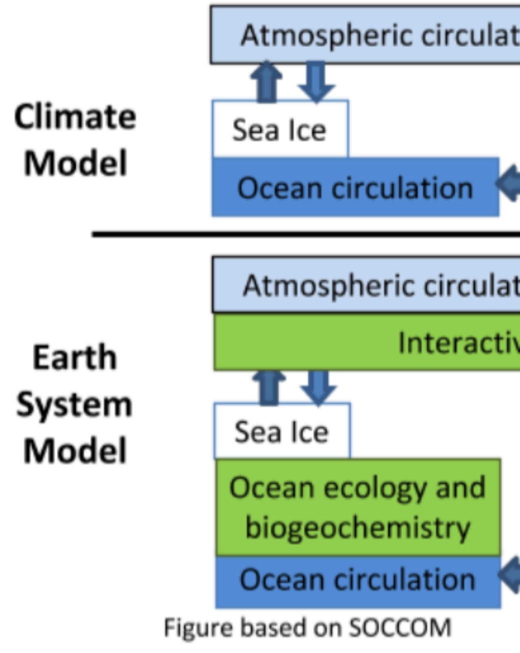
Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/complexity2.bb 

4.1.2 Earth System Models

Earth System Models (ESMs) represent advanced and complex descriptions of the Earth's atmosphere, ocean, land and surface. The **figure shows the difference between a climate model and an ESM**. The componenets in green boxes (biochemical) makes a climate model an ESM.



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Major advances to climate models and ESMs skills have been made through improving parametrization of processes (parametrization: method of replacing processes that are too small-scale or complex to be physically represented in the model by a simplified process). By modelling new feedback processes, the number of processes and complexity in the models has increased. For example: the addition of carbon storage in the ocean and land surface, affecting the carbon cycle response to GHG induced climate change.

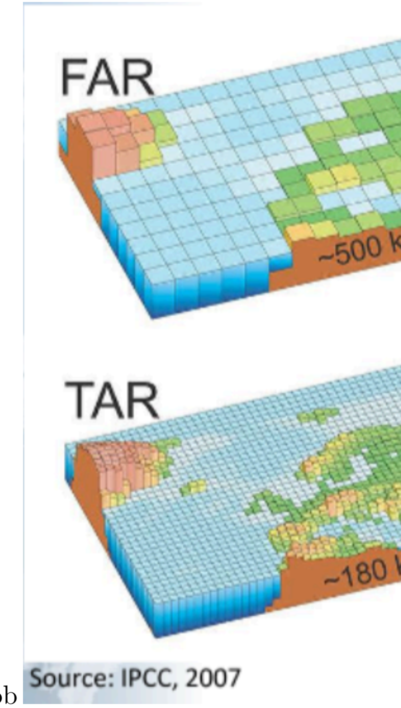
4.1.3 Spatial and Temporal Resolution

Although we know that climate variables such as temperature vary continuously over the surface of the Earth at each moment, calculating such properties for the entire globe and for each moment is beyond the reach of even the fastest supercomputers.

- **Spatial resolution**: specifies how large (in degrees of latitude/longitude or in km/miles) the grid cells in a model are. Not every horizontal layer has the same thickness: close to the earth's surface more detail is required. A typical global climate model might have grid cells with a size of about 50-100 km, although now researcherse are also starting to make simulations with grid sizes of 25 km.
- **Temporal resolution**: refers to the size of the time steps used in the models and how often (in simulated or "model time") calculations of the various properties are being modelled. Although the data are often not saved for future use, often time steps of 1 hour are used.

4.1.3.1 Increase of spatial resolution

The figure below shows the increasing spatial resolution of climate models used through the first four IPCC assessment reports: first ("FAR") published in 1990, second ("SAR") in 1995, third ("TAR") in 2001 and fourth ("AR4") in 2007. In the fifth report from 2014 the resolution of several global models was about 50 km (IPCC, 2013). The increased spatial result was a result of **increased computing power** and a **request for better representation of all kind of climate effects**, including extreme events.



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4.1.3.2 Example of impact of high spatial resolution

In this figure the **sizes of the grid boxes in a GCM and RCM are shown**. Climate models produce area average information. Therefore, the rainfall in the GCM grid box is on average over the whole grid box not more than drizzle. The chance that there will be rainfall in the whole are of a RCM grid box at the same moment is much higher. Therefore, RCMs will give a better indication of shower intensity (and spatial differences).

Non-hydrostatic weather forecast models use a much higher spatial resolution and, therefore, give a better indication of shower intensity.

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4.2 Differences between climate projections, predictions and scenarios

Climate

A **climate projection** is the response of the climate system to different GHG scenarios, often based upon simulations with climate models. The emissions/concenttration/radiative forcing scenario used is based on **assumptions**, that may or may not be realized, and are therefore subject to **substantial uncertainty not related to the climate system**.

A **climate prediction** or **climate forecast** is the result of an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future, e.g. at **seasonal, interannual or decadal time scales**. While seasonal forecasts are routinely issued in some regions, climate predictions at longer time-scales are still at an early research stage, for example within the CMIP5 climate modelling community. In the same way as weather forecasts depend on the initial state of the atmosphere, climate predictions depend on an accurate description of the initial state, mainly in the oceans. In contrast to climate projections, climate prediction **rests on initial simulations of observerd conditions** and is limited to time scales from subseasonal to decadal. Subseasonal to decadal predicitons (S2D) - explained in the related section in chapter 1 - is also known as climate prediction.

As mentioned in the related section in chapter 1 on subseasonal to decadal prediction, **predictions are typically initial value problems**. In this case, **short-term evolution from an initial state is analysed with constant boundary conditions**. Also, probability can be verified in time to provide meaningful feedback. While with **projections**, one looks typically at **changing statistics in response to changing boundary values**. In this case, the probability of projections cannot be given.

Weather

A weather forecast **predicts the state of the atmosphere over a short period of time** - for Europe usually up to about two weeks - and is **independent of the initial state of the atmosphere** (and the upper ocean). The initial state is obtained by means of the global network of meteorological stations and observing systems.

4.2.1 Climate scenarios

A climate (change) scenario is an **image of a potential future that is based on knowledge of the past and assumptions on future change**. The IPCC scenarios are based on a clear logic and a **data-driven storyline (or narrative)** of what events have occured in the past and how the future may unfold. A climate change scenario is the **difference between a climate prediction and a reference period in the past** (e.g. 1981-2010). The term “climate scenario” is also regularly used for individual climate projections.

Climate (change) scenarios are generally based on climate projections that use GHG emission or concentration scenarios:

4.2.2 Emission scenarios and RCPs

For an overview of emission scenarios and RCPs, see the dedicated section in the previous chapter.

4.3 How is the quality of models evaluated? (what is a climate model bias?)

4.3.1 Climate model bias and model skill

For a definition of **climate model bias**, the link between model bias and model skill and an overview of reasons for climate model bias, see the dedicated part in the previous chapter.

4.3.2 Types of climate ensembles

For an overview of (the different types of) climate ensembles and examples of those, see the dedicated section in the previous chapter.

4.3.3 Climate Model Intercomparison Project (CMIP)

There are many institutions involved in developing and running their own climate models. Although they all base their models largely on the same existing knowledge of the climate system, there are also differences in e.g. how certain processes are described, which data are used for calibration of the models, etc.

In 1995 the Coupled Model Intercomparison Project (CMIP) started. CMIP is a framework for coordinated climate model experiments, allowing scientists to analyse, validate and improve GCMs in a systemic way. "Coupled" refers to the fact that all included models are coupled atmosphere-ocean GCMs. This video from the World Climate Research Programme gives an overview of the CMIP.

Data from the fifth CMIP project were used extensively in the IPCCs 5th Assessment Report (IPCC, 2013, 2014) for:

- Improving the understanding of climate and assessing the mechanisms responsible for model differences
- Making projections for the future for policy makers and adaptation research
- Evaluating how realistic the different models are in simulating the recent past

4.4 The use of climate model data

Climate model data have clear **advantages over observations**. The most important are:

- Data can be provided for **locations and periods without observations**
- Climate models are the **only source that can be used for the future**
- Climate model **ensembles can provide more information for the past/current climate and for the future** with which **uncertainties** and **natural variability** can be estimated.

To use them in a correct way, one should be aware of the **limitations and assumptions** behind the data too.

4.4.1 What climate model data are available?

Climate data for the **past/current climate**:

- Climate model **simulation (projection) runs**. When making a run for the future, always a run for the recent past is made.
- Reanalysis (see dedicated part in previous chapter)

Climate data for the future:

- Climate model **simulation (projection) runs**, for various emission/concentration scenarios (**RCPs**)
- **Seasonal to Decadal Precitions (S2D)** (see dedicated part in previous chapter)

In most cases **observational data** are also needed to use the climate model data (e.g. to **determine the skill/bias**).

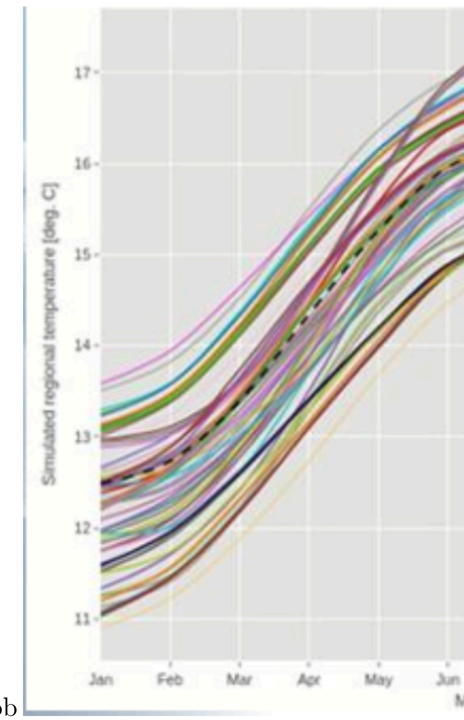
Reanalysis data are often used as **alternatives for observations**. Reanalysis provide a **coherent and consistent description of the status of the atmosphere and ocean at all locations and dates**. Moreover, they can provide area-average data that can be compared more directly with climate model projections.

4.4.2 Names of climate model data files

Names of climate model output files may seem very complicated. However, they are always build up in a systematic way containing at least the following information:

- **Institute** that made and runs the model
- **Model** name
- **Period** simulated

For example, in the figure below the first part of the first name refers to the institute (CSIRO-BOM: Australian institute) and the second part refers to the model used (ACCES). The figure shows an example of the average historical global temperature (1981-2010) over a eyear as simulated by many GCMs. In the C3S Climate Data Store (CDS), the model name is given with the institute and country in brackets.



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4.4.3 Names of climate variables

Specific codes are used for climate variables. To be able to extract correct data from climate model data you have to know the codes or check them. This is also true for derived climate indices. Some examples:

Code	
TN or Tasmin	minimum daily temperature
P or RR	daily or hourly precipitation
FF	wind speed
TXx	maximum value of daily maximum temperature (°C) in a season, month or year
RX1day	highest 1-day precipitation amount (mm) in a season, month or year

Always check the dimensions of climate variables e.g. m.s^{-1} or km.h^{-1} for wind speed.

See for example for the **names of derived variables** the **data dictionary of the European Climate Assessment Dataset** (ECAD).

4.4.4 Assumption on bias

Before selecting or using climate model data, one should check the skill of the model. For this purpose, the climate model run for the past is compared with the observations (or reanalysis).

Below figure is an example with many **different climate models for the average temperature for the period 1981 - 2010 - for South Europe/Mediterranean**. The **dashed line is based on reanalyses**.

In climate research it is **generally assumed that the bias will remain the same in the future, although this cannot be checked**. Biases may not be the same throughout the year and they **may not be the same for averages and extremes**. There are different methods to remove the biases (not treated here). **Bias correction datasets** are also available for some climate model runs in the **EURO-CORDEX project**.

4.4.5 Use one or more projections?

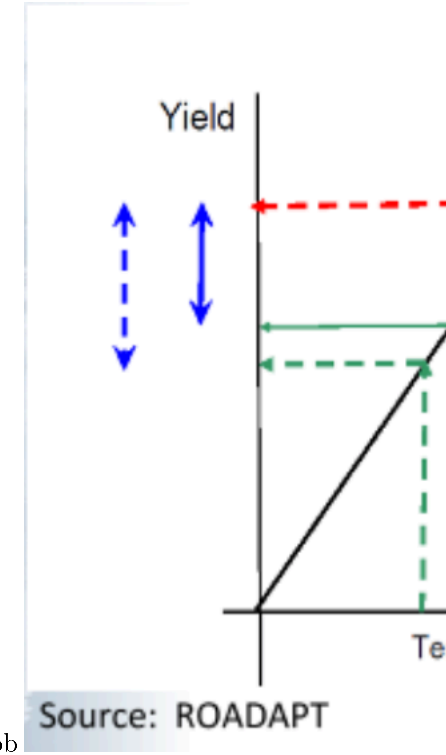
The user of climate projections or climate scnearios should not trust the results of only one climate projection or scenario for impact analyses, as **there is no such thing as 'best GCM', 'best RCM' or 'best climate scenario'.** Therefore, it is advisable to **make use of a group of projections (ensemble) or a set of climate scenarios**. Depending on which uncertainties one wants to take into account, a different ensemble should be selected. Only in cases where one wants to check whether climate changes are relevant at all, it could be sufficient to just use one projection or scenario (e.g. with the highest change in the relevant climate variable).

When using an ensemble or a selection of scenarios or climate model runs, **take care that the relevant uncertainties are spanned**. The **climate data evaluation tool** (DCEM; under development) developed by C3S is very **useful to see which model runs have a high or low change in the future.**

4.4.6 Importance of bias correction

Since climate model runs always contain biases, **you cannot get an idea of the changes in the future by comparing observations directly with the uncorrected climate model projections for the future**. To get an idea of the changes in the future you have to **compare the climate model run from the recent past with the climate run of the future**. In case of **impacts** you often **have to bias correct the climate model runs first**.

Below is a schematic example of the **possible effect of climate model bias on the estimation of the impact of climate change**. The climate model output has a systematiclly too low temperature. Since the impact model has a treshold and a non-linear relation with temperature, one makes an overestimation of the impact of climate change on yield without bias-correction.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/bias-correction.bb 

4.4.7 Spatial resolution and downscaling

Downscaling is a general concept that embraces various methods for increasing the spatial resolution. Basically, there are two fundamentally different approaches to this:

- **Dynamical downscaling**: makes use of a Regional Climate Model (**RCM**) having **higher spatial resolution**
- **Statistical or empirical downscaling**: uses **observations at local and coarser scales to determine the relations between them**. These relations are then used to translate the information on coarser scales which are available only in e.g. GCMs to **get information at higher spatial resolutions**.

4.4.8 Required spatial resolution

Depending on the purpose of the use of climate data and the area that should be covered, one can use GCM or RCM.

For example, when looking at **water management in the Iberian Peninsula**, one wants to have **relative high spatial detail**. **RCMs** do have a higher spatial resolution and are therefore probably the most logical choice. When looking at **world food security**, data for the whole globe are needed and therefore **GCMs** will probably be used.

4.5 Developments in climate model research

Climate models are constantly being improved. When using climate data, always check the newest available data sets. Some subjects of current climate research are:

- **More complex models** (more components, ESM)
- **Resolution** increases in GCMs (e.g. Primavera project) and RCMs (e.g. EURO-CORDEX)
- How to **improve the simulation of past trends**? When models can simulate trends well, we can have more trust in simulated projections.

- How to make evaluation of climate models easier (development of **tools**) and how to **evaluate more aspects of climate such as natural variability and extremes**.

4.6 References and Links

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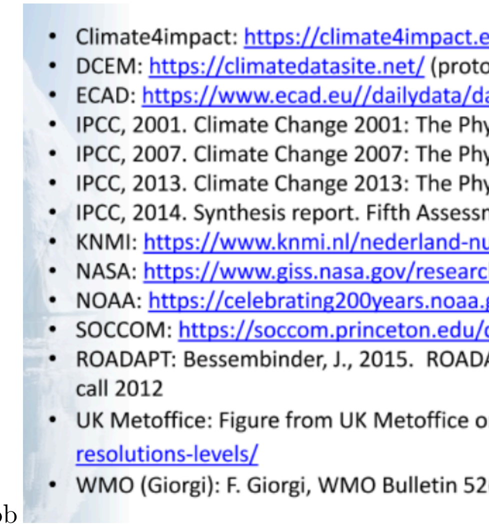


Chapter 5

Climate Data Discovery

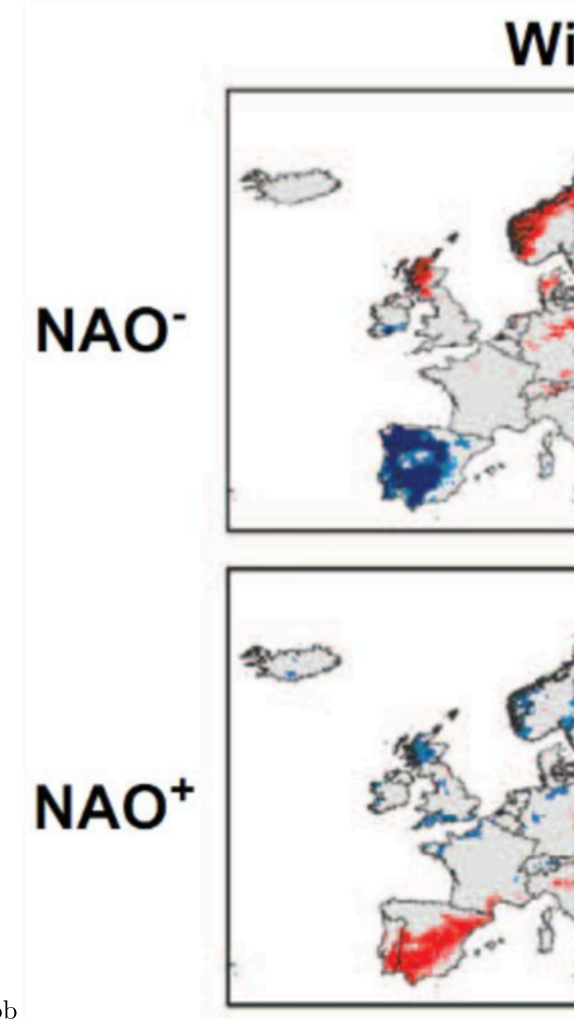
See also introductory video for this part.

5.1 Difference between weather and climate

For an overview of the basic differences between weather and climate (models), see the dedicated part in the first chapter. In short:

- **Weather**: conditions of the atmosphere over a short period of time
- **Climate**: average behavior of the atmosphere over relatively long periods of time (usually >30 years).

Climate variability is often expressed as **anomaly**, in months-seasons-years. Depending on the location, these can be influenced by e.g. the North Atlantic Oscillation (Europe) or El Niño/La Niña:



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5.1.1 Weather and climate vs. decision making

The types of data needed, depends on the topic/sector covered and type of decisions that need to be made. For example in the water sector, agricultural sector and insurance sector both **weather** (daily decisions), **climate variability** (systemic changes) and **climate change** (transformational changes) information could be needed:

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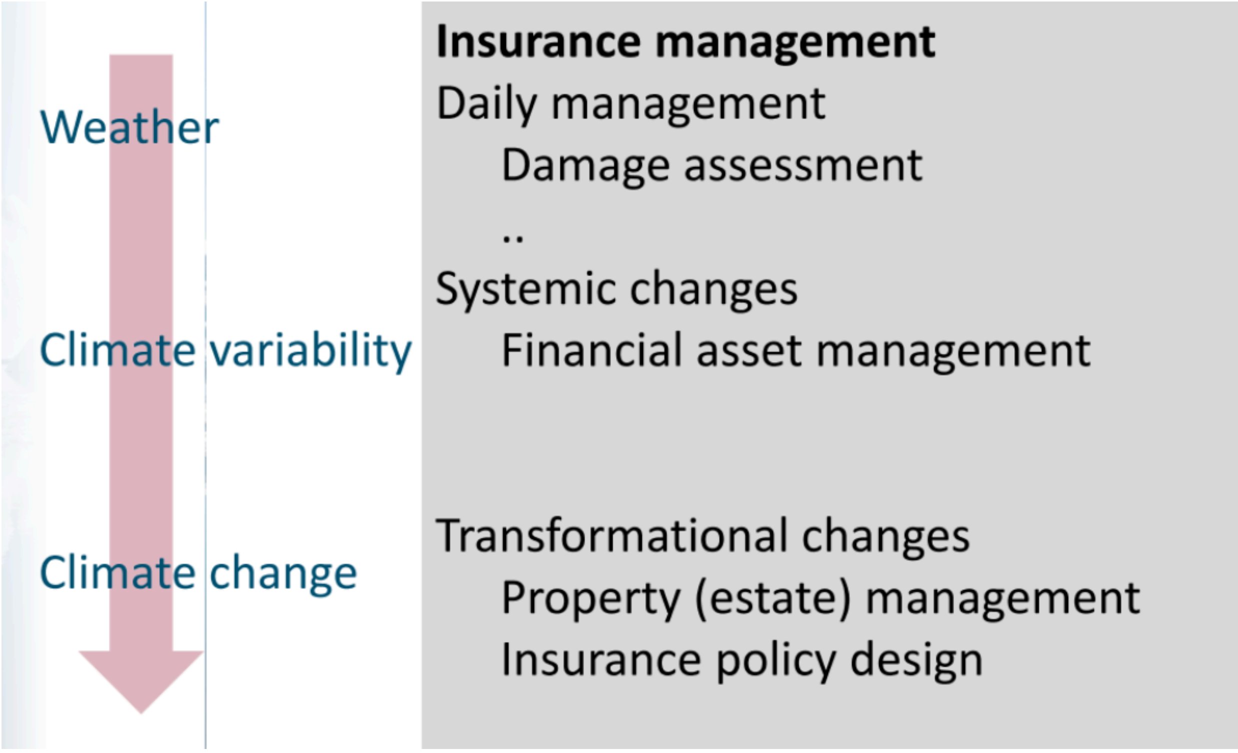

Figure 5.1: info-ins

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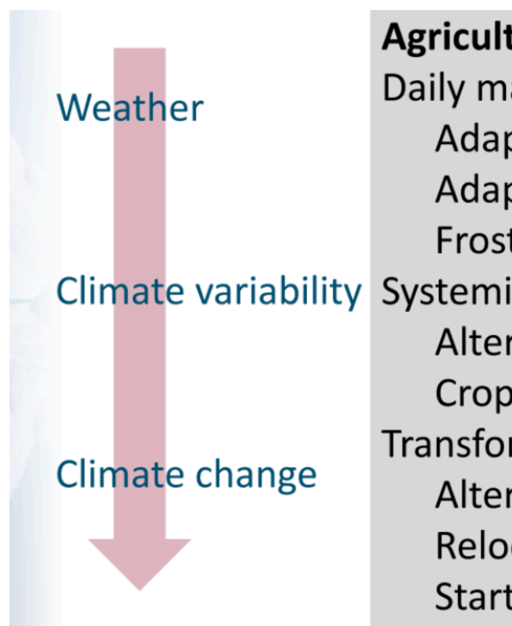

5.2 Different sources of climate data

See also the online video. This lesson goes further in depth on charateristics and utilisation cases of the different types of sources:

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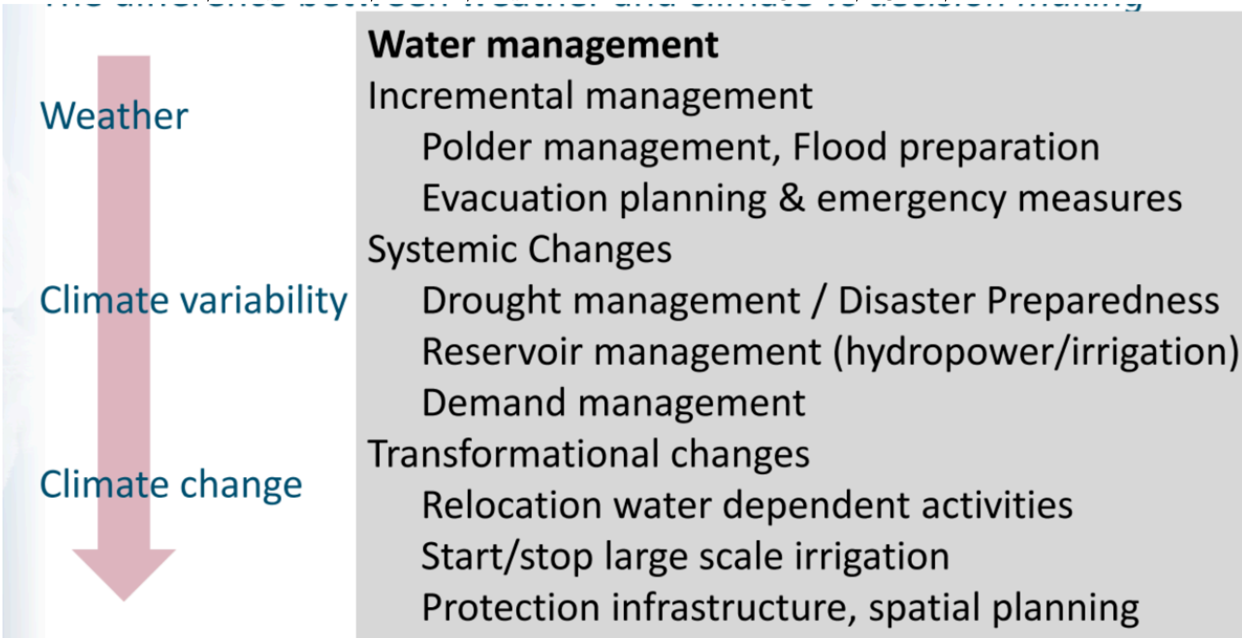

Figure 5.2: info-water

- **In-situ (direct) observations** (such as weather stations). For more information see the dedicated section in the first chapter.
- **Satellite observations (indirect)**. For more information see the dedicated section in the first chapter.
- **Reanalysis** products. For more information see the dedicated section int the first chapter.
- **Weather model forecasts**
- **Seasonal to decadal climate forecasts (S2D)**. For more information see the dedicated section in the first chapter.
- Climate change (model) **projections**. For more information see the dedicated section int the first chapter.
- **Sectoral climate indices**

5.2.1 Relations between the different data sources

Observations are needed for 2 things:

- Find **the state of the atmosphere for a certain moment**, from where to start **model simulation** development (= ***initial conditions***)
- Observed data are needed for **model development**. Models are constantly validated and improved where needed.

5.2.2 Sources available on C3S

As in-situ measurements are rarely useful for climate (impact) assessments, the original data can only be found at the original provider. However, C3S provides **gridded products of Essential Climate Variables** (ECVs). For an overview of existing ECVs, see the dedicated part in the first chapter.

- Observations from **global climate data archives**
- Observations from **baseline and reference networks**
- **Climate monitoring products for Europe**
- Etc.

5.2.2.1 Observations

- **In-situ observations**
  - Available at C3S from +- 1850
  - Gridded observation products are available, e.g. **Eobs**, **GPCC**, …
- **Satellite** observations
  - Available at C3S from +-1970
  - Merged observation products available, e.g. GPCP
  - Improved continuity, quality, …
- Other gridded products:
  - **Atmosphere** (**composition**): Long-lived GHGs, ozone, aerosols, …
  - **Atmosphere** (**surface**): precipitation, clouds, …
  - **Ocean** (physics): sea surface temperature, …
  - **Land** (hydrology): soil moisture, albedo, leaf area index, …
  - …

5.2.2.2 Data produced by models: suited for particular time horizons

- **Reanalysis** products.
  - available from 1950s
  - remain close to the observation, advantage to be availble for all locations at any moment in time
  - **Continuous** (hourly) data (space/time)
  - good alternative to observations for regions with few observation points
  - better than observations that are interpolated with geostatistical technique (discouraged!)
  - Latest data available on C3S: **ERAS** (**ERA5**-Land, **AgERA5**), **RRA**, …
    - Specialized high-resolution sets will become available as well.
  - See separate lesson on reanalysis
- **(Weather model forecasts)**
  - run from now —> 14 days future
- **Seasonal [to decadal] climate forecasts (S2D)**
  - Seasonal: now —> +12 months
    - Are 'initialized' climate models, NOT a weather forecasts
    - Montly statistics have predictive skills, *not* hourly/daily time series
    - Available at C3S (graphical + numerical): **SEAS5**/ECMWF, **GloSea5**/UKMO, **System6**/MeteoFrance, **SPSv3**/CMCC, **GCFS1**/DWD, **CFSv2**/NCEP, **MRI-CPS2**/JMA
    - See lesson on seasonal forecasting products
  - Decadal: now —> few decades
- **Climate (model) projections**
  - … —> +-1800 —> 2100 —> …
  - Not initialized, NOT a weather forecast, and NOT a reanalysis —> they **only have statistical meaning** (to analyse difference between historic and future climate)
  - **Follow prescribed GHG emission scenarios** (RCPs)
  - Important to use multiple models and multiple RCPs
  - Examples available at C3S: **CMIP5**, **CORDEX**, CMIP6 will be available soon.

These types of data can be used to **derive specific sectoral impact indices**. Sectoral impact models (water, agriculture, agriculture, energy, insurance, …) and **data** such as river discharge, crop development indicators, power potential, etc… are also available at C3S.

Bias correction may be needed, increasing from top to bottom of model data list (see lesson on bias correction).

5.3 Strategies to find the data you need: "Be specific"

See also the accompanying online video. The main message is: "Be specific" about:

5.3.1 Time horizon and region/location

- Most data are gridded, don't follow political/sectoral classifications
- The time horizon depends on the problem to be adressed. It might be monthly or sub-daily.
- Choice can affect the base-period for change assessment (1961-1990, 1981-2010, …)
- **Historical** questions (can be very specific in place and time) versus questions about the **future** (generally larger areas & longer periods)

5.3.2 Source (observation or model-based)

- If from model: from which model, and which scenario?
- Often **you need both**: using observations/reanalysis to assess bias/skill of predictions/projections for chosen model, variable, location, season of interest, …

5.3.3 Variable of interest

- Each variable has different meaning and use
- Depends on the problem assessed:
  - **Time series** (for impact model forcing) vs **statistics**. E.g. agriculture: "number of days with temperature below zero", floods: "number of times a certain amount of rain falls in 500y period". Statistics = *climate impact indices*. Time series can be used to feed your own model.
  - Mean vs. extremes, percentiles vs treshold, single/combined —> generally agreggated from daily data
  - Set of (standard) **Climate Indices** (CCI) = **tools on CDS to compute those on demand**.

5.3.4 Model selection

For more information about model selection, see the dedicated chapter below

Which model to chose? In CMIP5: more than 40 models available. They differ in:

- Resolution
- Complexity and structure
- Parametrization
- Representation of earth system feedbacks (and strenths of those)

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5.3.5 Scenario selection

Even though the UNFCCC in Paris agreed we should follow RCP2.6-scenario, you often need to **assess more than one RCP or Shared Socio-Economic Pathway (SSP).** Especially when you are interested in analysis for the end of the century.

When you are **only interested in changes in the next decade**s (<2050), **choices in RCP-SSP become less relevant**.

5.3.6 Model selection for seasonal forecast

Since the predictive skill of models are complementary (region, lead time, …), it is recommended to use a combined product: the **Multi-Model Ensemble**.

See also **lesson on uncertainty** below.

5.3.7 References

- Eumetsat infrared image 31 July 2018 1500hrs. Link
- Köppen climate classification of Europe. Link.
- Nobre, G. G., et al. (2017). “The role of climate variability in extreme floods in Europe.” Environmental Research Letters 12(8): 084012, DOI: 10.1088/1748-9326/aa7c22
- ECMWF
- GPCC Vizualizer. Link.
- C3S_312a_Lot3_TVUK_2016SC1 - Product User Guide and Specification, p8

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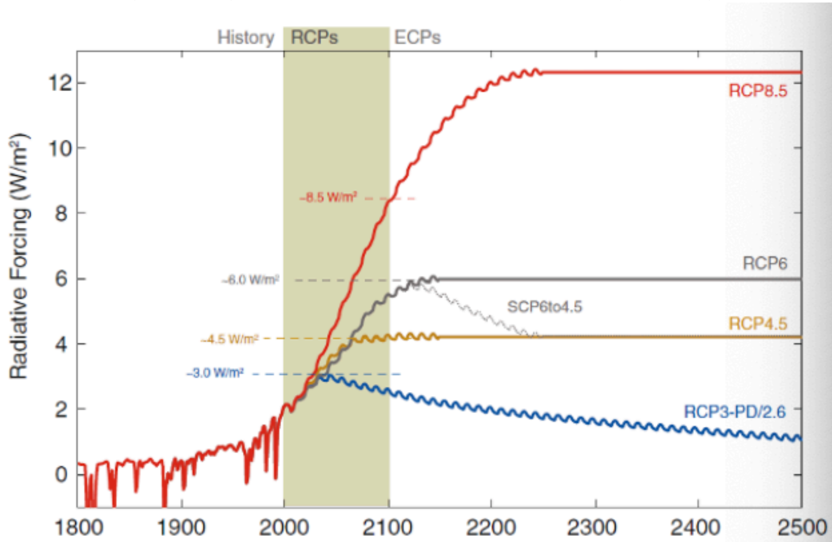

Figure 5.3: rcpexample

- C3S_312a_Lot6_IUP-UB – Greenhouse Gases - Product User Guide and Specification (PUGS) – Main document , p32
- IPCC-AR5 WG1, Table 9.1 Flato, G., et al. (2013): Evaluation of Climate Models. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F. et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- RCP figure: Meinshausen, M., et al. (2011). “The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300.” , DOI: 10.1007/s10584-011-0156-z
- SSP Figure. Link.

5.4 Strategies to find the data you need: Climate data processing chain (Advanced)

See lesson *Climate Data Discovery - Advanced Level* : link

5.4.1 Overview of climate processing chain

Note: **sectoral impact studies** mostly bypass the part between domain selection and re-formatting, but nevertheless important to know the details.

5.4.2 Variable Selection

- Near surface data (single level)
- Higher atmosphere (pressure levels)
- Near surface is NOT level 1000hPa:
  - Strong gradients with height in boundary layer
  - E.g. Tair_2m, Wind_10m
- Beware of (extreme) extremes

5.4.3 Domain selection

- Not too small

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/chain-overview.bb

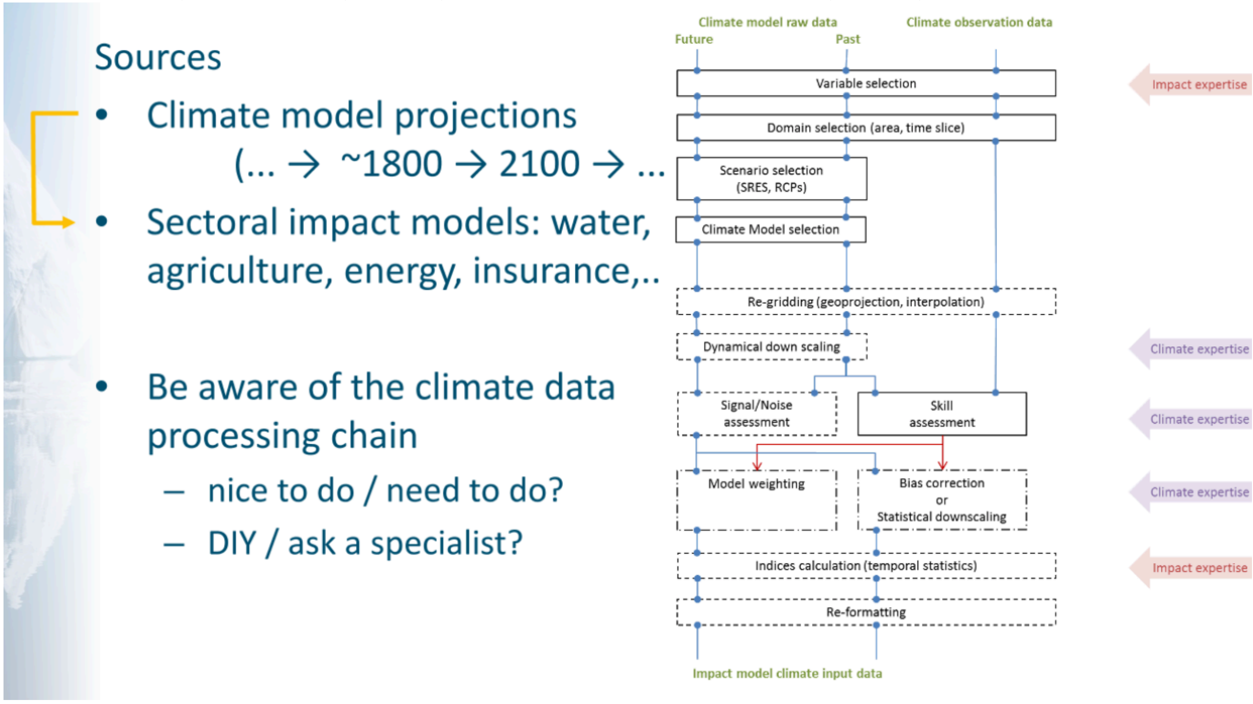

Figure 5.4: chain-overview

- sampling variance
- sampling gradienst
- Relatively simple BC/DS-method is sufficient

- Beware of sharp gradients
  - Coast line vs. model land mask
  - Steep topography
  - Large land use contrasts

5.4.4 RCPs and SSPs

Main message: be consistent.

- 4 RCPs set by IPCC-AR5 (depending on radiative forcing, depending on GHG concentrations). IPCC-AR4 similar, before: SRES (except RCP2.6)
- 5 Shared Socio-Economic Pathways (SSPs). Similar in IPCC-AR4, before: SRES

5.4.5 Climate model selection: how to distinguish? (climate sensitivity, transient response, (dis)similarity, spatial scale, ...)

For more information about model selection, see the dedicated chapter below

- 40+ GCMs: different resolution, complexity, parameterisations, feedback strenghts, etc..
- Consider (**equilibrium climate sensitivity**) ECS/ (**transient climate response**) TCR
- Consider model **(dis)similarity**:
  - model lineage and model behaviour
  - local spread in #T-#P

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	SSP1	SSP2	SSP3	SSP4	SSP5
RCP8.5					√
RCP6.0		√	√	√	√
RCP4.5	√	√	√	√	√
RCP2.6	√	√		√	

Figure 5.5: rcp-ssp-consistency

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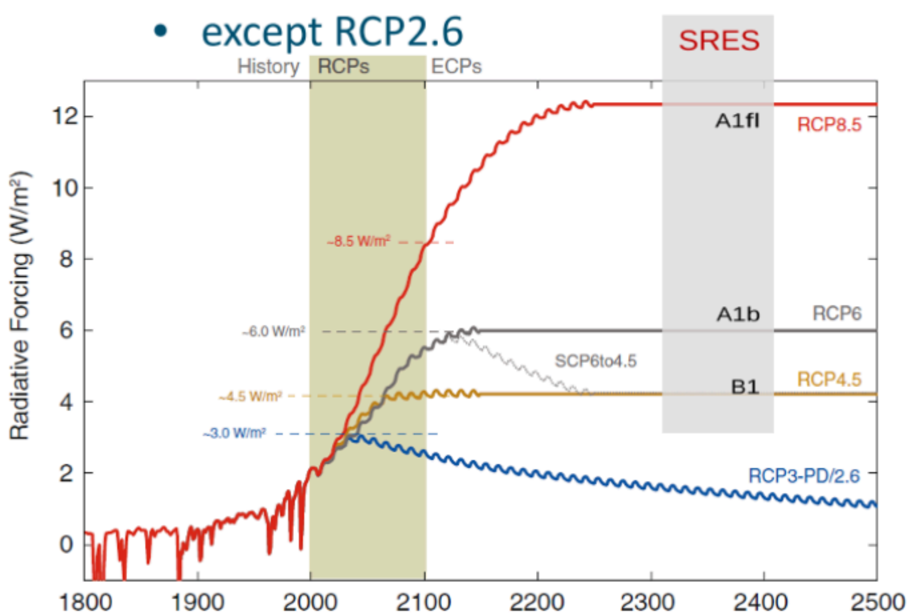

Figure 5.6: 4-rcps

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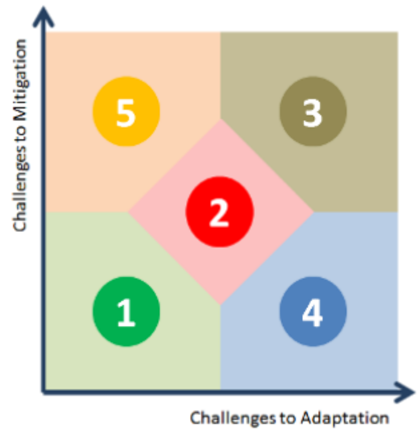

Figure 5.7: 5-ssps

- Consider **area**:
  - for small areas pick model with best skill
  - At larger spatial scales: **Multi-Model Ensembles** (MME) show better than single model

5.4.6 Dynamical and statistical downscaling

For more information about bias correction and the importance, see the dedicated chapter further on

5.4.6.1 Why downscaling?

GCM/ESM low resolution:

- Poor spatial gradients (topography, coast lines, land use, megacities)
- Poor extremes (esp. precipitation)

5.4.6.2 How to do downscaling?

- RCM higher resolution, limited area
- Needs nesting in GCM/ESM
- (statistical downscaling)

5.4.6.3 Statistical and Dynamical downscaling

Dynamical downscaling: uses high-resolution climate models for a regional sub-domain, often using lower-resolution global climate models as boundary conditions

Statistical downscaling is a 2-step process:

1. **Statistical relationship** is derived **between observed small-scale variables and larger global climate model scale variables**
2. Statistical relations are used to **estimate the future climate at the smaller scale based on the largescale variables from GCM projections** of the future climate.

Dynamical downscaling: regional climate model uses the global clmiate model (GCM) as boundary condition:

- GCM / RCM selection

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Model	Equilibrium Climate Sensitivity (°C)	Transient Climate Response (°C)
ACCESS1.0	3.8	2.0
ACCESS1.3	n.a.	1.7
BCC–CSM1.1	2.8	1.7
BCC–CSM1.1(m)	2.9	2.1
BNU–ESM	4.1	2.6
CanESM2	3.7	2.4
CCSM4	2.9	1.8
CESM1(BGC)	n.a.	1.7
CESM1(CAM5)	n.a.	2.3
CNRM–CM5	3.3	2.1
CSIRO–Mk3.6.0	4.1	1.8
FGOALS–g2	n.a.	1.4
GFDL–CM3	4.0	2.0
GFDL–ESM2G	2.4	1.1
GFDL–ESM2M	2.4	1.3
GISS–E2–H	2.3	1.7
GISS–E2–R	2.1	1.5
HadGEM2–ES	4.6	2.5

Figure 5.8: ecs-tcr

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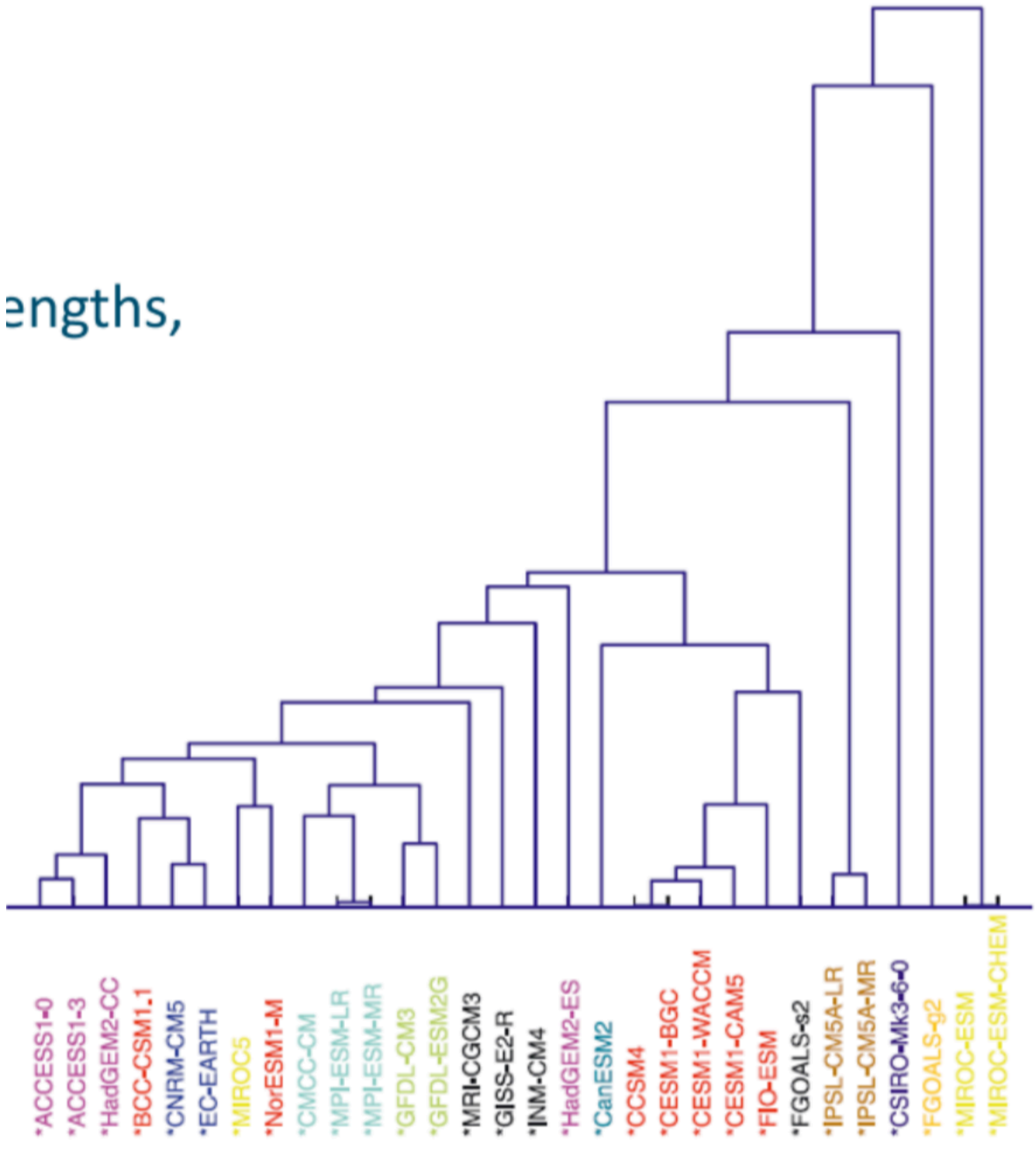

Figure 5.9: model-lineage

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/local-spread.bb

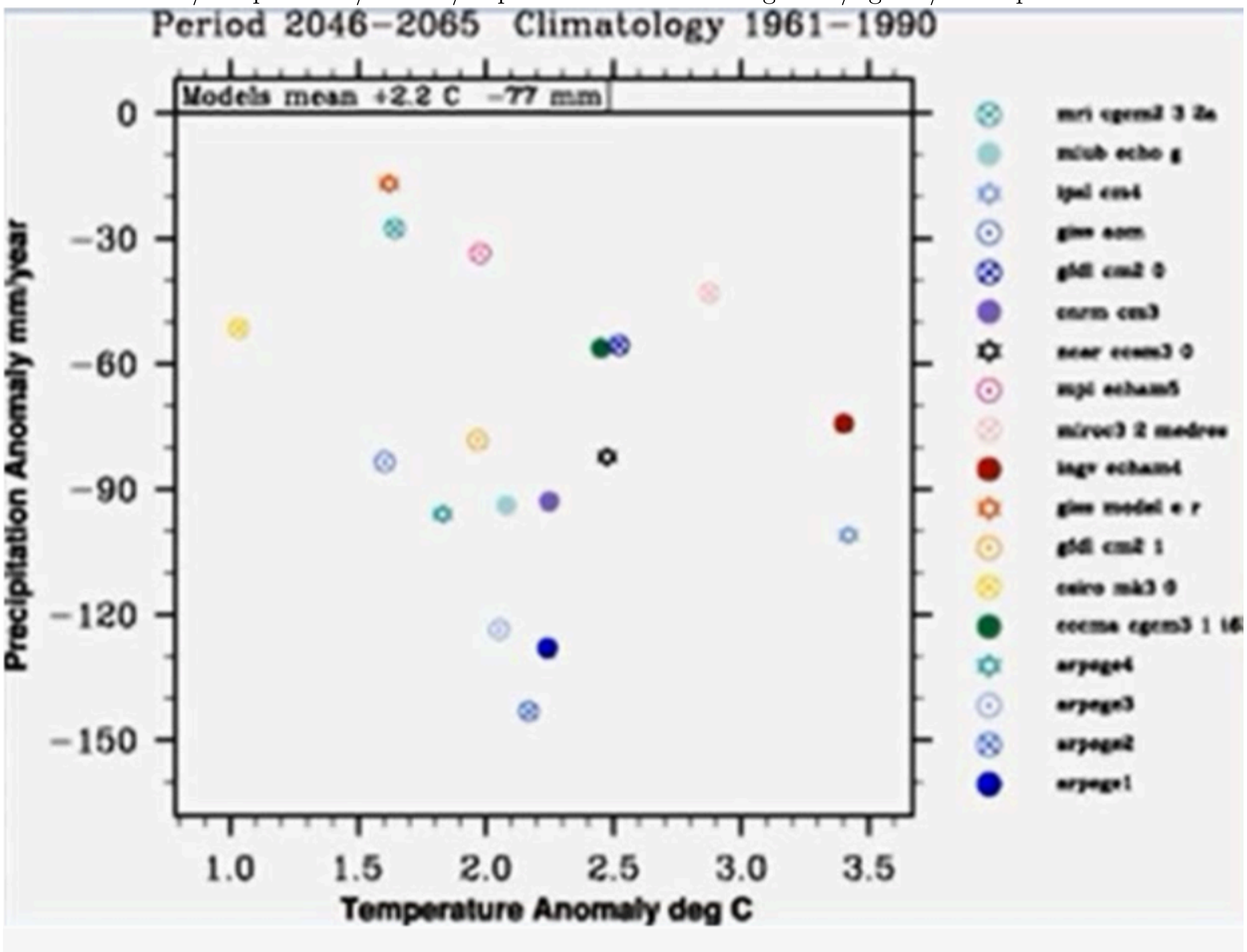

Figure 5.10: local-spread

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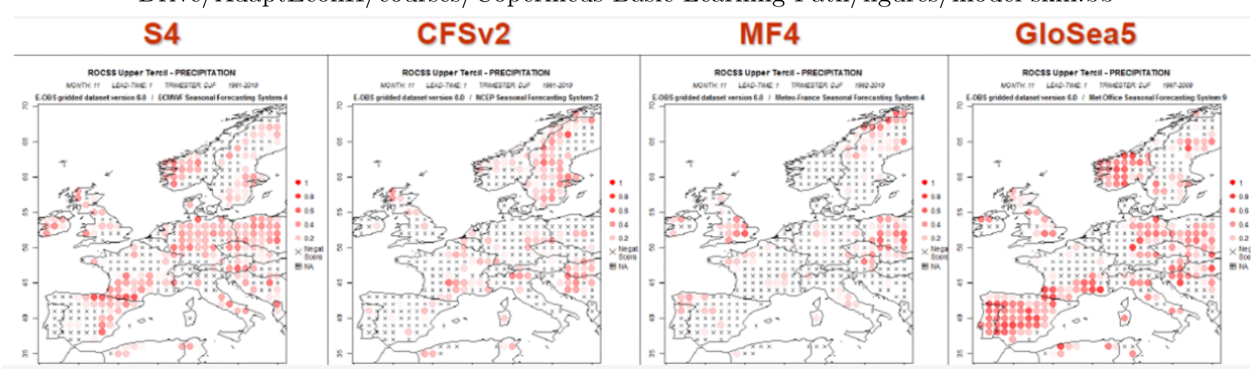

Figure 5.11: model-skill

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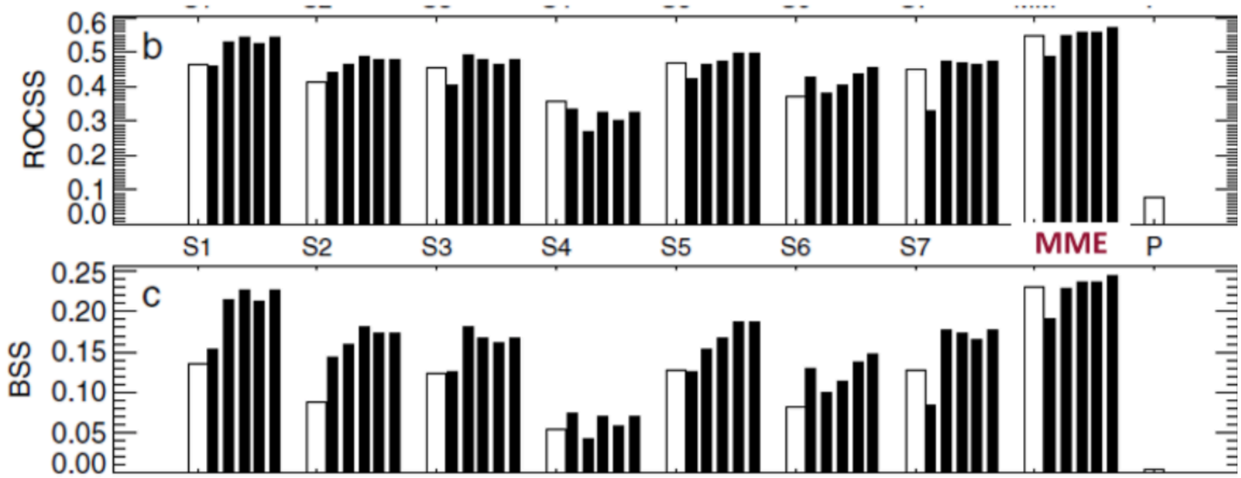

Figure 5.12: multi-model-skill

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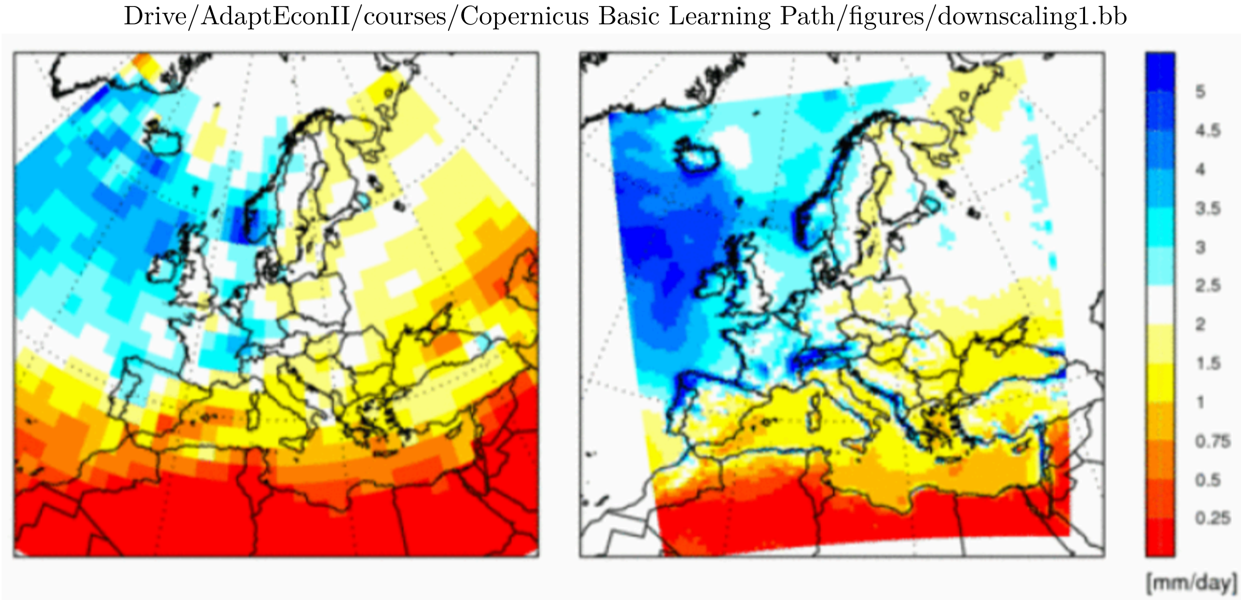

Figure 5.13: downscaling1

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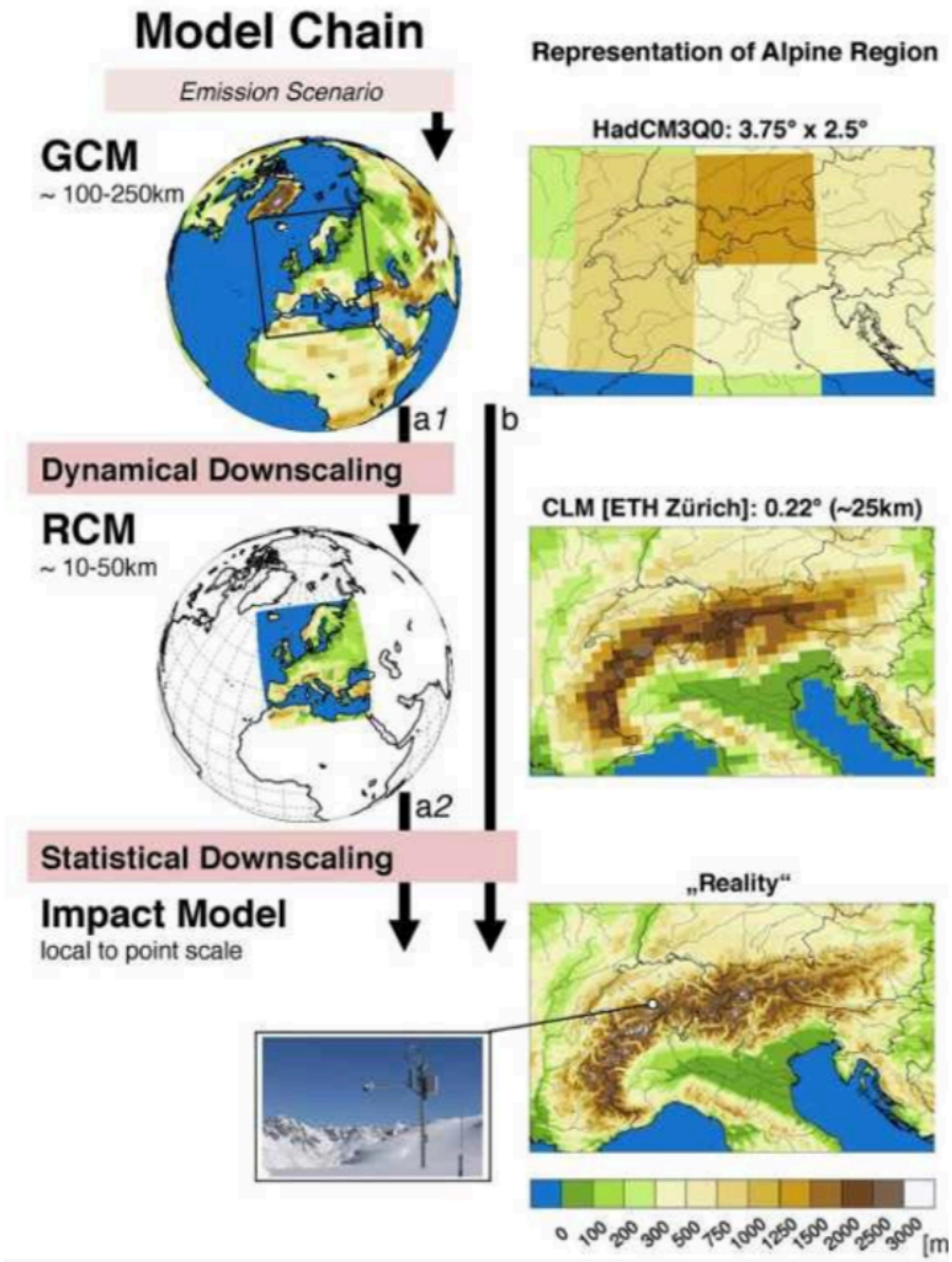

Figure 5.14: downscaling2

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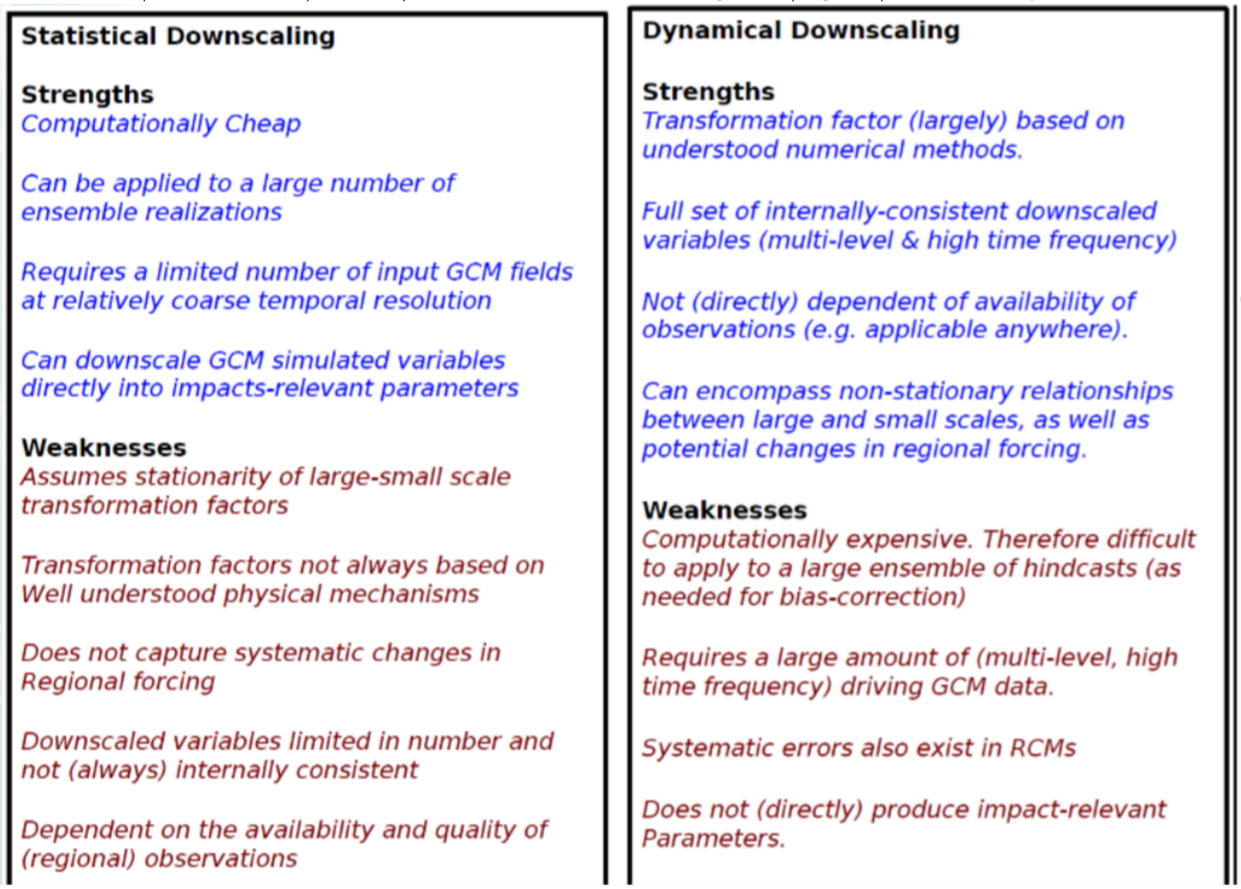

Figure 5.15: statistical-dynamical

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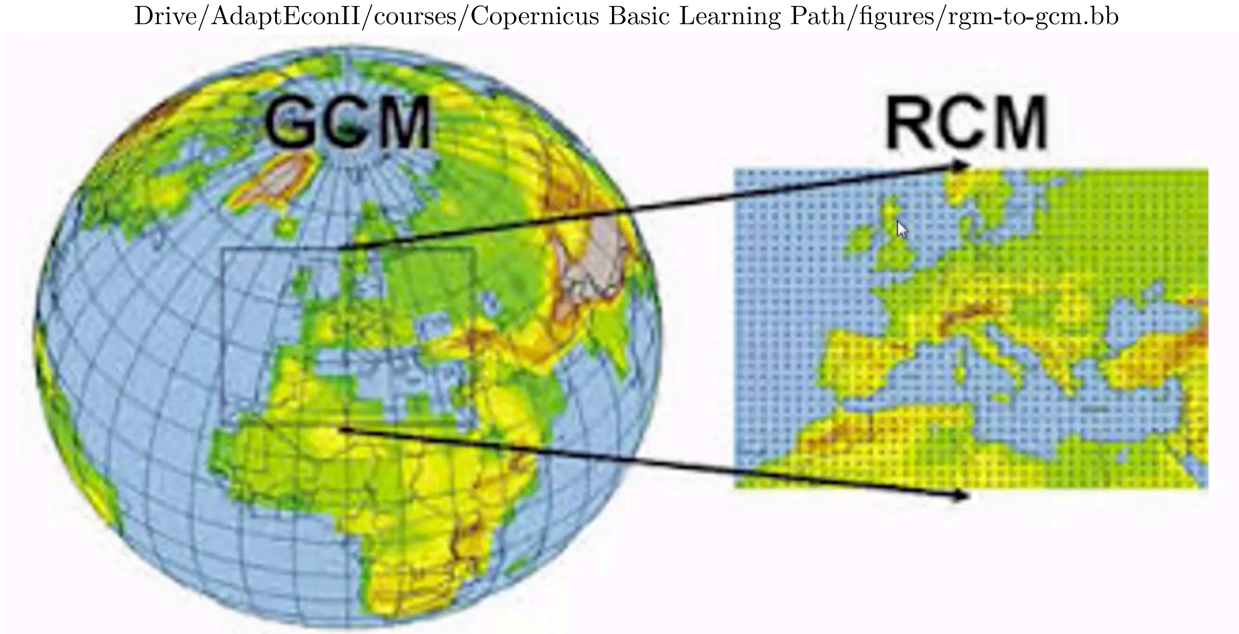

Figure 5.16: rgm-to-gcm

- IPCC-AR5 / **CMIP5**: 40+ GCMs
- IPCC-AR5 / **CORDEX**: many RCMs
  - Each region (generally) sparse matrix 2-5 GCMs x 2-5 RCMs (e.g. Europe 4x6 = +- 18)
  - delta-x = +- 44 km / 11 km
- For selection:
  - Consider ECS/TCS (similar to parent GCM)
  - Consider model (dis)similarities

Statistical downscaling: statistical model is used to transform a GCM result to a result at local scale:

5.4.7 Skill assessment, model weighting and bias correction

- All ESM/GCM/RCM have systematic biases: vary by model, region, season, parameter…
- Can be corrected to some extent
- Small biases give 'trust':
  - Model selection (yes/no)
  - Model weighting (continuous)
- **Statistical downscaling** and **bias correction** = technically very similar (see lesson on bias correction)

5.4.8 Indices calculation (temporal statistics) for different variables

- Be specific: varirable of interest
- Depends on the problem assessed:
  - Time series for impact model forcing vs. statistics
  - Mean vs. extremes, percentiles vs tresholds, single/combined, … (generally aggregated from daily data)
  - Set of standard climate indices (CCI)
- **Temperature**: TG, TX, TN, …
  - Cold extremes: TG10p, FD, CFD, …
  - Warm extremes: TG90p, SU, CSU, WSDI, …
- **Precipitation**: RR, RR1, …
  - Dry extremes: SPI3, SPI5, CDD, …
  - Wet extremes: R95p, R99p, R20mm, RX1d, RX5d, CWD, …
- Others:
  - **Wind**: FG, FXx, FG6Bft, DDeast, …
  - **Biological**: BEDD, GSL, HI, …
  - **Combined**: WW, WD, CW, CD, TCI, …
  - **Pressure**: (PP, NAO, ..), SST (ENSO, PDO, …)

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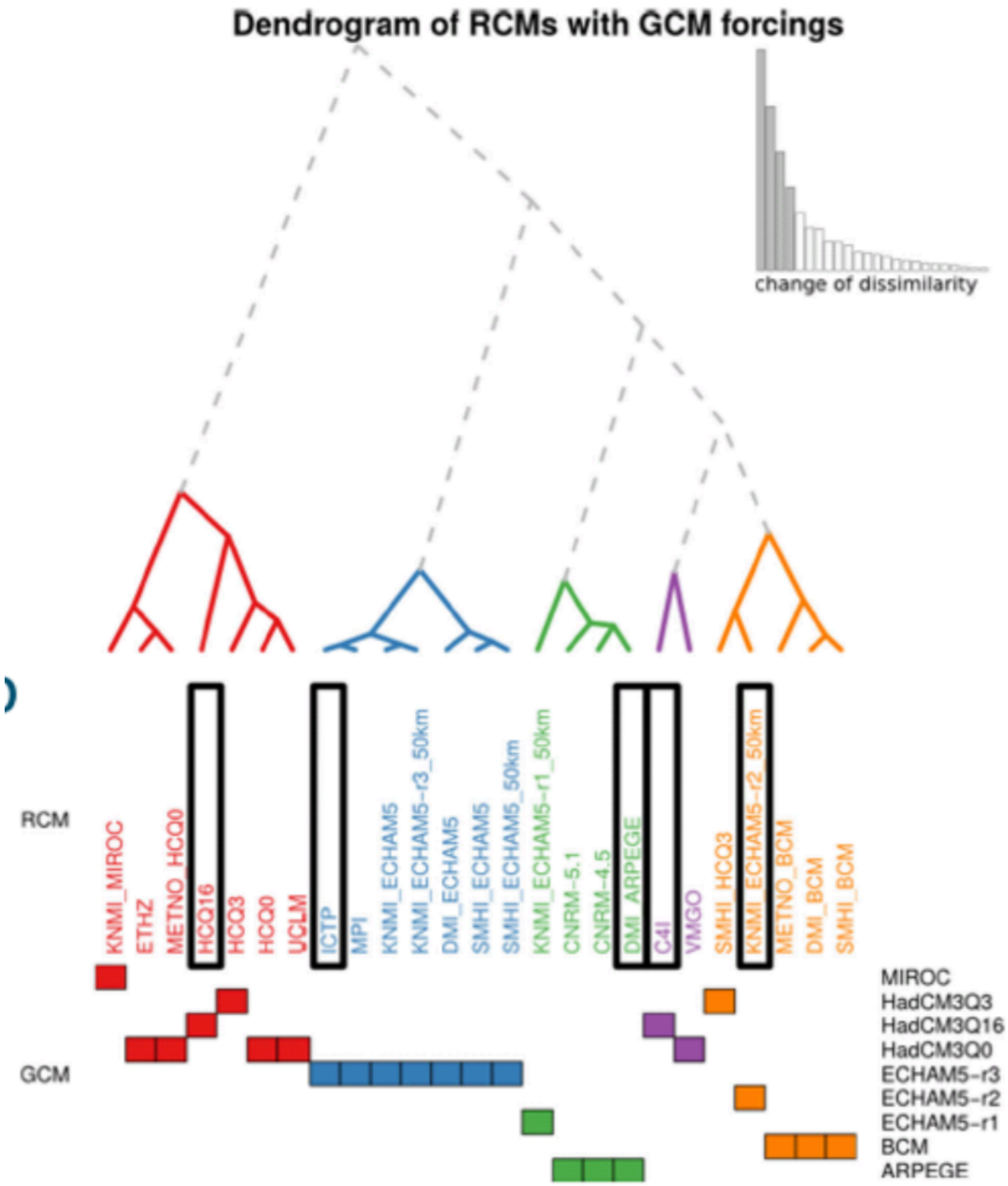

Figure 5.17: dissimilarities

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Figure 5.18: dyanmical-downscaling

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GCM/ESM	RCM
ECEARTH	CCLM4
HadGEM2-ES	HIRHAM5
MPI-ESM-LR	RACMO22e
IPSL-CM5A-LR	RCA4
	WRF33
	ALADIN53

Figure 5.19: gcm-rcm-combined

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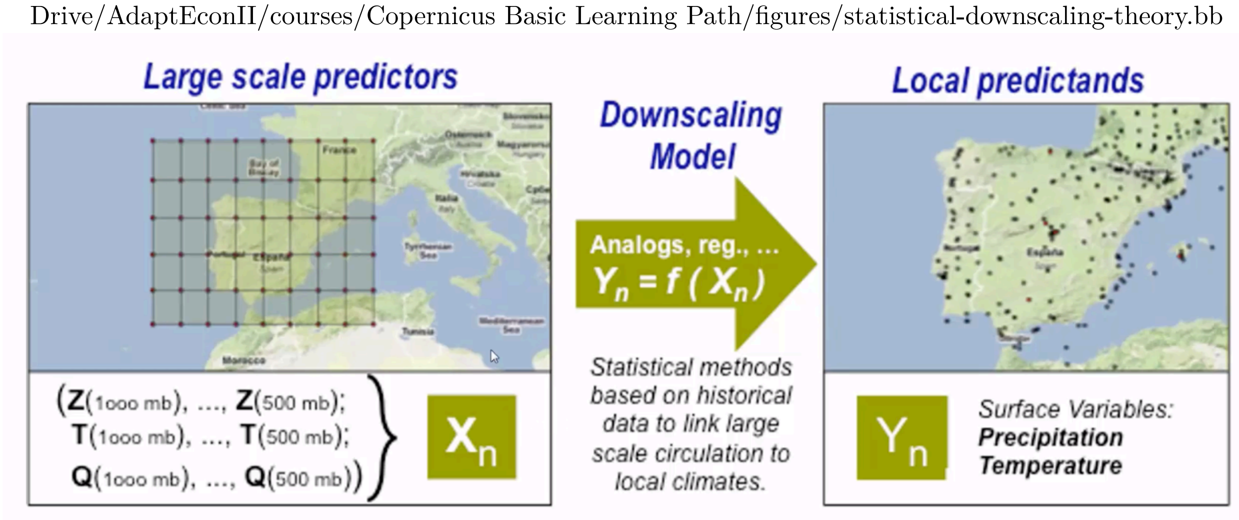

Figure 5.20: statistical-downscaling-theory

Chapter 6

Climate Change Uncertainties

6.1 Definition of uncertainty

Uncertainty is **any departure from complete deterministic knowledge of the relevant system** (based on Walker et al., 2003).

Uncertanties in climate change can be **categorized** differently. For example by **types** (sources) or by **levels** (the difficulty to describe them).

6.2 Why taking uncertainty into account?

This research explained in the video (30 min.) shows that people *do* make better decisions based on uncertainty information.

Source: Susan Joslyn, University of Washington. From Workshop on Communicating Uncertainty to Users of Weather Forecasts, held in Whistler, BC Canada, May 2015.

The **main reasons** why it's important to assess and communicate about uncertainties:

- **Necessary** for **impact and risk analysis**
- In many cases, decision-makers can **achieve superior outcomes when they take uncertainties into account (**to distinguish situations that do and do not require precautionary action)
- Communicating uncertainty **enhances credibility**, **makes climate information more trustworthy**

6.3 Types of uncertainty and how to deal with them

There are many types or sources of uncertainties. The following types will be explained in the coming sheets:

- Natural variability
- Measuring errors
- Inhomogeneities
- Uncertainties in statistics due to due to limited data
- Biases
- Imperfect knowledge about the development of the climate system
- Imperfect knowledge about the socio-economic future

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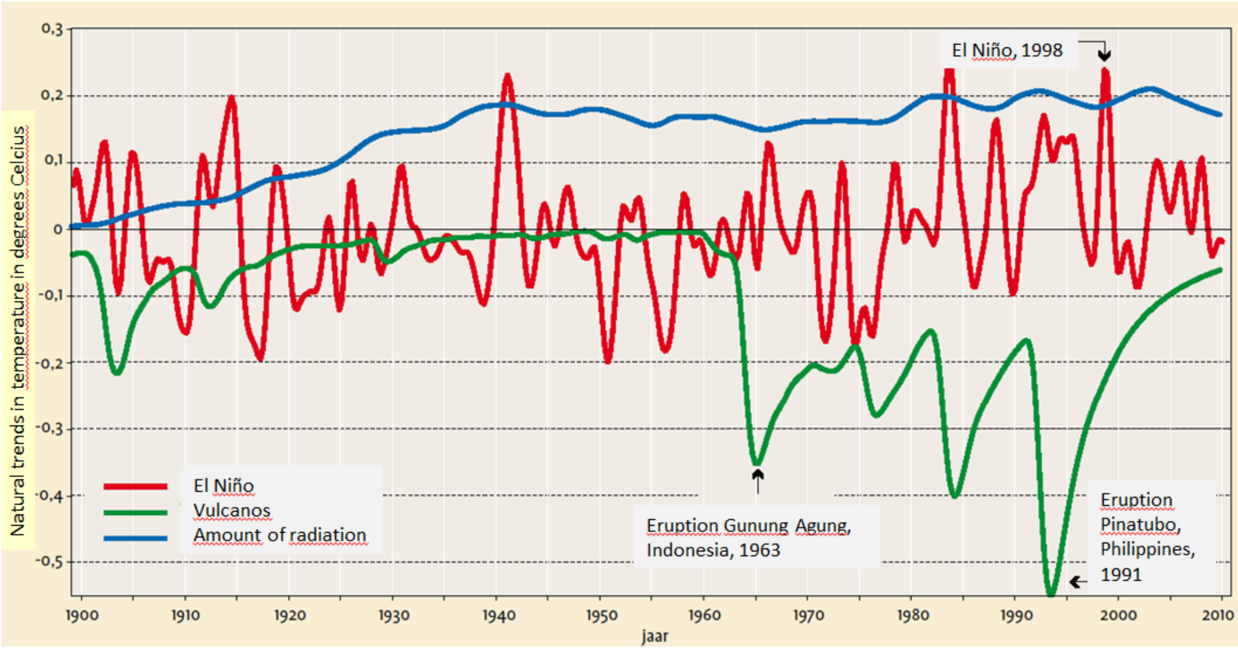

Figure 6.1: natural-variability

6.3.1 Natural variability

Natural variablity (day-to-day variation, year-to-year variation, and decade to decade variation) is the **temporal variation of the atmosphere–ocean system around a mean state due to natural internal processes within the climate system**.

- Examples of **internal variability**: the different position of *high and low pressure areas*, differences in *air circulation*, resulting in day-to-day variations in temperature or rainfall
- Examples of **variations in natural forcings**: *solar intensity*, volcanic eruptions

Three **natural causes of global temperature variations** (Source: De Bosatlas van het klimaat, 2011, The Netherlands): El Niño/La Niña, volcanos and amount of radiation:

6.3.2 Model Bias

Differences in statistics of the observations for the reference period and the climate model simulation for the same period we call **biases**.

The figure gives a **schematic representation of climate model biases**. There is a **systematic difference** between the **observed probability distribution** and the **modelled distribution**. The bias can be corrected for using the differences. It shows also that the bias can be different for median values and extremes. See also .

Source: Source: Maraun, D. Curr Clim Change Rep (2016) 2: 211. Link.

6.3.3 Inhomogenieties

Inhomogeneities are **apparent changes in climate in long-term time series for reasons such as relocations of stations and/or instruments**, slow or abrupt **changes in the environment** and **changes in instruments and measurement practices**.

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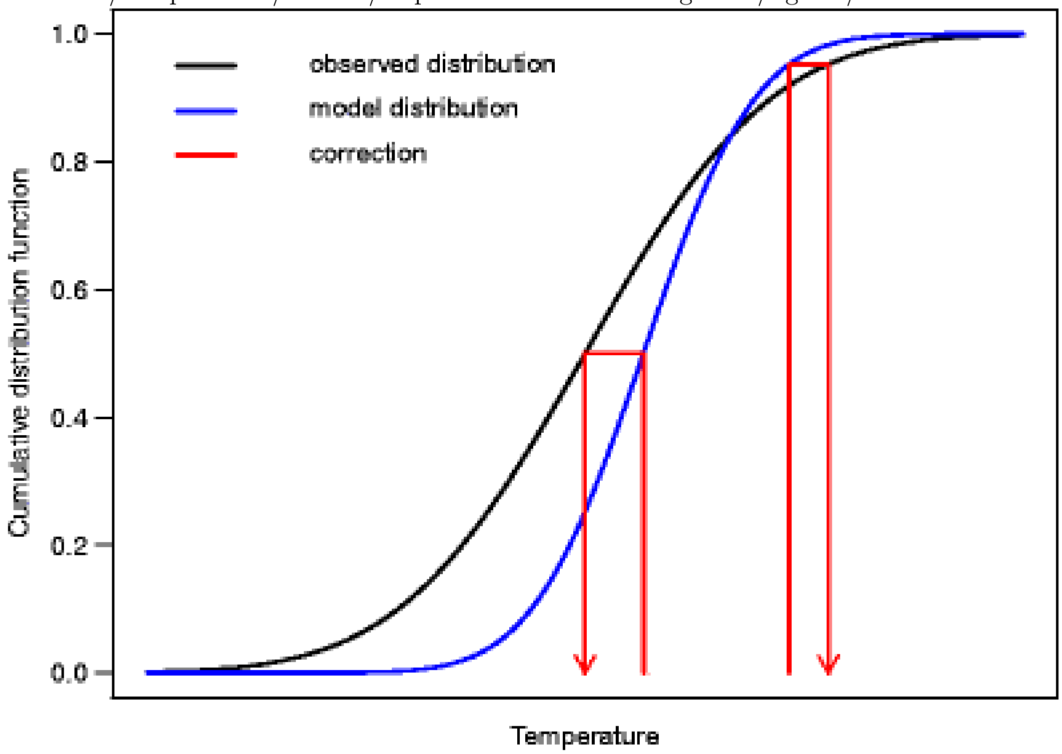

Figure 6.2: model-bias

The figure shows the monthly mean surface air temperatures on Wutaishan (China), with a step change in January 1998 caused by station relocation:

Source: Qingxiang Li, National Meteorological Center, CMA, Beijing, China,. Link.

Dealing with inhomogenieties: To anticipate on a change of instrument or location, **parallel measurements are generally undertaken**. However, if not possible, **homogenization is then mostly done by calculating statistical corrections from mutual comparisons of stations**.

Figure: Parallel measurements in De Bilt in the Netherlands in September 1950 anticipating a screen change from pagoda (1) to Stevenson (2).

Figure: Mean maximum temperature in the summer for De Bilt. The dashed line gives the trend line after correction for the inhomogeneities in 1950 and 1951.

Source both figures: KNMI. Link.

Homogenization and trends: Homogenization can have an influence on the trend, shown in the figures below.

Figure: The trend in annual mean minimum temperature in the period from 1961 to 2010 of the homogenized series.

Figure: The differences in trend between the original series and the homogenized series.

Source: ECA&D, Antonello Angelo Squintu et al., 2018. Link.

6.3.4 Uncertainties in statistics due to limited data

Sometimes called '**sampling uncertainty**', regularly this is indicated with a 95% band.

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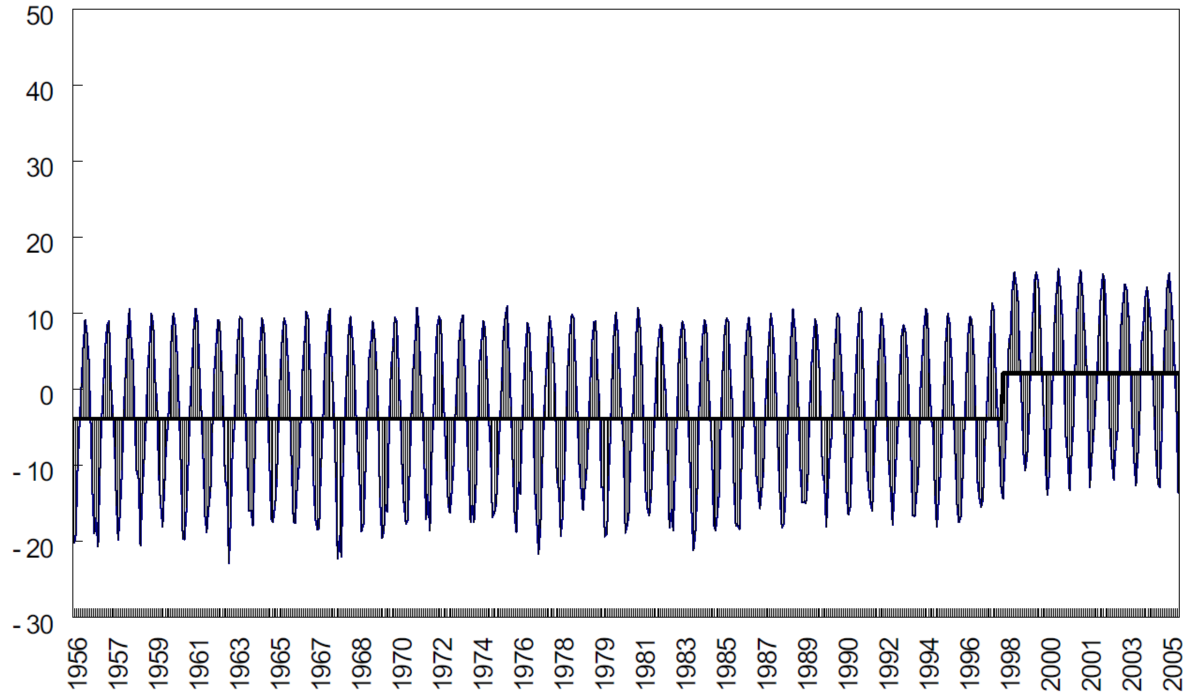

Figure 6.3: inhomogenieties

The figure shows that **the further back in time, the broader the uncertainty band**. This is caused by the fewer measurements during that period.

Source: Berkeley Earth Group, 2012. Link.

6.3.5 Model Uncertainty

Describing the future climate, model and scenario uncertainty are important additional uncertainties. Model uncertainty is the **imperfect knowledge about the climate system**, quantified with the help of a large number of climate models that simulate the future climate for the same emission scenario.

Figure: Reference scenario: a *business-as-usual scenario with unconstrained emissions* (RCP 8.5)

Source link (EPA).

6.3.6 Scenario uncertainty

Scenario uncertainty is the **imperfect knowledge about the socio-economic and technological developments in the future**, resulting in different emissions causing the emission of greenhouse gasses. This uncertainty is **quantified by comparing the (average) impact of the various emission scenarios or Representative Concentration Pathways (RCP) on the future climate**. Model and scenario uncertainties can be reduced by doing more research to better understand the systems. Using higher resolutions is one of the approaches to better simulate the climate system. See also the lesson on Data Resourches & Climate Models.

Figure with **Reference scenario**: a business-as-usual scenario with unconstrained emissions; **Mitigation scenario**: a stringent stabilization scenario with high emissions reductions:

Source link (EPA).

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Figure 6.4: pagoda

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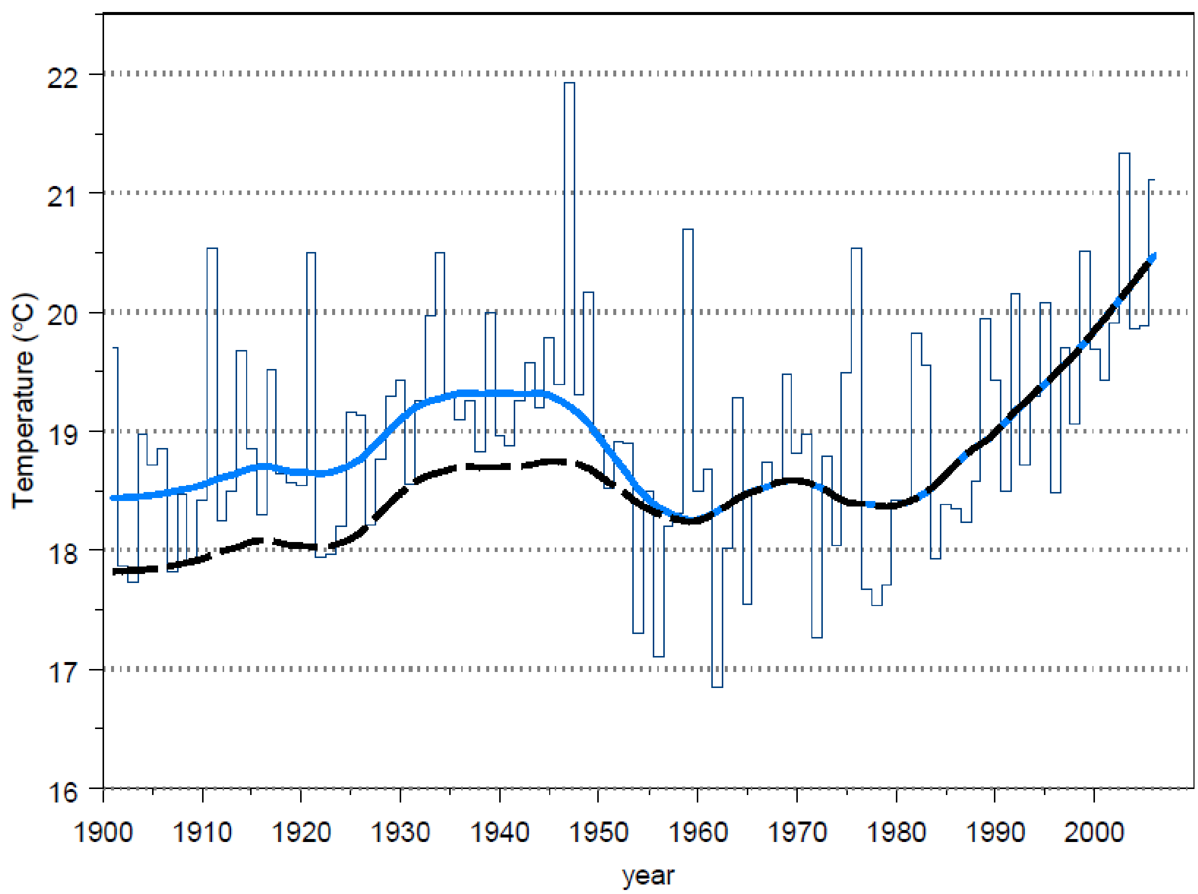

Figure 6.5: de-bilt-inhomo

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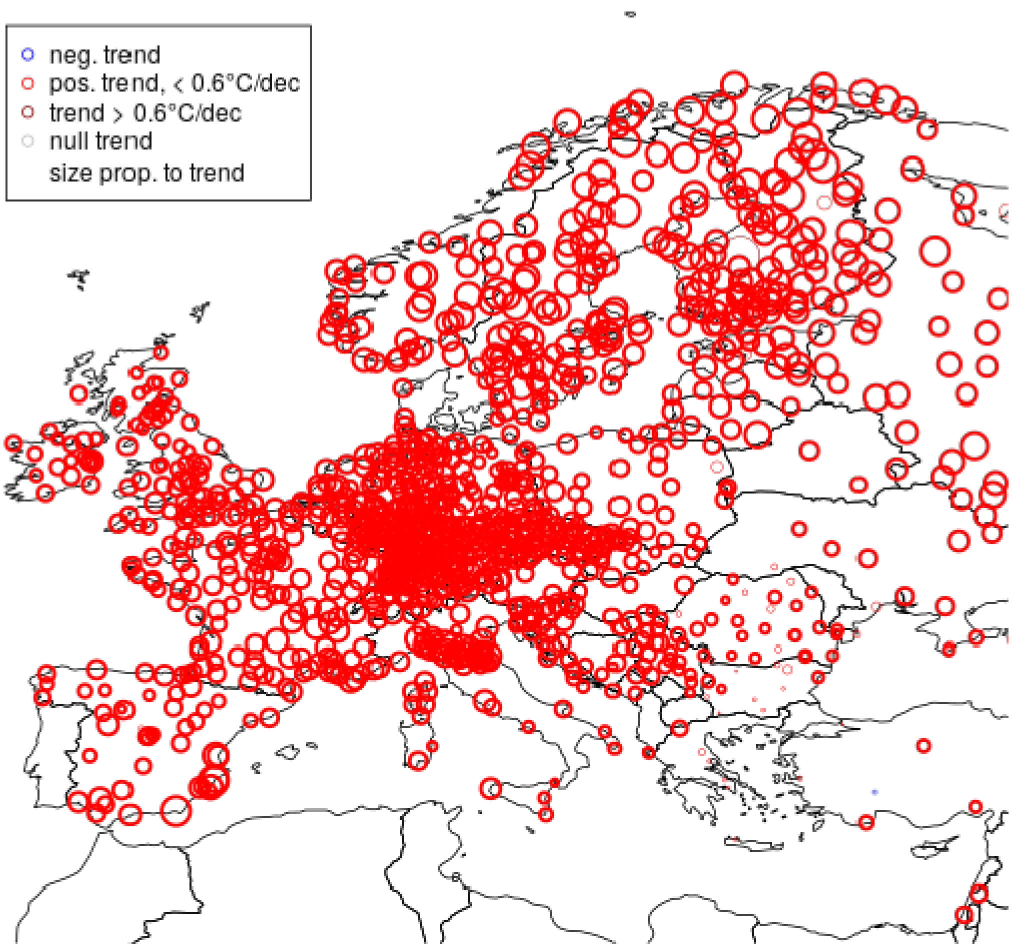

Figure 6.6: trend-annual-mean

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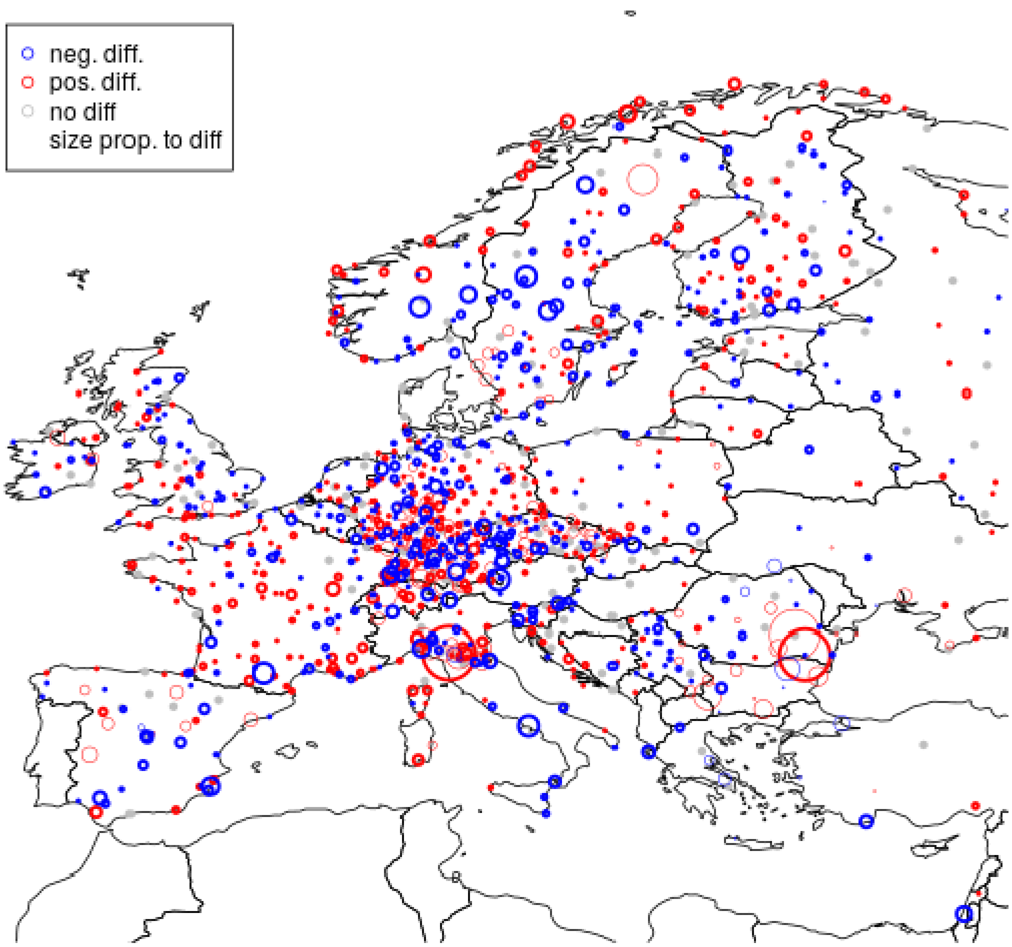

Figure 6.7: trend-homo

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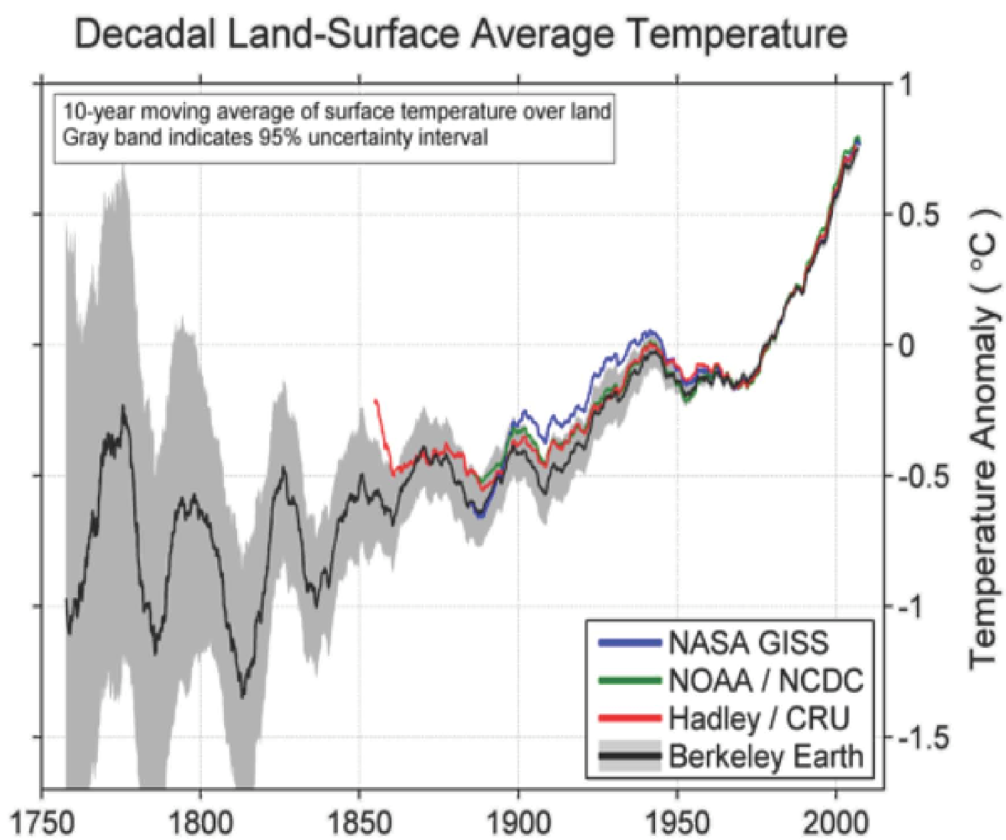

Figure 6.8: limited-data

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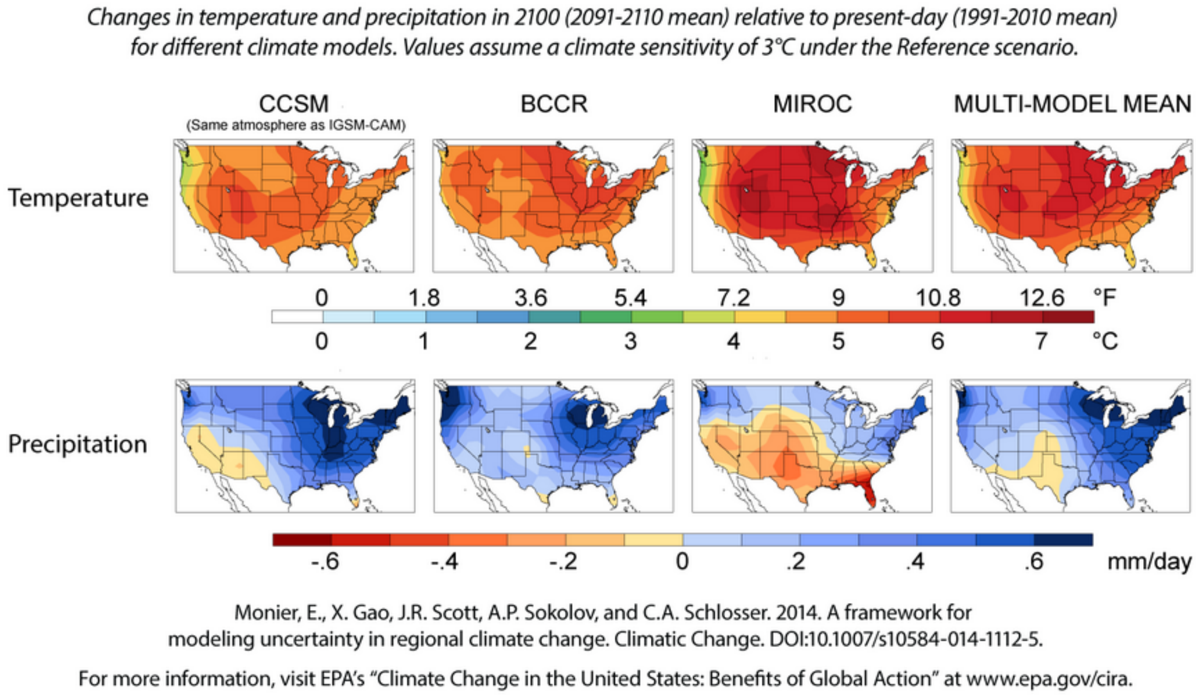

Figure 6.9: reference-scenario

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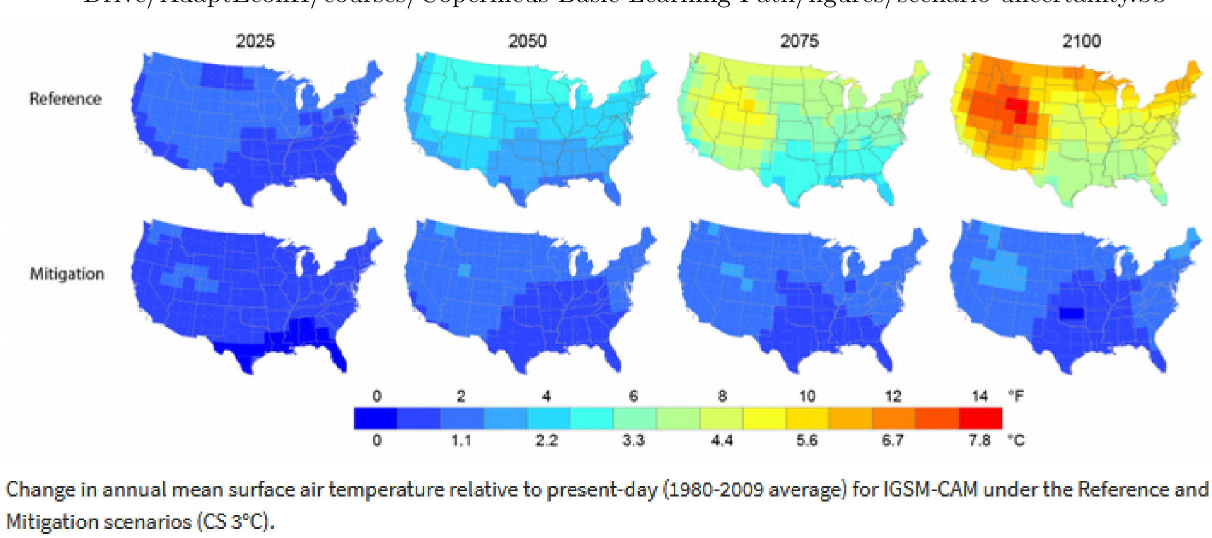

Figure 6.10: scenario-uncertainty

6.4 Levels of uncertainty

Levels indicate **how difficult it is to describe uncertainty**. Level 1-5 are in between complete certainty (left from level 1) and total ignorance (right from level 5). Level 4 and 5 are often referred to as "deep uncertainty", in which:

- We can not quantify nor use probabilities
- We know there could be surprises
- We know neither the mechanisms, functional relationships nor statistical properties
- We do not agree on or do not know the (future) valuation of the outcomes

Source: Walker W.E., Lempert R.J., Kwakkel J.H. (2013) Deep Uncertainty. In: Gass S.I., Fu M.C. (eds) Encyclopedia of Operations Research and Management Science. Springer, Boston, MA. Link.

6.5 Communicating uncertainties

6.5.1 Perception

Scientific facts do not necessarily convince people. Instead, beliefs are shaped by the social groups people consider themselves to be a part of. Those groups are based, for example, on **political or religious affiliation**, occupation or sexuality. **If people are confronted with scientific evidence that seems to attack their group's values, they're likely to become defensive.** They may consider the evidence they've encountered to be flawed, and strengthen their conviction in their prior beliefs.

*Dr. Katharine Hayhoe pleads for starting your climate communication with **making a real connection with your public:** start to look at what value you share. Don't start throwing facts…. Watch her movie*:

6.5.2 Framing

Instead of bombarding people with piles of evidence, science communicators can focus more on how they present it. **The problem isn't that people haven't been given enough facts. It's that they haven't been given facts in the right ways.** Researchers often refer to this packaging as **framing**: setting the issue within the appropriate context to achieve the desired interpretation. An example: for the general public it's better to use the word 'range' instead of 'uncertainty', which could be interpreted as 'ignorance'. *Source: Rose Hendricks. Link.*

Figure: Communicating the science of climate change.

Source: Somerville, R.C. and Hassol, S. J., 2011. Communicating the science of climate. Phys. Today 64(10), 24. DOI: 10.1063/PT.3.1296

6.5.3 Do's for effective communication

Dahlstrom (2014) summarizes recommendations for effective climate change communication:

- **Close the distance.** Climate change is often seen as a distant problem, both physically and temporal, and invisible. Closing the distance and making climate change visible by showing local climate change impacts can be effective. - **Provide an action perspective.** Otherwise the public can feel paralyzed, especially with rather disastrous depiction of climate change.

Moser (2014, 2017) argues:

- **Focus shift to adaptation** ('preparedness' for climate change) instead of only mitigation of climate change. Climate change has become more 'real', local and tangible the last decades, and this could be used more in climate change communication, though empirical research is needed to support this claim.

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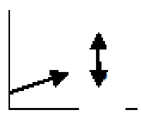
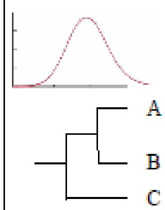
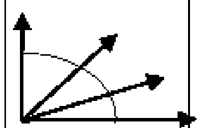
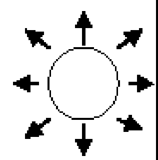
		Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**	
Complete Certainty	**Context**	A clear enough future (with sensitivity) 	Alternate futures (with probabilities) 	Alternate futures (with ranking) 	A multiplicity of plausible futures (unranked) 	Unknown future 	**Total ignorance**
	Systemmodel	A single system model	A single system model with a probabilistic parameterizati on	Several system models, one of which is most likely	Several system models, with different structures	Unknown system model; know we don't know	
	Systemoutcomes	Point estimates with sensitivity	Several sets of point estimates with confidence intervals, with a probability attached to each set	Several sets of point estimates, ranked according to their perceived likelihood	A known range of outcomes	Unknown outcomes; know we don't know	
	Weightsonoutcomes	A single estimate of the weights	Several sets of weights, with a probability attached to each set	Several sets of weights, ranked according to their perceived likelihood	A known range of weights	Unknown weights; know we don't know	

Figure 6.11: levels-of-uncertainty

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Terms that have different meanings for scientists and the public		
Scientific term	**Public meaning**	**Better choice**
enhance	improve	intensify, increase
aerosol	spray can	tiny atmospheric particle
positive trend	good trend	upward trend
positive feedback	good response, praise	vicious cycle, self-reinforcing cycle
theory	hunch, speculation	scientific understanding
uncertainty	ignorance	range
error	mistake, wrong, incorrect	difference from exact true number
bias	distortion, political motive	offset from an observation
sign	indication, astrological sign	plus or minus sign
values	ethics, monetary value	numbers, quantity
manipulation	illicit tampering	scientific data processing
scheme	devious plot	systematic plan
anomaly	abnormal occurrence	change from long-term average

Figure 6.12: communicating-cc

6.5.4 The Uncertainty Handbook

The Uncertainty Handbook

Contains 12 principles for smarter communication about climate change uncertainties:

1. **Manage** your audience's **expectations**
2. **Start with what you know**, not what you don't know
3. Be **clear about the scientific consensus**
4. Shift **from 'uncertainty' to 'risk'**
5. Be clear **what type of uncertainty you are talking about**
6. Understand **what is driving people's views about climate change**
7. The most **important** question for climate impacts is **'when', not 'if'**
8. Communicate through **images and stories**
9. Highlight the **'positives' of uncertainty**
10. **Communicate effectively about climate impacts**

Source: The Uncertainty Handbook, Climate Outreach and University of Bristol, authored by Dr Adam Corner, Professor Stephan Lewandowsky, Dr Mary Philips and Olga Roberts, 2016.

6.5.5 Storytelling

Jones & Anderson Crow (2017) propose to use stories for science communication. With stories, one can communicate scientific knowledge that fits into the cultural values and world views of the receiver (Jones & Song, 2014). Also, research indicates that using stories to communicate science can offer increased comprehension, interest and engagement compared to traditional "logical-scientific", or just factual communication (Dahlstrom, 2014).

In this TED Talk Judith Black explains how to use storytelling for climate change communication (16.35 min).

6.5.6 Confidence and uncertainty

In the **IPCC**, **likelihood or probability is only assigned if confidence is high enough**. Confidence is the degree of agreement of the authors in the correctness of a result.

This schematic illustrates the **process for evaluating and communicating the degree of certainty in key findings that is outlined in the Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties** *(Mastrandrea et al. 2010)*:

6.5.7 Standardized lexicons of uncertainty

David V. Budescu, 2016: **Some types of uncertainties can be communicated as precise values** (e.g., there is a 0.5 chance), as **ranges** (e.g., the probability is between 0.3 and 0.6, or the probability is at least 0.75), as **phrases** (e.g., it is not very likely), or by **combining some of these modalities**.

People, overwhelmingly, **prefer to communicate uncertainty by using verbal terms because they are perceived to be more natural and intuitive**. Most people tend to **avoid the use of precise numerical values** because they can imply a **false sense of precision**. Research also shows that people's interpretations of probability phrases vary greatly (see Wallsten & Budescu, 1995).

Therefore often "standardized lexicons of uncertainty" are developed such as the example from IPCC below (source pdf link):

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/ipcc-confidence.bb

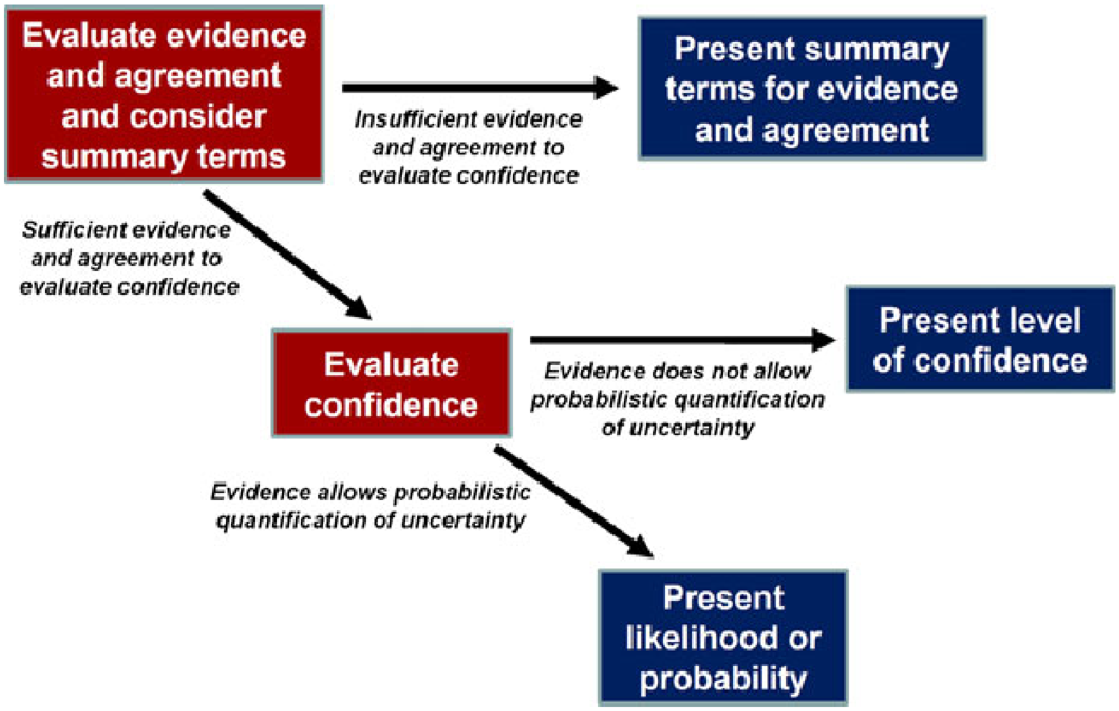

Figure 6.13: ipcc-confidence

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The following terms have been used to indicate the assessed likelihood, and typeset in italics:

Term*	**Likelihood of the outcome**
Virtually certain	99–100% probability
Very likely	90–100% probability
Likely	66–100% probability
About as likely as not	33–66% probability
Unlikely	0–33% probability
Very unlikely	0–10% probability
Exceptionally unlikely	0–1% probability

Figure 6.14: lexicons

6.5.8 Suggestions to improve the IPCC likelihood statements

6.6 *Example of likelihood statement IPCC:*

David V. Budescu (2016) tested the public's understanding of the IPCC likelihood statements.

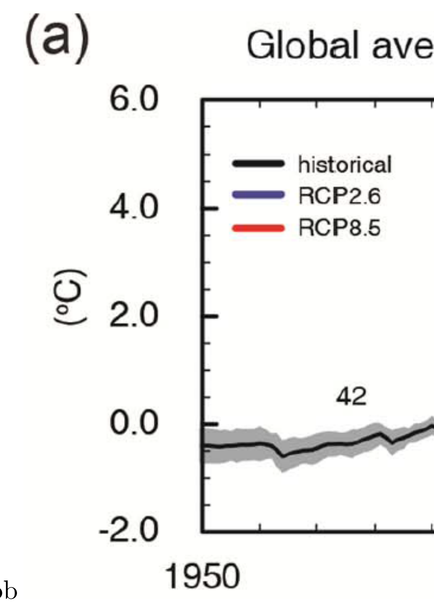
In all the samples the **public interprets the probabilistic statements in the IPCC reports as less extreme – much closer to 50% - than intended by the IPCC authors**. He gives the following recommendations to improve the effectiveness of communication:

- **Change the thresholds defining the bounds of the categories to reflect the general public's intuitive interpretation** and exclude overlapping categories.
- **Probabilistic terms** should **always be accompanied by a range of numerical values**.
- **In case of high confidence**, authors should be **allowed to narrow the range**. For example, if by default Likely is mapped into the 60% - 85% range, **authors should have the option to use a narrower range (for example, Likely (65% -75%), if the data warrant such determination**.

6.7 Visulalisation of uncertainties

6.7.1 Focus on the main message

The first figure below is a rather difficult one to interprete. More or less the same information is shown in the second figure, but presented in another way: the sources of uncertainty in global decadal temperature projections are expressed as a 'plume' with the relative contribution to the total uncertainty coloured appropriately. The **shaded regions represent 90% confidence intervals**. In the **second figure it's clear at a glance that in 2100 uncertainty is mostly caused by RCP scenario uncertainty** (the green band is broadest):



Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/main-message-1.bb
Source link.

Source: *Sources of uncertainty in CMIP5 projections, Ed Hawkins, 2013:* link.

6.7.2 Distortion of the message

The **left graph**, however, could **easily be interpreted wrongly**. One could conclude that model uncertainty will increase until around 2025 and than decreases. However, as the right figure shows, this is not the

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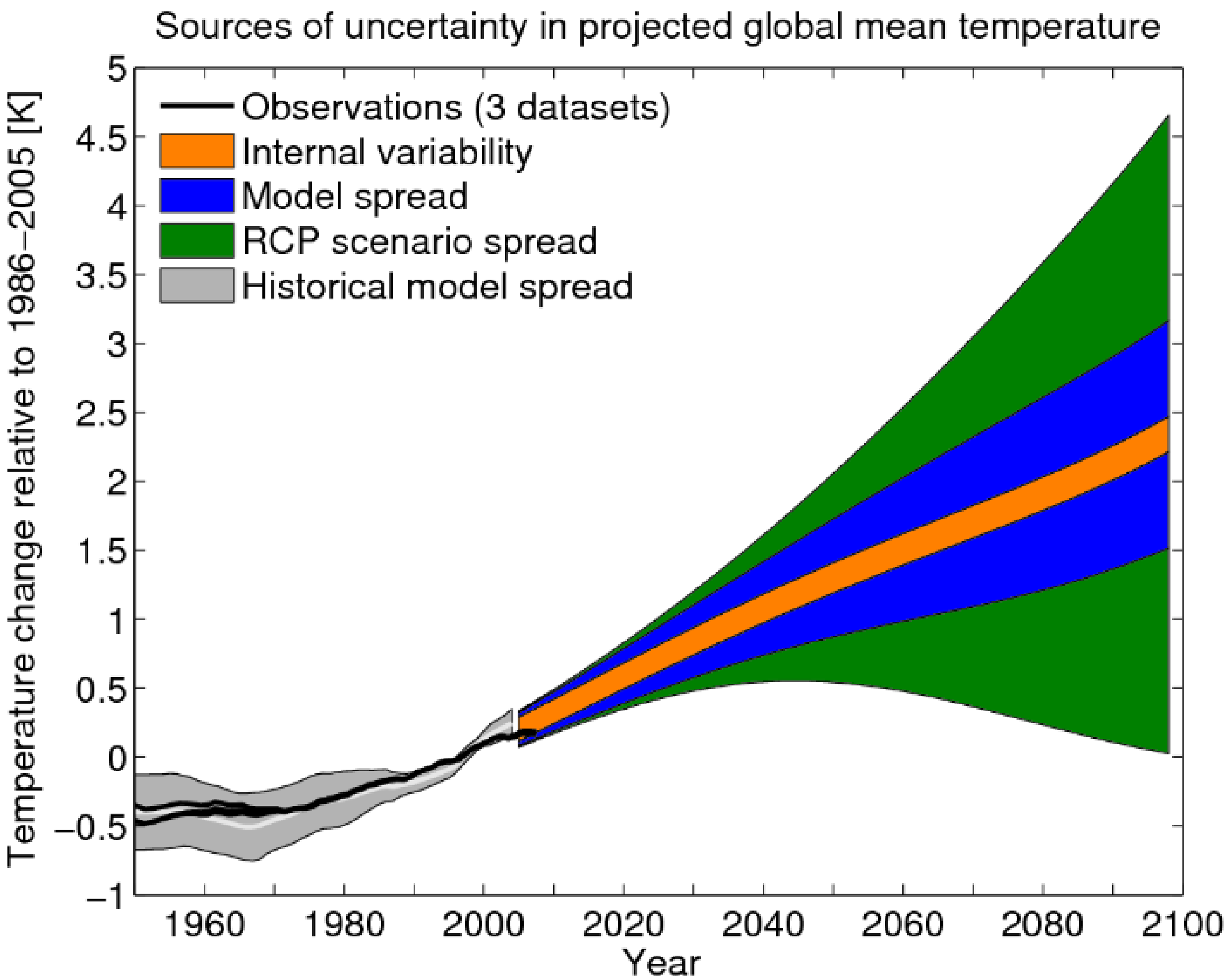

Figure 6.15: main-message-2

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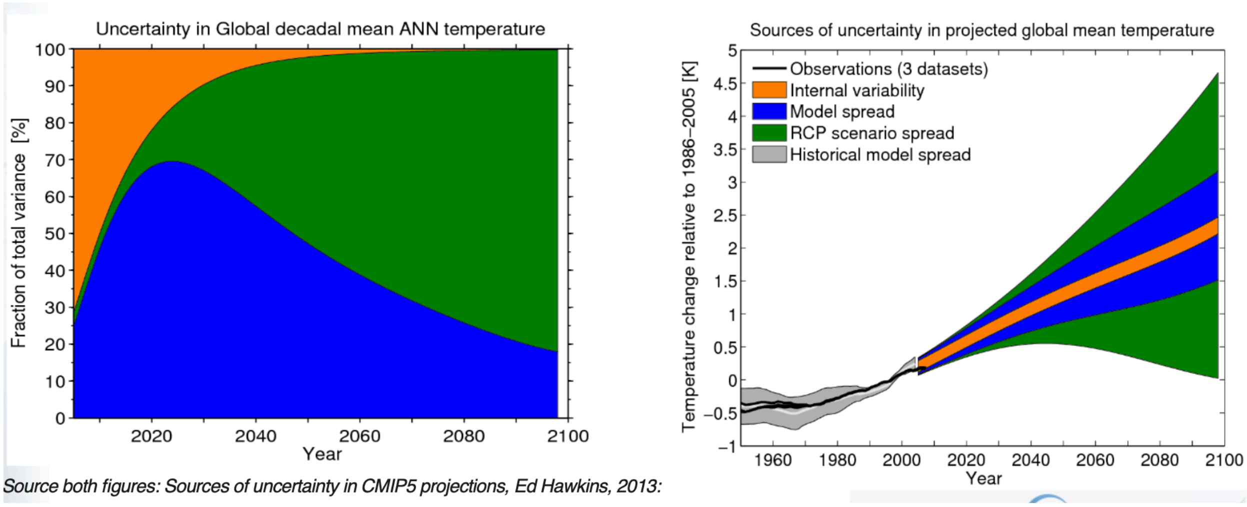

Figure 6.16: distortion-message

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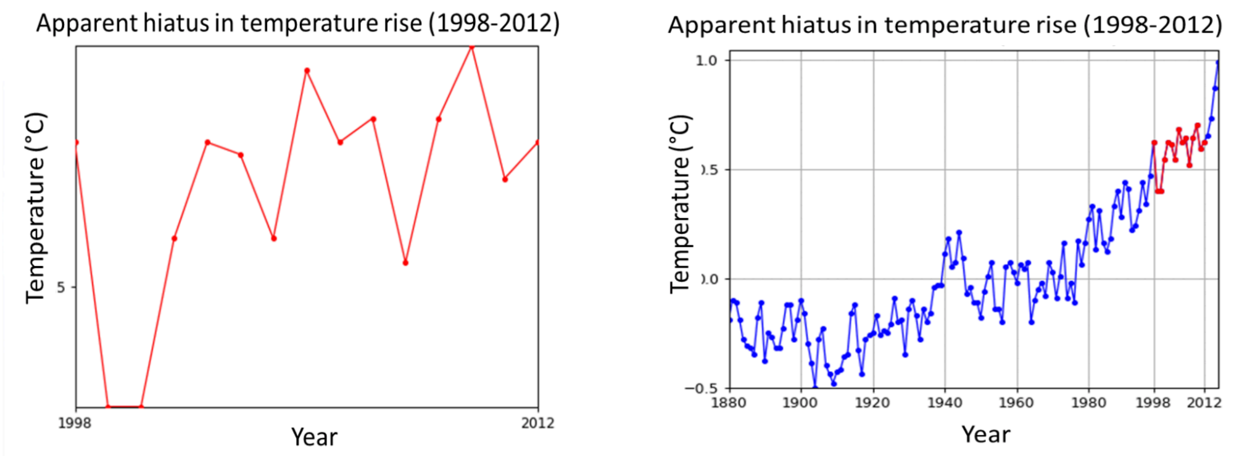

Figure 6.17: long-time-series

case. **Presenting the right graph together with the left graph will help giving the right context**, showing that the three types of uncertainty are increasing over time.

6.7.3 Show long time series, talking about long term trends

Natural variablity can be falsely interpreted as a trend, if a short time serie is presented. In the ***left figure*** it seems that there is **no upward trend in temperature**. People are referring to this period from 1998 to 2013 as the 'hiatus', the period in which temperature rise apparently slowed down. However, looking at the right figure with the long time series the upward trend is very clear. **Natural variability played a crucial role in the slowed rate in this short period** (**besides distribution of heat among others in the oceans**).

Source link.

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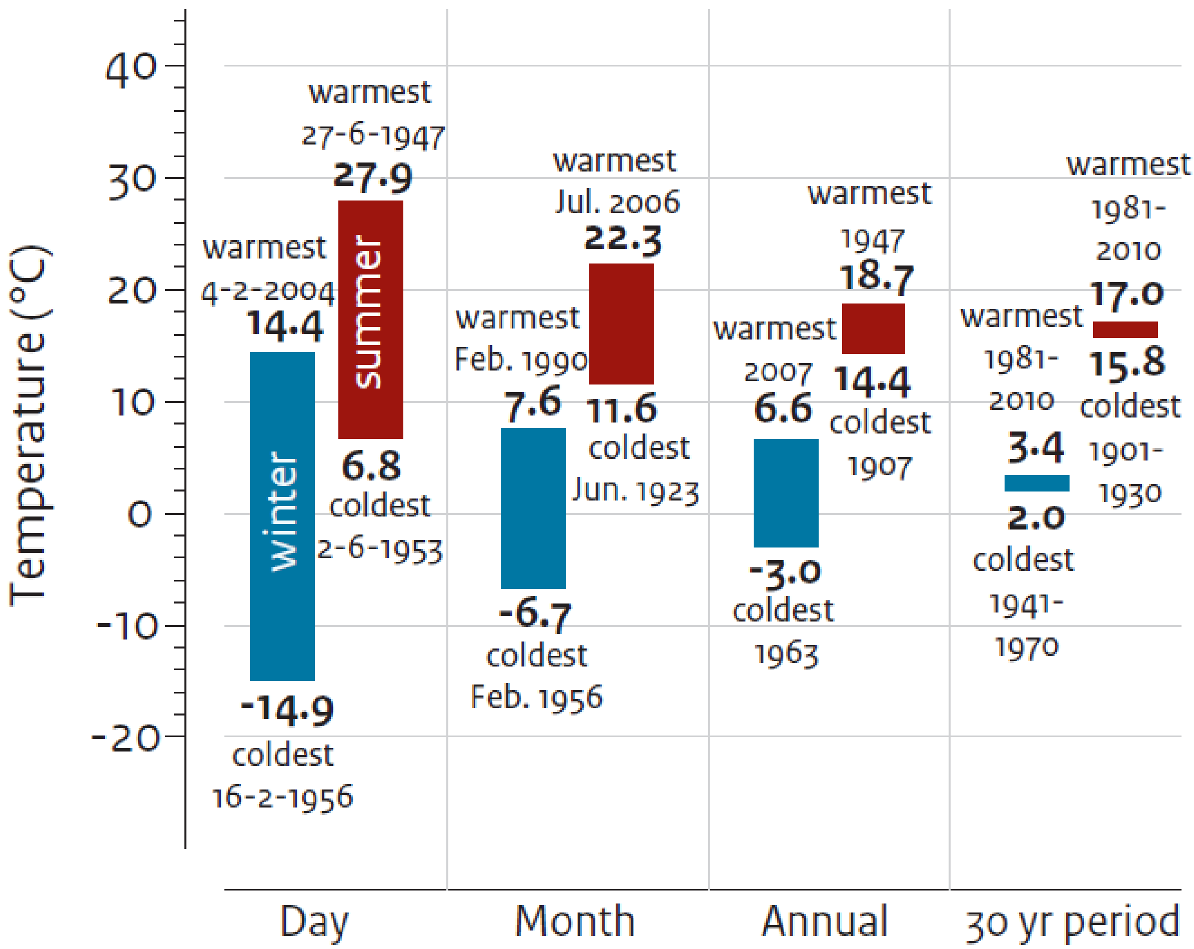

Figure 6.18: quantify-variability

6.7.4 Quantify natural variability

The longer the period of averaging, the **smaller the influence of natural variations on the avarage is.** However, even averages over 30 years will still show natural variability (the last column in the figure gives an example of 30 year natural variation for temperature minima and maxima). For **precipitation and wind**, in particular, **natural variations in the 30-year average climate may be more substantial when compared to human-induced climate change in the near future**.

When natural variation is large it's more difficult to detect human induced climate change.

Figure: Natural variation in temperature observed at De Bilt (Netherlands) since 1901 on different time scales.

Source link

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/period-variability.bb

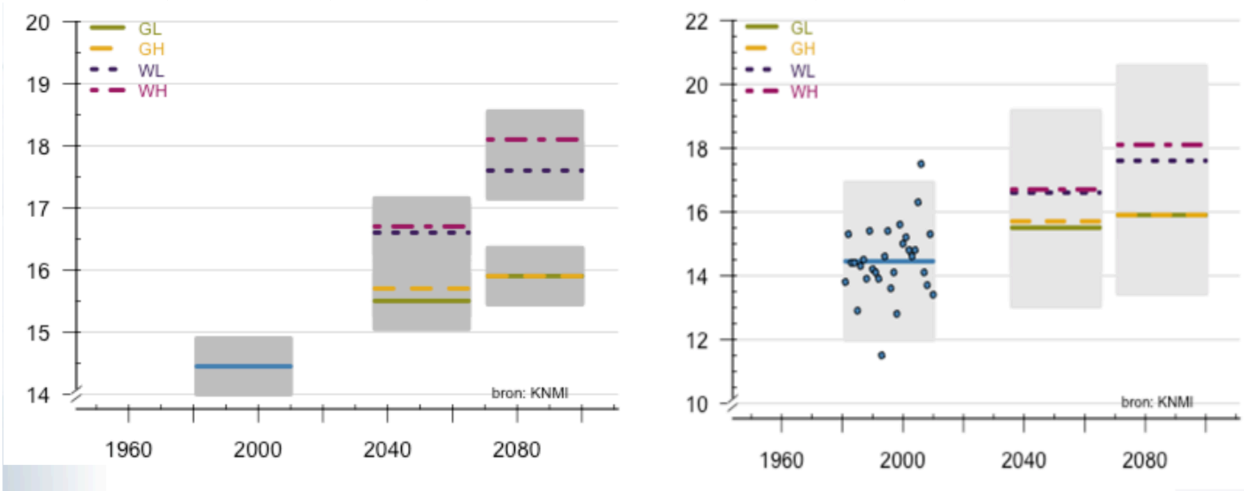

Figure 6.19: period-variability

6.7.5 Choose the period for describing natural variability

The **timescale** for describing the natural variations can **influence the message**. The two graphs below give both information about past (in blue) and future (in four colours) temperatures. In the ***left figure*** the **natural variability (in grey) is described using a time scale of 30 year**, in the ***right graph*** the **natural variability is descibed using a time scale of one year.** The **left figure** can be more relevant for **researchers**, since it may give insight in whether there are significant changes. For the **general public** the **right graph might be more helpful because extreme individual years can help to put future changes into context**.

The extreme high autumn temperatures in 2006 (blue outlier point) are remembered: those temperatures occured in the current climate, however in the future higher extremes can be expected. The left graph could give the impression that natural variation is smaller than it in reality is.

Figures: Maximum temperature in autumn in de Bilt for past (in blue) and for KNMI'14 scenarios (in four colours). Left: natural variability (in grey) for a time scale of 30 years; Right: natural variability (in grey) for a time scale of 1 year.

Source link

6.7.6 Probability density function

A probability density function (PDF) describes the **likelihood of e.g. certain temperatures** (see left figure). As with any bell curve, **those events that fall near the center** (events occurring in a mid-range temperature state) **are most likely**, and **events that occur in lower and upper temperature extremes have smaller probability**. These graph's are ***widely used by researchers, however are difficult to interpret by the general public***. Translating the PDF, giving only maximum and minimum frequencies and changes in the frequencies in the future, such as **the right figure can then be a better way to present probabilities**.

Source links left and right.

6.7.7 Effect of uneven number of scenarios

Both graphs below show the **past and future temperature development according to the IPCC projections**; left from the fourth assessment report of the IPCC (2007) and right from the fifth assessment report form the IPCC (2014).

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Figure 6.20: pdfs

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/uneven-scenarios.bb

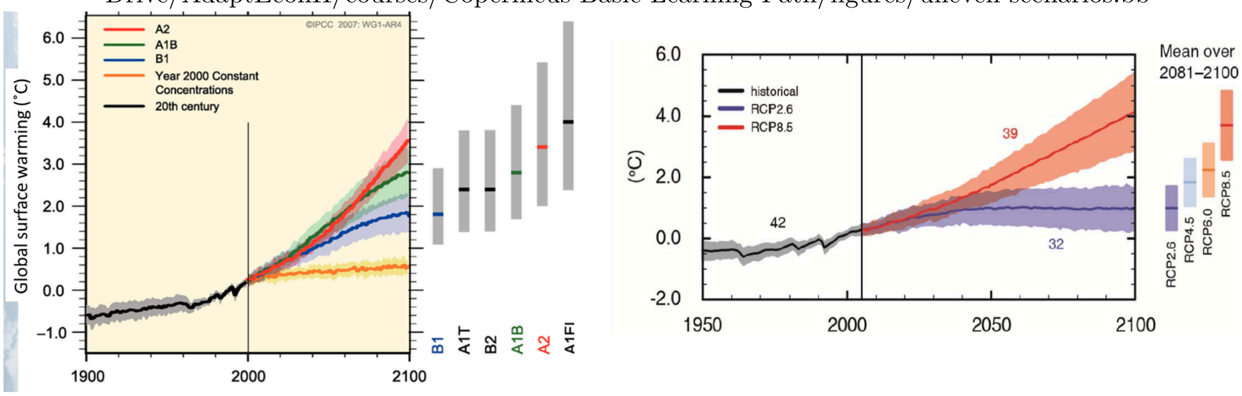

Figure 6.21: uneven-scenarios

Be aware that **people tend to interprete a middle projection (such as A1B in the left figure) as the most likely**. However, **no likelihood can be attributed to the projections**. **Giving an even number of projections, such as in the right figure, forces users to think of the most relevant projection for their specific study.**

Source left and right.

6.7.8 Combine weather and climate information

Information on (extreme) weather can help bridging the gap between climate change (seems to be far away) and **real live** (the experienced weather). The "weather and climate plume" in the figure shows at a glance:

- the **weather prediction for the coming 15 days** (the black line with grey band). The broader the grey band, the more uncertain the prediction.
- **what is normal for the time of the year** (the thin red and blue straight lines are the normal maximum and minimum temperature for the time of the year).
- **measured extremes**: the **highest** (red dotted line) and **lowest** (blue dotted line) temperatures ever measured.
- an **indication of the "normal" weather around 2050** (the red and blue band present the normal temperatures for the future, according to the Dutch climate scenarios). If the prediction is very extreme, red or blue points are given (in this example 3 red points). In a pop-up text box the extreme is put in perspective: how often it occurs and how much warmer that extreme could become in future.

Source link.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/weather-plume.bb

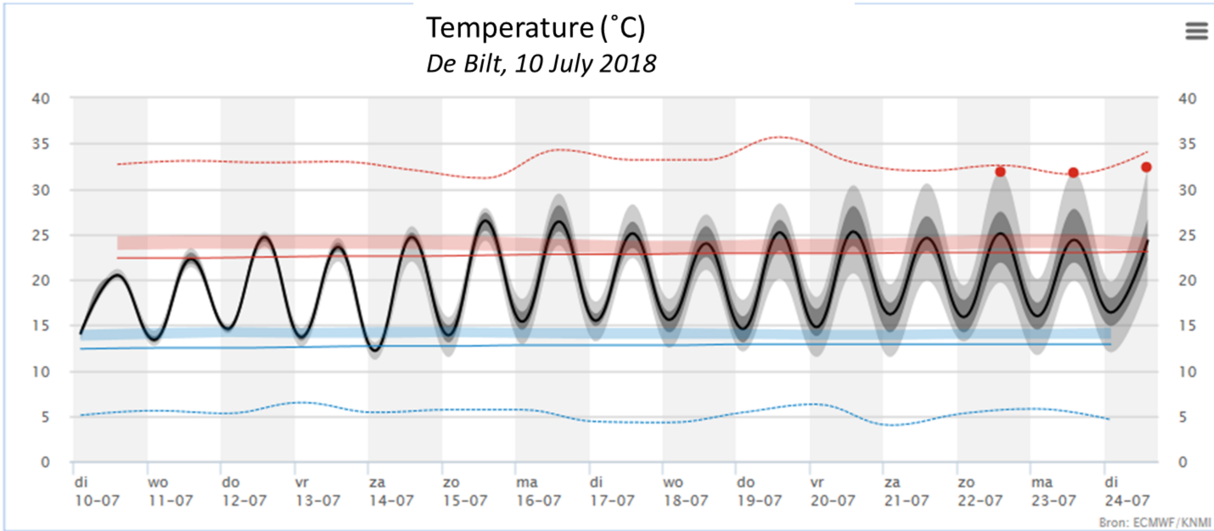

Figure 6.22: weather-plume

6.7.9 Don't present just one scenario

Giving **just one scenario would give a biased picture of the future since no information about uncertainty is given**. Leaving out the middle figure it would give the suggestion that summers would become drier, although there is a possibility that summer rainfail would slightly increase.

Figure below: Left the summer precipation in the current climate (224 mm), in the middle for around 2050, according to the WL scenario (+1,4%), and right according to the WH scenario (-13%).

Source link.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/multiple-scenarios.bb

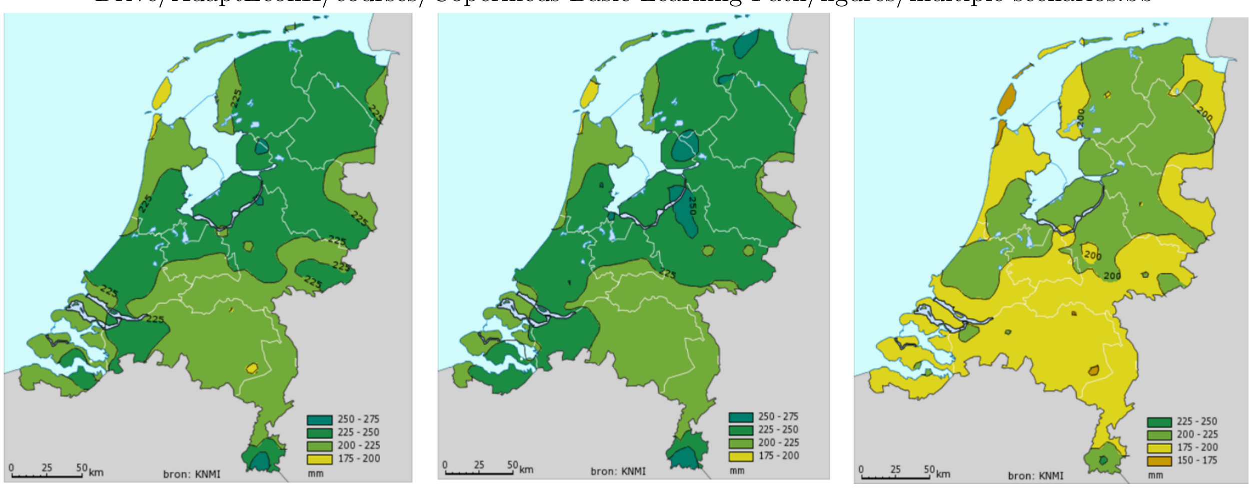

Figure 6.23: multiple-scenarios

Chapter 7

Climate data store and toolbox

—> see online lesson, or visit the Climate Data Store.

Chapter 8

Climate Observations

For a basic overview of different types of observations, see the dedicated section in the first chapter.

8.1 Differentiation between types of measurements (direct/indirect, remote, in-situ)

8.1.1 Direct vs. Indirect

Direct observations are observations you can measure directly, for example the temperature or pressure at a land station.

Indirect observations are observations that are derived from other observations. For example, past temperatures can be derived from tree ring or ice cores

8.1.2 In-situ vs remote

In situ sensors only measure their immediate environment. (e.g. weather stations on land measuring temperature or radiosondes)

Remote sensors measure over distances that extend significantly beyond the location of the instrument (e.g. radar, satellites, lidar)

8.2 Identification of different types of meteorological observing systems and their of observational representativeness including temporal and spatial (microscale, local scale, mesoscale, large scale, planetary scale) scales of phenomena, and measurement capability

There are different observing networks:

8.2.1 Weather stations on land

There are thousands of weather or meteorological stations measuring at or near the Earth's surface meteorological parameters such as atmospheric pressure, wind speed and direction, air temperature and relative humidity. These are observations at one location, or "in situ". The **number of stations is not evenly distributed over the Earth** (see figure). The World Meteorological Organisation (WMO) formulated

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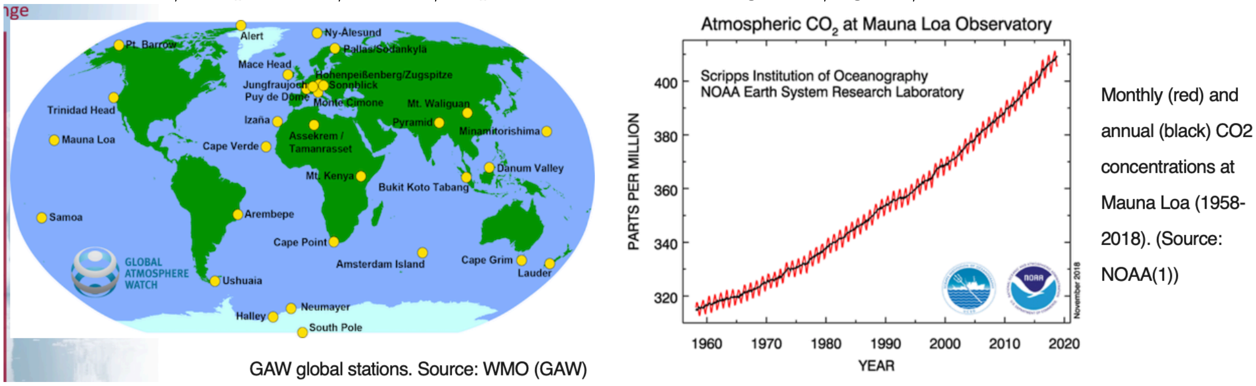


Figure 8.1: climate-stations

standards for these meteorological stations (e.g. temperature is measured at 2 meters height, around the station there should not be high vegetation). For more info see: WMO (Best practices)

The most common measured quantities by weather stations are:

- temperature (2 m)
- grass temperature (5 cm)
- soil temperature
- humidity
- precipitation
- radiation
- wind speed and direction
- clouds
- pressure
- visibility

Some stations have long time series with data for each day **since 1850**. Some stations also have information at higher **temporal resolution** (e.g. per hour). Most station data in Europe have been digitised.

8.2.1.1 Measurement conditions

To be able to compare and combine measurements between different meteorological stations there are **strict criteria for the set up of measurement sites and the measurement techniques**.

Measurements are generally done in **open areas** in the countryside that are representative for the surroundings.

Measurements in **cities are difficult**, it is hard to find a location where measurements are representative for a larger area. Differences in especially wind and temperature can be very large over short distances in a city. However, many people live in urban areas, and for example temperature is often somewhat higher in urban areas (Urban Heat Island = UHI). Therefore, there is an increasing number of measuring networks in cities. WMO guidelines of meteorological instruments and methods of observation: link.

A number stations also directly measure greenhouse gases as part of the WMO Global Atmosphere Watch (GAW) project. They measure relatively undisturbed air, at remote locations or near the top of mountains:

8.2.1.2 Pros and cons of land stations

Advantages:

- Some land stations measure since the 1850's, a lot more from the 1950's . Therefore **long time series** are availabe for these sites.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/observations-sea.bb

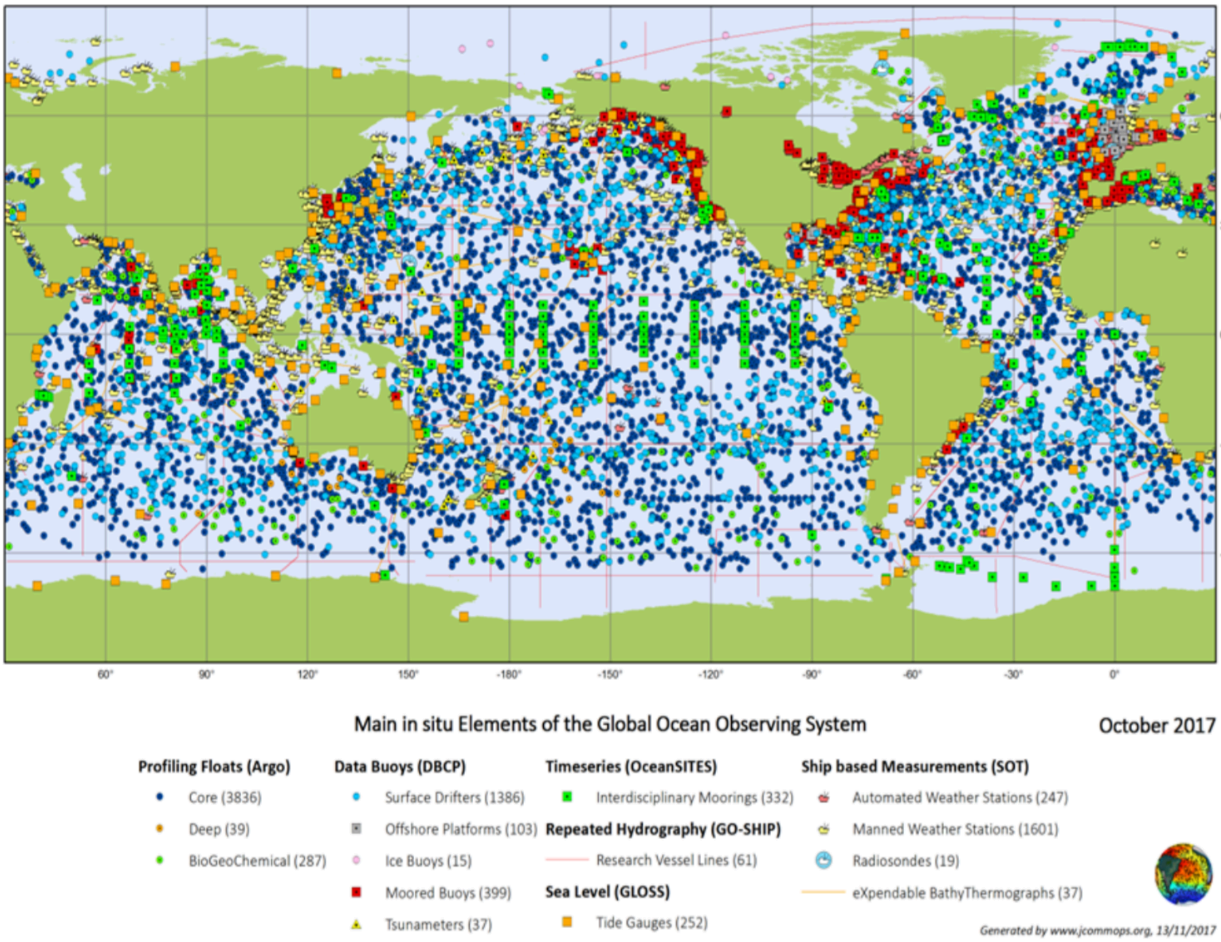


Figure 8.2: observations-sea

- **Direct measurement** of the Essential Climate Variables (ECV's)

Disadvantages:

- They are **not evenly distributed** along the globe. Especially the southern hemisphere and the arctic regions are underrepresented.
- In-situ measurements are **only representative for a small area** around the measurement site. Features like the urban heat island will be missed.
- **Inhomogeneities** are present in many time series because of changes to the measurement site or it surroundings

8.2.2 Observations at sea

Over the oceans the Global Ocean Observing System (GOOS) relies on:

- ships
- moored and drifting buoys
- stationary platforms.

Source: WMO (GOS)

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/ship-station.bb

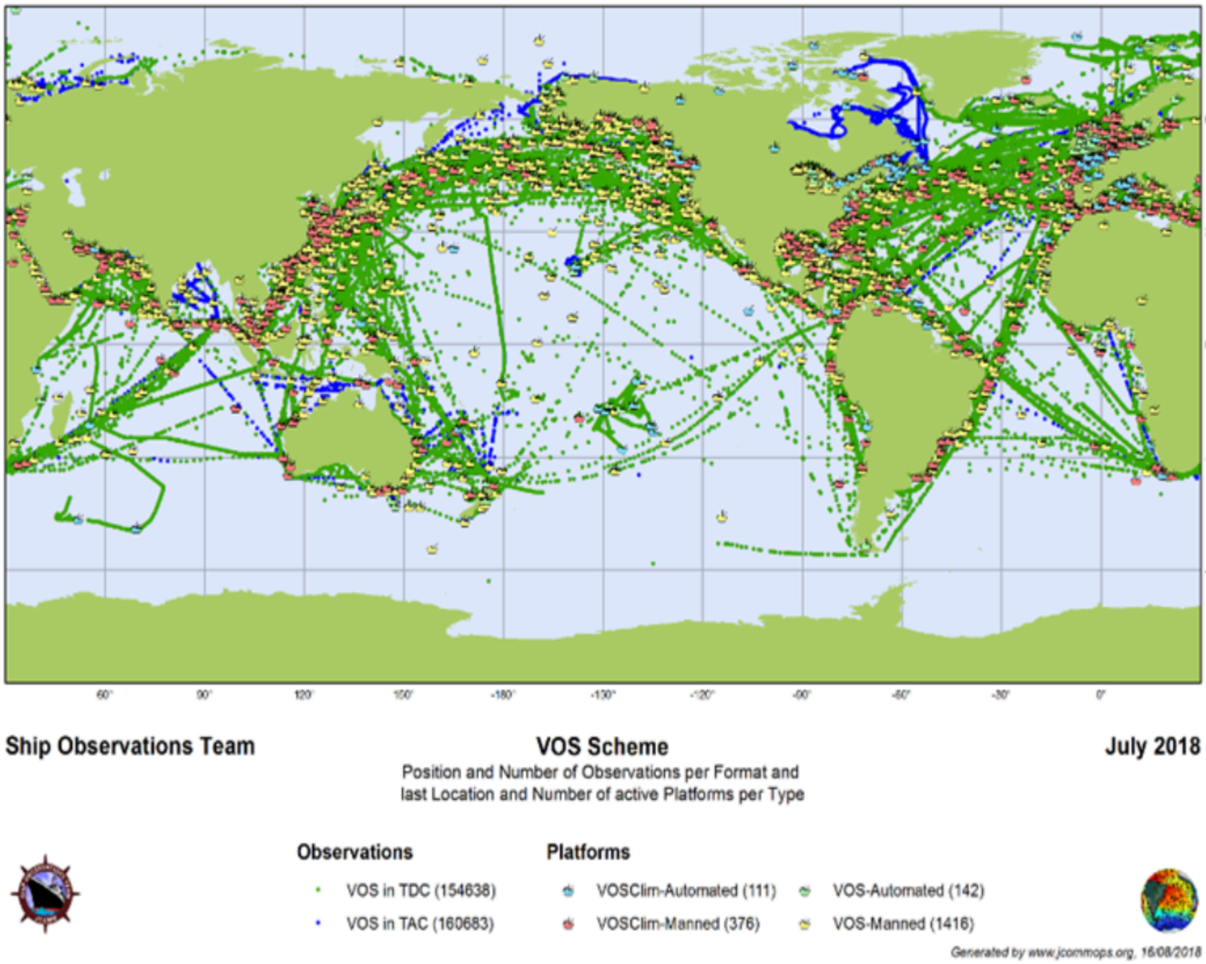


Figure 8.3: ship-station

8.2.2.1 Ships

Ships measure much the same variables as at surface land stations. Observations are made by ships recruited under the **WMO Voluntary Observing Ship (VOS) Programme**. They provide information on trajectories, not for one location. The number of observing ships is **around 4 000 (as reported in 2018).** About 1 000 of them report observations every day:

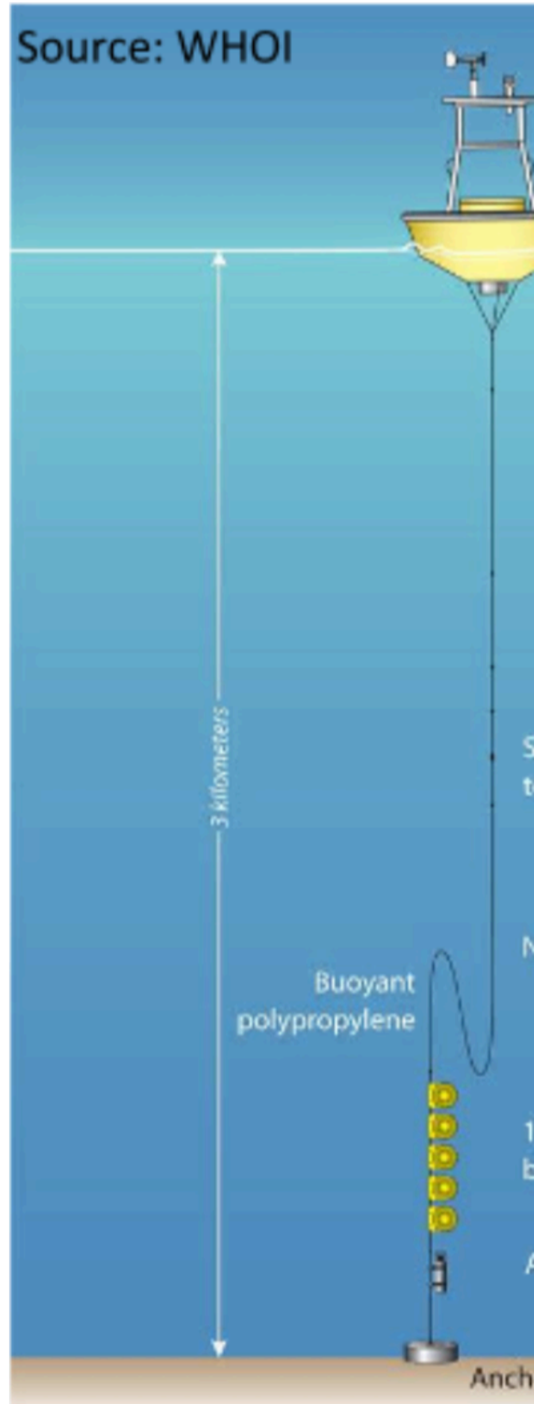
Source: Jcommops

8.2.2.2 Buoys

Buoys are instruments which collect weather and ocean data within the world's oceans. There are moored buoys (see figure below), which remain at the same location and drifting buoys move with the sea currents.

The **operational drifting buoy programme** comprised of about **1 200 drifting buoy**s provides over 27 000 sea surface temperature measurements per day. Half of the drifters also report sea level pressure providing about 14 000 reports per day (as reported in 2018).

For more information, see the official reference WMO descriptions.



Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/buoys.bb

8.2.2.3 Argo floats

Argo is an **array of over 3600 profiling floats** (as reported in 2018) **distributed almost uniformly across the global oceans**. They provide **temperature** and **salinity** profiles **from the surface to a depth of 2000m.** Argo provides **one of the most accurate and comprehensive means of observing global ocean temperature and salinity changes**.

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/argo.bb

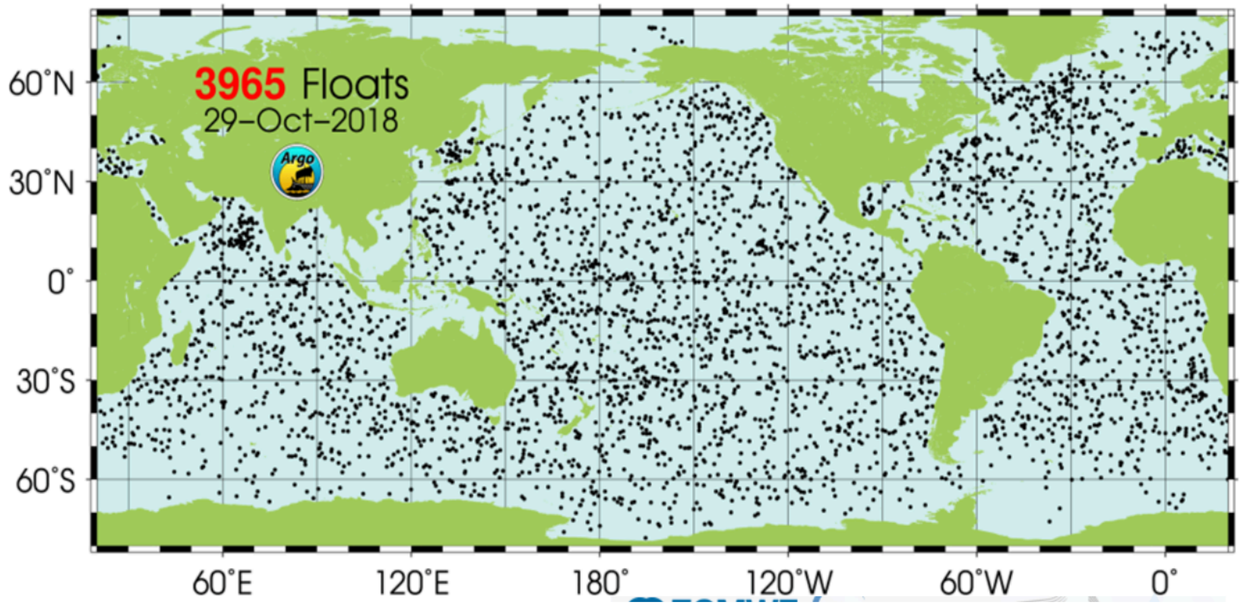


Figure 8.4: argo

8.2.2.4 Stationary platforms

Stationary platforms are mostly located in the vicinity of the coast, often located on oil or gas platforms. They are comparable to the measurement sites at land.

8.2.2.5 Pros and cons of measurements at sea

Advantages

- **Important for weather and climate models** because oceans cover a large part of the world.
- **Direct measurements** of the ECV's
- **Wide and uniform spatial distribution** (in case of Argo floats)

Disadvantages

- **No global coverage** of buoys and ships. Ship data are mainly available on the main shipping routes. Limited coverage at high latitudes, especially in seasonally ice-covered regions.
- Ships and drifting buoys **do not have a fixed location**
- **No long time series** at **fixed locations** (Argo since 2000)

8.2.3 Radio- and dropsondes

A **radiosonde** is an instrument that is **launched by a weather balloon** and measures the properties of the surrounding air up to a **maximum height of 30-35 km.** It measures **altitude**, **pressure**, **temperature**, **relative humidity**, **wind** (both wind speed and wind direction) and **geographical position** (latitude/longitude) and transmits them by radio to a ground receiver. Radiosondes measuring **ozone concentration** are known as ozone sondes. See video.

Dropsondes are the same device but then **dropped from an airplane** and are usually used in special weather situations, for example in hurricanes. See video.

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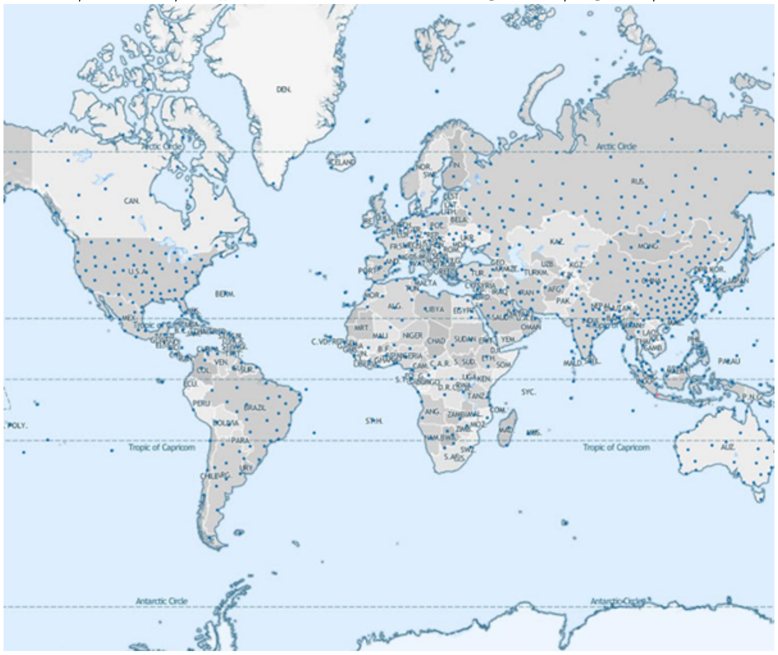

Figure 8.5: radiosonde-network

8.2.3.1 Radiosonde network

The global network consists of about **1,300 upper-air stations (2018)**. Over **two thirds of the stations make observations at 00:00 UTC and 12:00 UTC**. **Between 100 and 200 stations make observations once per day**. In ocean areas, radiosonde observations are taken by **about 15 ships (2018)**, which mainly ply the **North Atlantic**, fitted with automated shipboard upper-air sounding facilities.

Source: WMO (GOS)

8.2.4 Aircraft measurements

In collaboration with ICAO (International Civil Aviation Organization) and commercial and other airlines, aircraft-based observations are **received from over 3000 aircraft**, providing reports of **pressure**, **winds**, **temperature**, **humidity**, **turbulence** and other parameters during flight.

The **Aircraft Meteorological Data Relay (AMDAR) system** makes high quality observations of **winds** and **temperatures** at cruising level as well as at selected levels in ascent and descent (see figure). The amount of data from aircraft has increased dramatically during recent years - from 78,000 observations per day in 2000 to **more that 800,000 observations per day in 2017.** Providing great potential for measurements in places where there is little or no radiosonde data, these systems are making a **major contribution to the upper-air component of the GOS**. (Source: WMO (GOS))

8.2.4.1 Pros and cons of sondes and aircraft

Advantages

- **Vertical profiles** of the air.
- **High quality direct observations**.
- **Increasing amount of data**.
- Aircraft measurements also provide **data from above the oceans**.

Disadvantages

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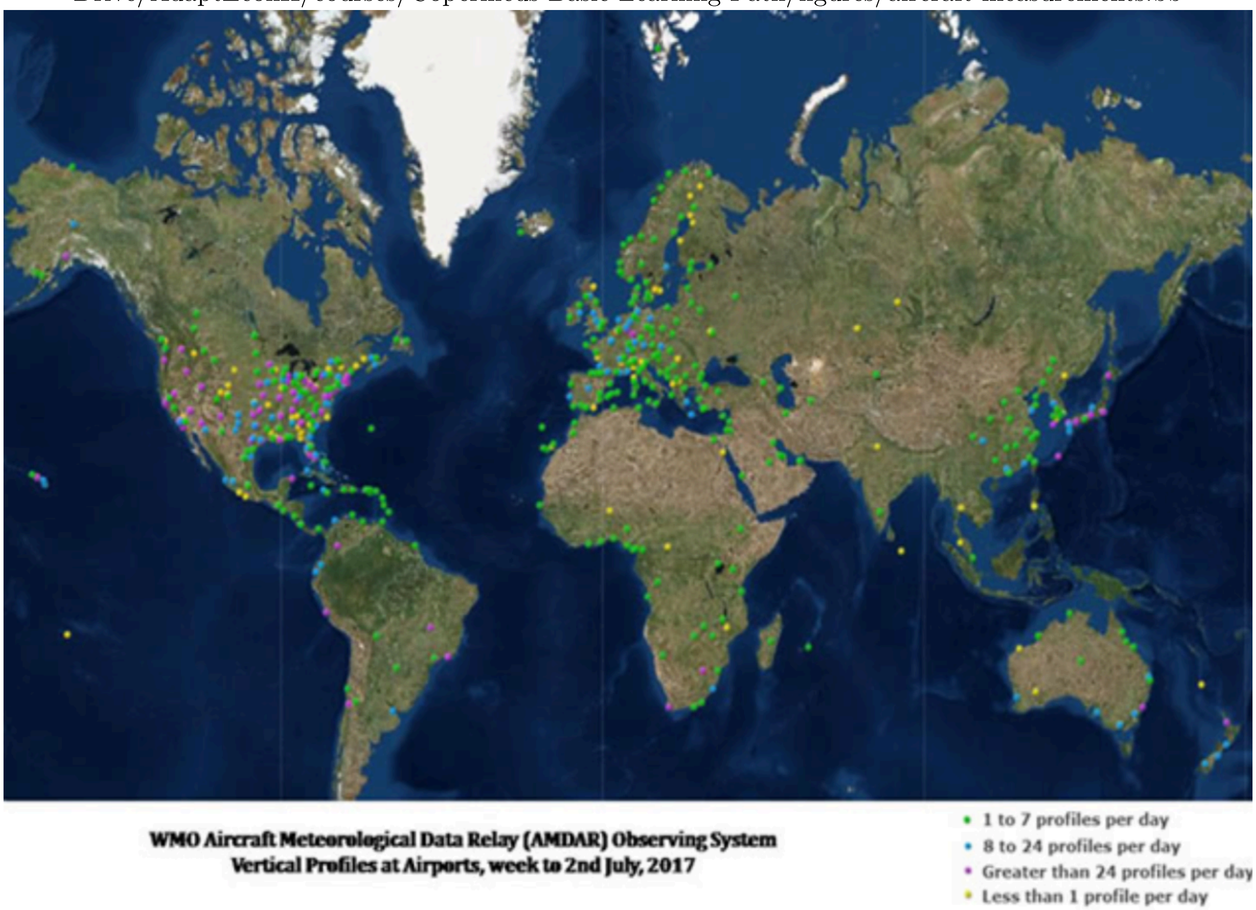


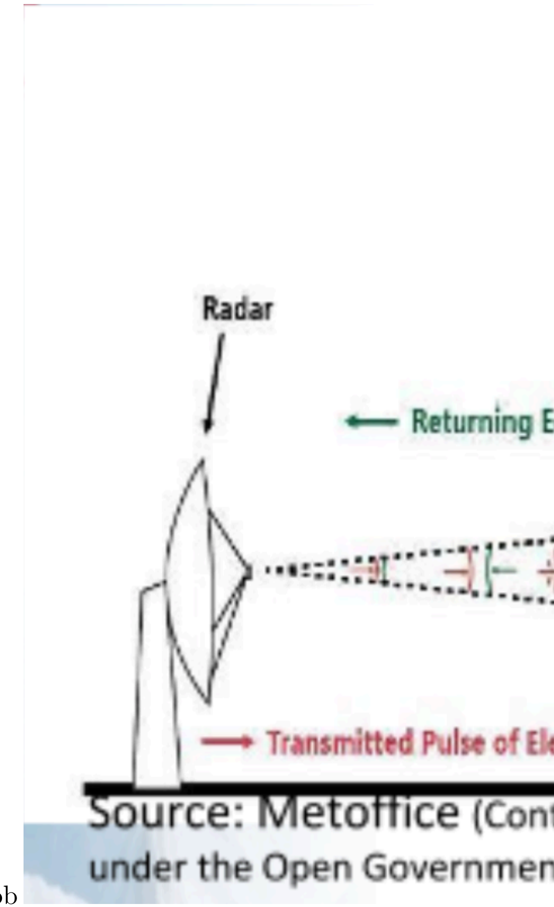
Figure 8.6: aircraft-measurements

- **No long time series**
- **No fixed** location (sondes drift with the wind)
- **No global** coverage. Lower coverage in the southern hemisphere, on the ocean and the polar regions.
- **Only 1 or 2 measurements per day**

8.2.5 Radar

Weather radars have been used in the detection of precipitation rates since the 1950s. The first figure below shows and example of a rainfall radar image. In principle the method is based on sending out a radar pulse and measuring the return signal. The signal has to be translated into a precipitation rate with the help of in situ measurements (see second figure).

Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/rain.bb 



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Dual polalized or doppler radars can measure wind and rainfall. They enable more accurate determination of precipitation types and sizes. This makes it easier to see whether the precipitation consists only of rain or also contains snow or hail (see video explanation).

Radar networks have been established around the world. A radar network database is maintained by the WMO and is important to assist with the international exchange of radar data and to protect radio-frequency spectrum allocation. (WMO (GOS):

8.2.6 Lidar

Instead of using a radar pulse, Lidar (**Li**ght **D**etection **A**nd **R**anging) uses laser light to study atmospheric properties from the ground up to the top of the atmosphere or from aircrafts to the ground. Such instruments have been used to study, among others, atmospheric gases, aerosols, clouds, wind and temperature.

Example of a Lidar image made from an aircraft. (Source: UCAR COMET):

8.2.6.1 Pros and cons of radar and lidar images

Advantages:

- Higher **spatial coverage** than ground measurements
- High **frequency** measurements
- Data almost **directly** available
- Information about the **upper air**

Disadvantages

- Time series from about the **end of the 90's until present**.

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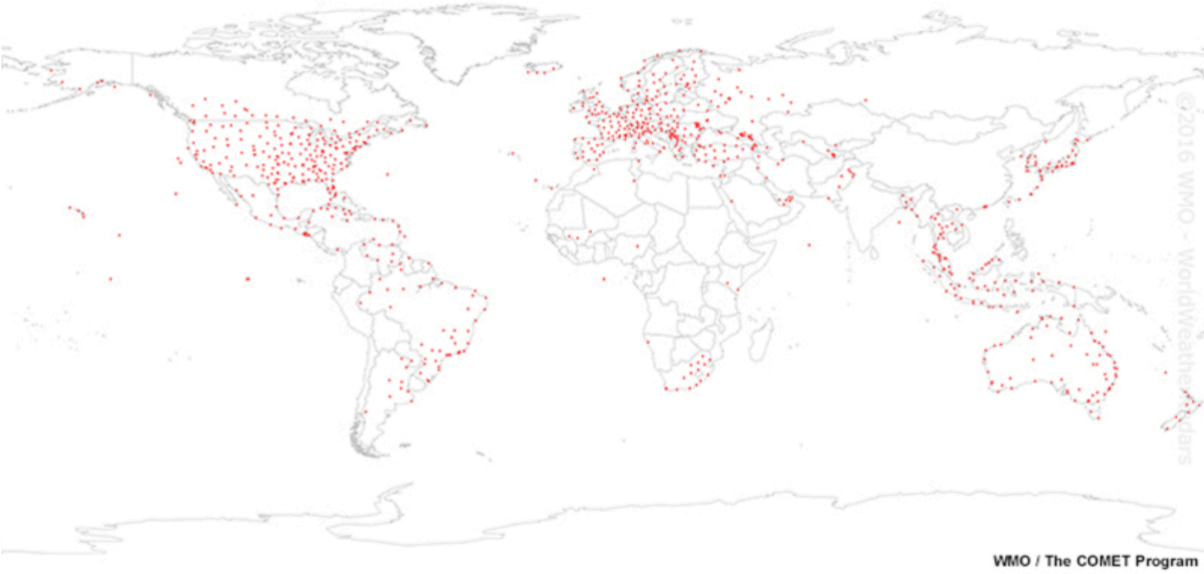

Figure 8.7: radar-network

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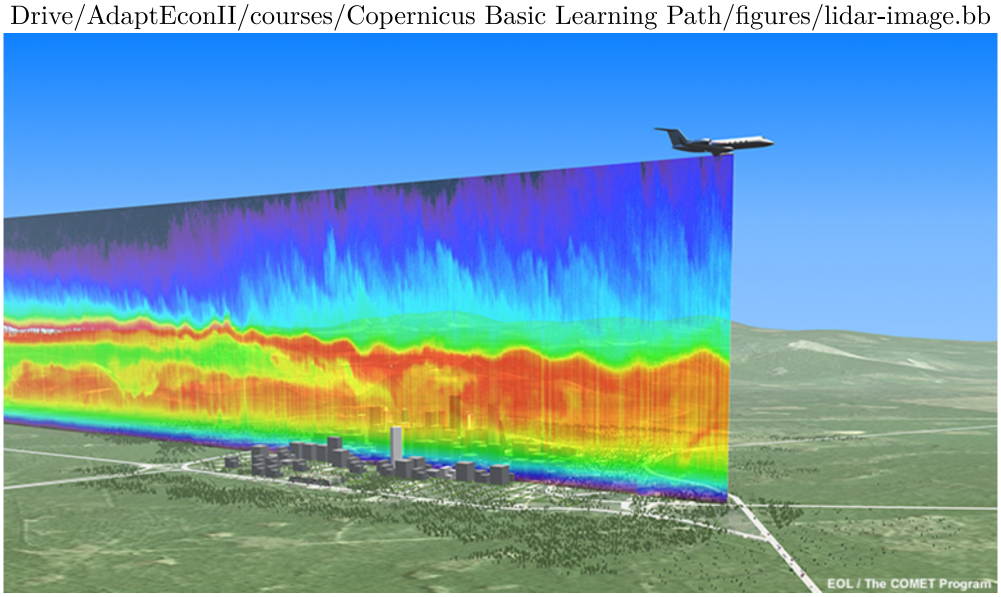


Figure 8.8: lidar-image

- The lidar and radar signal **has to be translated into the desired climate variable**. This introduces **additional uncertainties** and ground observations are needed to make this translation
- Systematic **disturbances** in the signal due to the atmosphere
- **No global coverage**. Lower coverage in the southern hemisphere, on the ocean and the polar regions.

8.2.7 Satellites

The **first weather satellite was launched in 1960**. Since then, many more satellites were launched providing a huge amount of atmospheric data.

Satellites are equipped with **visible** and **infra-red imagers** and sounders from which one can derive many **meteorological parameters**, like clouds, temperature, humidity, radiation, wind, wave height, wave patterns, sea currents, ice coverage, greenhouse gases and much more.

The first satellite mission designed to measure CO2 was the Interferometric Monitor for Greenhouse Gases (IMG) on board the ADEOS I satellite in 1996.

8.2.7.1 How do satellites measure CO2?

Solar **short wave radiation** is **reflected by the earth and atmosphere and is measured by satellites**. Also **long wave radiation** from the earth **reaches the satellite**.

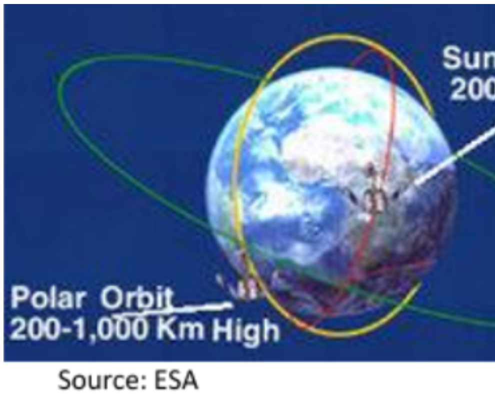
Since **different greenhouse gases absorb radiation at different wavelengths**, the **amount of radiation that reaches the satellite at different wavelengths says something about the composition of the atmosphere**.

More information about satellites can be found on: Link.

8.2.7.2 Types of satellites

- **Geostationary satellite**: earth-orbiting satellite placed at an altitude of around 35800 km directly over the equator, that revolves in the same direction the earth rotates (west to east), and therefore constantly observes the same path of the earth.
- **Polar orbiting satellite**: closely parallels the earth's meridian lines, thus having a highly inclined orbit close to 90°. It passes over the north and south poles each round. As the earth rotates to the east beneath the satellite, each pass monitors and area to the west of the previous pass. These strips can be pieced together to produce a picture of a larger area.

Several over the polar-orbiting satellites are equipped with sounder instruments that can provide **vertical profiles of temperature and humidity in the atmosphere in cloud-free areas**. Geostationary satellites can be used to measure e.g. **wind velocity** in the tropics by tracking clouds and water vapour. Recent developments have made it possible to derive temperature and humidity information directly from satellite information.



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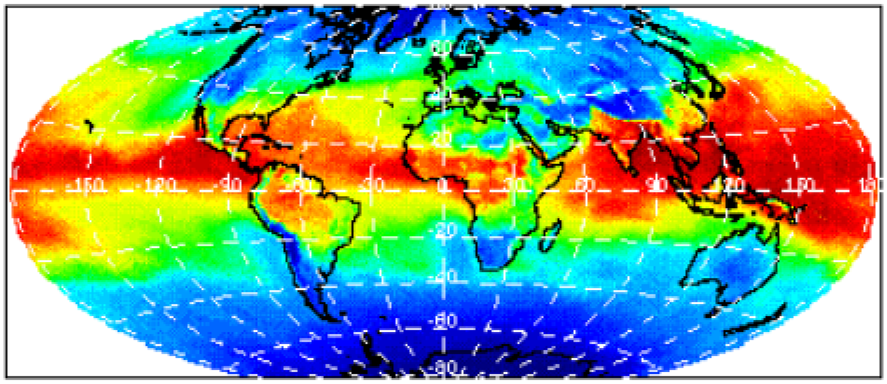

Figure 8.9: satellite-orbiting

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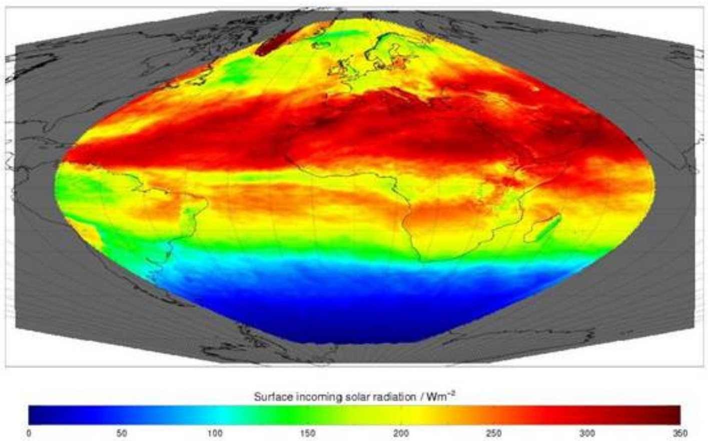

Figure 8.10: satellite-stationary

The below panel is an **example of a climate data set based on a polar orbiting satellite** (here: total water vapor in a column). It covers the entire globe, including ocean, desert, and sparsely populated regions.

The below panel is an **example of a geostationary satellite** (here: global radiation), covering only a part of the globe.

8.2.7.3 Pros and cons of satellite measurements

Advantages:

- High **spatial coverage** (data for regions without ground stations are available) and high spatial **resolution**
- Data almost **directly** available

Disadvantages:

- Time series from about the **end of the 90's until present**.
- The satellite signal has to be **translated into the desired climate variable**. This introduces additional **uncertainties** and ground observations are needed to make this translation
- **Systematic disturbances** in the signal due to the atmosphere

8.2.8 Historical data records

The **first daily time series start around 1850**, but were still **very scarce**. From about 1950 on there was a much better coverage with weather stations. The first climate data were recorded manually, but many have been digitised by now.

Records of the climate before the start of the regular measurement around 1850 are scarce. Therefore scientists have used **other types of information to estimate climate variables further back in time**:

- Old **shipping reports** mentioning the weather at sea
- **Corals** can be used to estimate oceanic temperature and sea-level changes
- **Tree**-rings and **ice**-cores can be used to infer changes in temperature and precipitation.

8.2.8.1 Shipping reports

Millions of (**mainly wind) observations** were made from ships in the **late 19th and early 20th centuries** or even earlier. Until recently they were only available from **paper logbooks**, but gradually they are being **digitized**. Some of these have been included in the latest assessments of climate, like the Intergovernmental Panel on Climate Change (IPCC) report. However, **many more logbooks have yet to be included**.

Also other written reports, like farmers' logs, travelers' diaries and newspaper accounts can tell us something about past climates.

8.2.8.2 Tree rings

Trees can live for hundreds—and sometimes even thousands—of years. Over this long lifetime, a **tree can experience a variety of environmental conditions: wet years, dry years, cold years, hot years, early frosts, forest fires and more**.

Tree rings can **tell us something about the conditions the tree grew** in. For example, rings usually grow **wider in warm**, wet years and they are **thinner in years when it is cold and dry**. If the tree has experienced stressful conditions, such as a drought, the tree might hardly grow at all in those years.

Scientists can **compare modern trees with local measurements of temperature and precipitation from the nearest weather station**. Very **old trees can give information about the climate before regular weather observations started**.

8.2.8.3 Corals

The way corals can tell us about past climates is **comparable to tree rings**. Like their land-based counterparts, **corals add seasonal layers**, which **appear as bands in their hard calcium-carbonate shells**. Corals **respond to small changes in temperature, rainfall, and water clarity in a matter of months,** making them a **uniquely sensitive climate record**.

8.2.8.4 Ice cores

In the polar regions and high in the mountains **ice has accumulated from snowfall over many millennia**. Scientists drill out ice cores from these ice sheets or glaciers. The ice encloses **small bubbles of air that contain a sample of the atmosphere**. From these it is possible to **measure directly the past concentration of gases** (including carbon dioxide and methane) in the atmosphere.

Most ice core records come from Antarctica and Greenland, and the **longest ice cores extend to 3km in depth**. The **oldest continuous ice core records to date extend 123,000 years** in **Greenland** and **800,000 years** in **Antarctica**.

8.2.8.5 Pros and cons of historical data

Advantages: **long** time series, **only way to obtain climate information of the past** and test climate models

Disadvantages: **not as precise as direct instrumental measures**, very **few proxy datasets**.

8.2.9 Global Networks

The **World Meteorological Organisation** (WMO) facilitates the **establishment, maintenance and continuing expansion of a global observation network**, the activities of which are coordinated within the **Global Observing System** (GOS) of the **WMO World Weather Watch** (WWW).

The WMO co-sponsored **Global Climate Observing System (GCOS) and Global Ocean Observing System (GOOS**) also play a major role in **improving the collection of required data for the development of climate forecasts and climate change detection**.

The **WMO** Integrated **Global Observing System** (WIGOS) acts as its **umbrella for these networks**, using the **WMO Information System** (WIS) to **connect together all regions for data exchange, management and processing** (source text and figure: WMO (GOS3).

8.3 Describe instrument and measurement uncertainty and the factors that are used to assess systematic and random errors, and the propagation of errors

There are many challenges which have to be tackled when observing the climate, including (Met Office link for more information):

- **Incomplete geographical coverage** of measurements.
- **Gaps** in historical climate records.
- The need to use some **indirect measurements** of climate change.
- **Biases and errors** in data.
- **Varying standards** for taking observations.
- **Collecting information to assist interpretation** of climate records.
- **Calculating changes** in climate.
- **Estimating uncertainties** in climate **observations**.

8.3.1 Measurement guidelines

GCOS (the **Global Climate Observing System**) issued **ten principles climate observation networks should meet** to assure data quality and longevity of records. They can be read at **link to WMO**

Some examples:

- A **suitable period of overlap** for new and old observing systems is required
- The **details and history of local conditions, instruments, operating procedures, data processing algorithms and other factors pertinent to interpreting data** (i.e. metadata) should be documented and treated with the same care as the data themselves
- The **quality and homogeneity of data** should be regularly assessed as a part of routine operations
- **Operation of historically-uninterrupted stations** and observing systems should be **maintained**
- **High priority for additional observations should be focussed on data-poor regions**, poorly-observed parameters and regions sensitive to change

8.3.2 Data homogenisation

Abrupt or gradual changes in data series can develop through:

- **Changes in the instrument**
- **Replacement of the instrument** to another location
- **Changes in the surrounding of the station**, for example the growth of trees or the expansion of cities in the neighbourhood.

The inhomogenities in the climate data series **can become so large that without corrections the series cannot be used for climate research any longer**. Therefore, **methods to correct for these inhomogenities are necessary**. After homogenisation, historical values are again comparable with recent values.

Homogenisation of time series is **mostly done in a statistical way by calculating corrections from mutual comparisons of stations**.

8.3.2.1 Data comparison

One way to study the influence of changes in measurement technique is by **making simultaneous measurements with historical and current instruments next to each other**.

8.3.2.2 Climate data records

A Climate Data Record (CDR) is "a **time series of measurements of sufficient length, consistency and continuity to determine climate variability and change**."

It can be made by **combining data from different observational resources**, like satellite data, ground observations and airsondes, hereby profiting from all the advantages of the different measurement techniques

Gaps in observational series can be filled with help of climate models. In their turn, CDR's can also be used as input for climate (reanalysis) models.

Chapter 9

Bias correction and Downscaling

9.1 Terminology

- In the scientific literature both 'bias correction' and 'bias adjustment' are used, here we use **bias correction**.

9.2 Why are models biased and do we need bias correction?

- **Why do we need bias correction?** —> direct output from Climate Data Store could be used, but: for impact studies these outputs are often not useful because of significant biases, for example:
  - **Temperature** can be consistently too high
  - Rainfall too high or low
  - Model does an incorrect simulation of the monsoon, the rains start too early or too late
  - Climate models tend to overestimate the number of days with rain and underestimate precipitation extremes.
- **Why are the models biased?**
  - Limited spatial resolution (large grid boxes)
  - Simplified physics
  - Incomplete knowledge of the earth's climate system

9.3 Examples of model bias

9.3.1 Geographical differences

Precipitation example: for a result of model precipitation estimates (a), there is a certain bias (*Multi Model Mean Bias*) depending on the location (b). This can also be expressed in *Multi Model Mean of Absolute Error* (c) and *Multi Model Mean of Relative Error* (d). A similar analysis can be made for **temperature**.

9.3.2 Differences in amount of bias

When looking at model bias for temperature and precipitation for different regions (x-axis), it can be seen that the predicted change in temperature is equal to the bias in the model. For precipitation the bias is even more important. Lots of models over- or underestimate precipitation (sometimes only 50 % of what is observed on-site/in-situ)

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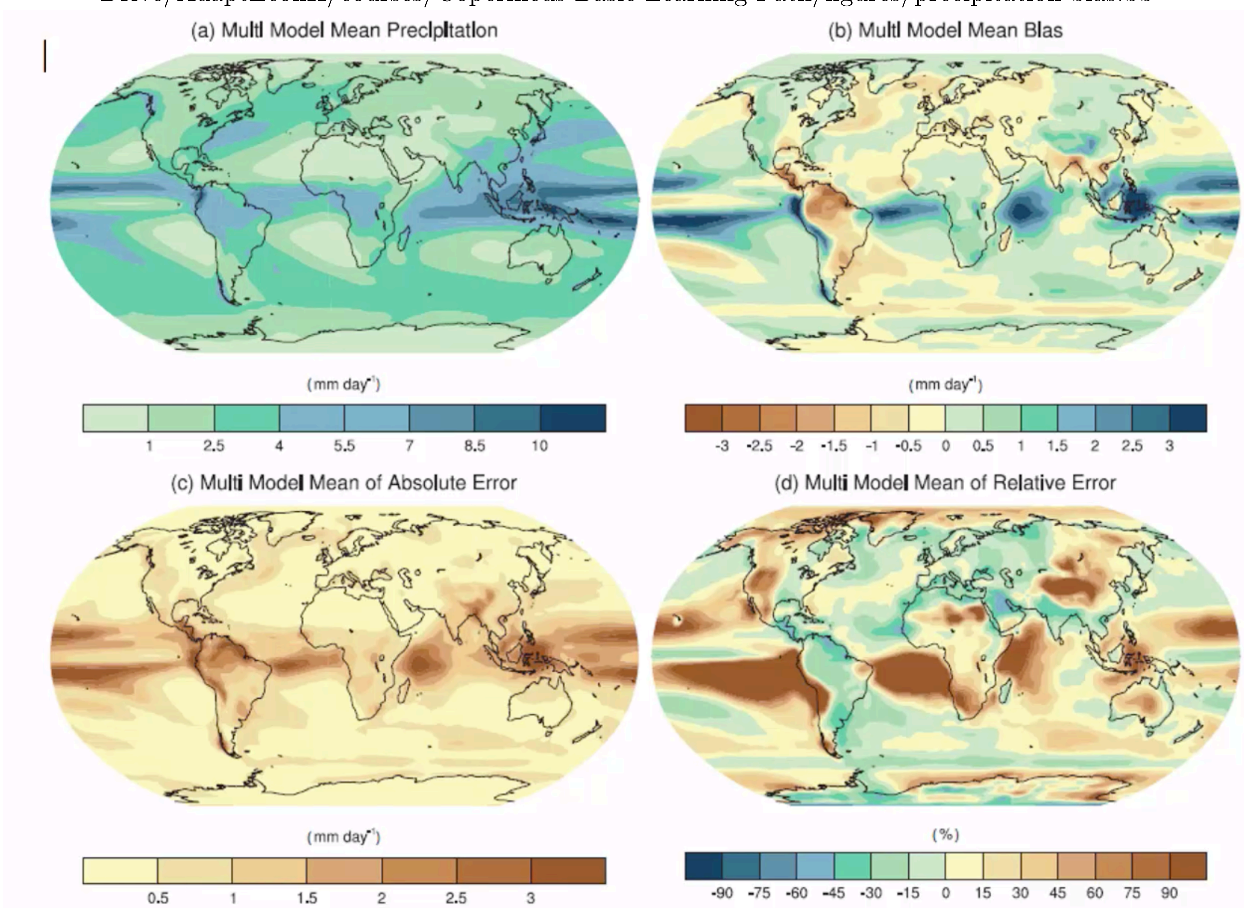

Figure 9.1: precipitation bias

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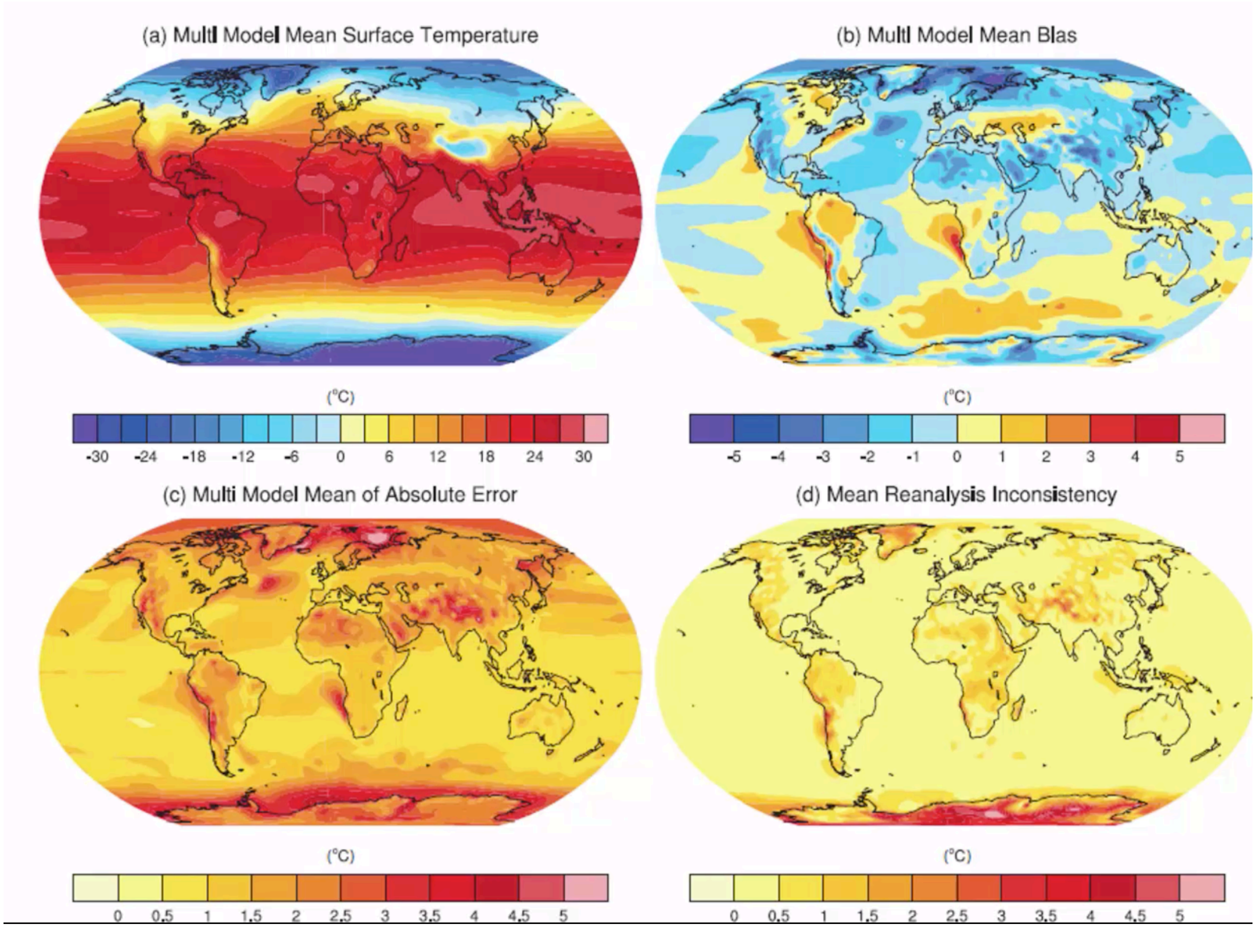

Figure 9.2: temperature-bias

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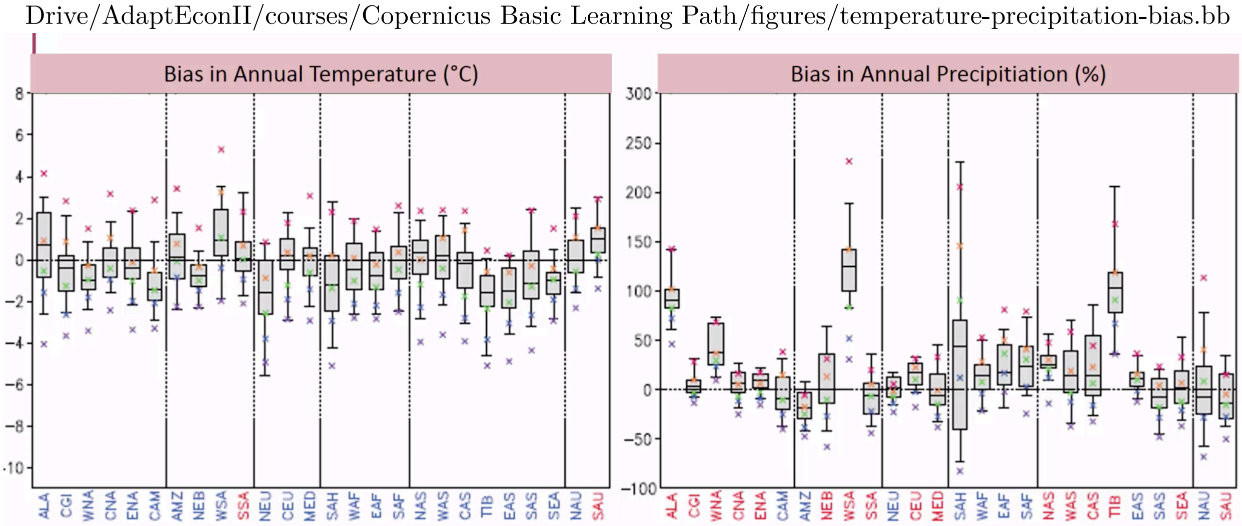

Figure 9.3: temperature-precipitation-bias

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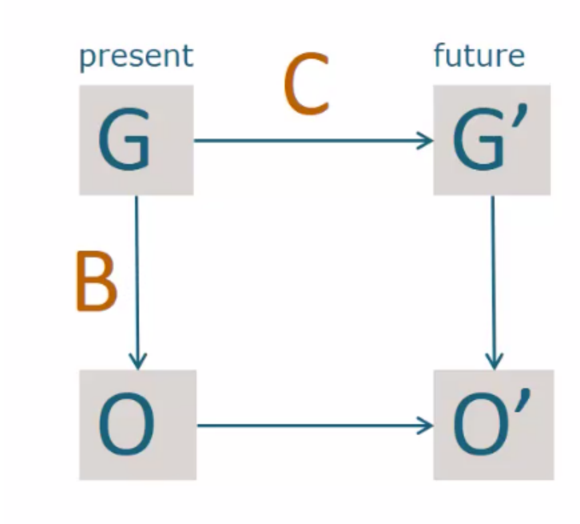

Figure 9.4: bias-correction-theory

9.4 Impact of model bias on climate assessments

- If your main **interest is relative change** in future climate, bias is **not a big problem**.
- Bias is important for:
  - **Threshold analysis** (crop behavior at certain temperatures, …)
  - **Water availability** analysis: bias in rainfall can have large impact
  - Estimation of **extremes**: future changes in flood risk can be calculated wrong

9.5 Theory of bias correction and downscaling

For an overview of theory of dynamical and statistical downscaling, see [the dedicated chapter above][Dynamical and statistical downscaling theory]

Bias correction model: present climate as simluated by the climate model (**G**) or observed (**O**) : difference is bias **B**. We also have change (**C**) to a future climate as modeled by the model (**G’**) and the future observed climate (**O’**).

- **Assumptions** applied when using this model:
  - **Bias of present and future model is equal**
  - The **climate model results of the current climate is more or less correct**
- **function B** can have different shapes:
  - *Linear* function
  - *Scale transfer* function with **mean**, **variance** and **shape**.
- **B** can be **estimated**:
  - Dynamical (using climate models)
  - Statistical, using:
    * weather typing/analogues
    * weather generator [(non) stationary]
    * transfer functions: (non) linear or PDF mapping functions (with distribution)

9.6 Bias correction example - tutorial

See excel files `Bias correction tutorial COP10 ULS.xlsx`and `Bias correction tutorial COP10 ULS-solution.xlsx`. Given data (for Kenya) is the historical rainfall (observations + 4 GCM model results) and 4 GCM predictions.

1. **calculate average** rainfall for observations + each of the GCM models —> large differences, bias needed
2. **calculate absolute bias** by **substracting observations from global climate model results**.
3. To **correct future data** (2070-2099) and calculate **future average rainfall**, we need **relative bias correction factors**: divide the observation output by the GCM output.
4. To correc the future data, multiply the non-bias corrected GCM output with the relative bias correction factor, and calculate the average for each GCM.

Chapter 10

Regional reanalysis (UERRA-HARMONIE) & Surface Reanalysis (MESCAN-SURFEX)

10.1 Importance of Regional Reanalysis

Atmospheric reanalysis is a method to **reconstruct the past weather by combining historical observations with a dynamical model**. It provides a physically and dynamically **coherent description of the state of the atmosphere**. The synthesis is accomplished by assimilating the observational data into a meteorological model and thereby forcing the model to reproduce the observations as closely as possible. The main **advantage** of reanalyses is that they provide a **multivariate, spatially complete, and coherent record of the atmospheric state** – far more complete than any observational dataset. Another advantage is that **reanalyses are produced with a single version of a data assimilation system** – including the forecast model used – and is therefore **not affected by changes in method**.

10.2 Copernicus Regional Reanalysis for Europe service

The Copernicus Regional Reanalysis for Europe service produces and delivers a **regional reanalysis (RRA)** including **long-term datasets of Essential Climate Variables (ECVs).**

The service is implemented in several steps. First, a system developed in the FP7 pre-operational project UERRA (Uncertainties in Ensembles of Regional ReAnalysis) is used to [**1**] **update the existing RRA in near real time**. In combination with the RRA produced already in the pre-operational project, the service offers a consistent RRA from 1961 to near real time.

Moreover, an [**2**] **improved model version will be developed within the service**. The model will be used to create a **pan-European reanalysis with very high resolution (5.5 km)** forced by the **global ERA5 reanalysis**. The improved system should become operational in the **second half of 2019**.

See also introductory video online.

10.3 Available data

- Period **1961 - "now"**, with monthly updates
- **11km horizontal resolution** including entire Europe
- **65 height lev**els
- **Hourly** for many parameters

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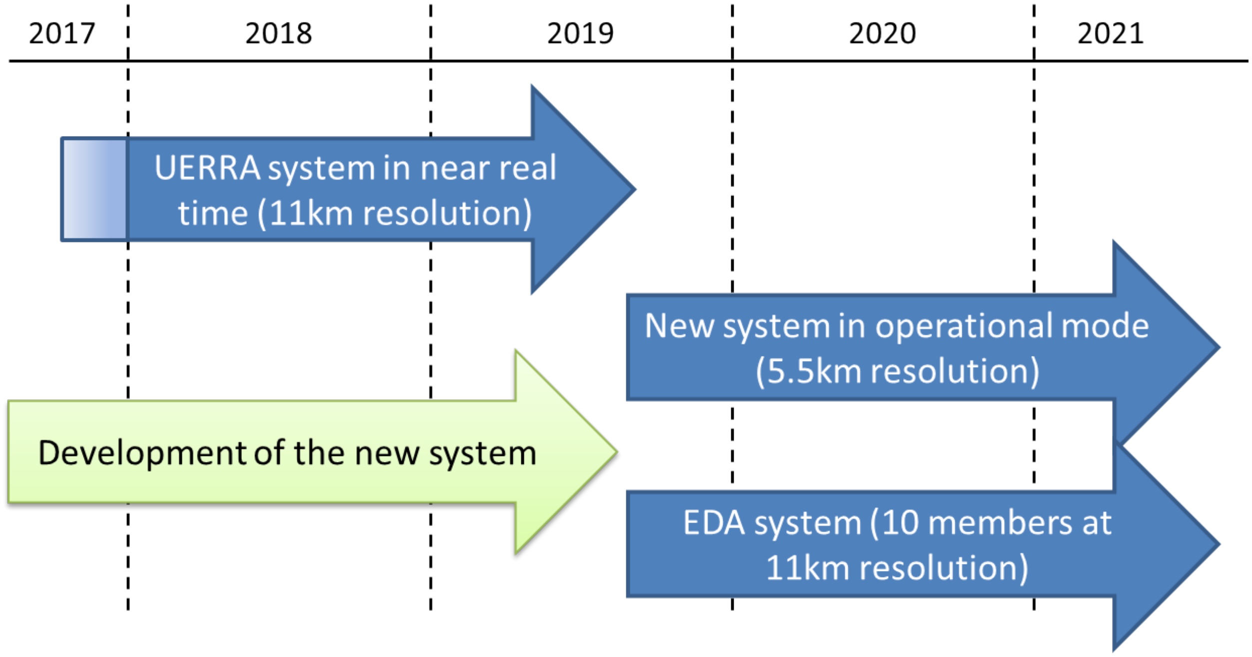

Figure 10.1: rr-for-europe

- **31 surface parameters** (less on i.e. height levels)
- Almost **500 TB of data**
- Additional data is available on surface and soil levels with **5.5 km resolution every 6th hour**.

10.4 Methodology

10.4.1 Global Reanalysis (ERA40/ERA-Interim) —> Regional Reanalysis (UERRA-HARMONIE)

The 3D-UERRA system is based on the HARMONIE Data Assimilation system, which is developed and used within the HIRLAM (High Resolution Limited Area Model) and ALADIN (Aire Limitée Adaptation dynamique Développement InterNational) consortia.

For the **period 1961-2001 ERA40 observations** with addition of Swedish and French observations are used. **After 2001 conventional data** (SYNOP, Ship, Buoys, Radiosondes, Pilot and Aircraft) are used that are operationally available.

The system uses global reanalysis data as lateral boundaries: **ERA40** for the **period 1961-1978**, after that **ERA**-interim.

10.4.1.1 UERRA-HARMONIE system: data assimilation

Reanalysis uses a **weather forecasting model to create a 'first guess' of the atmospheric state** at a certain time. The first guess is then **corrected on the basis of observations**. This corrective step is referred to as '**data assimilation**'.

The UERRA-HARMONIE system applies the so called **3D variational analysis** (3D-VAR). At fixed points in time the **model state is adjusted based on the observed state**, taking into account the statistics of model and observation errors. The UERRA-HARMONIE system is run with **four cycles per day**

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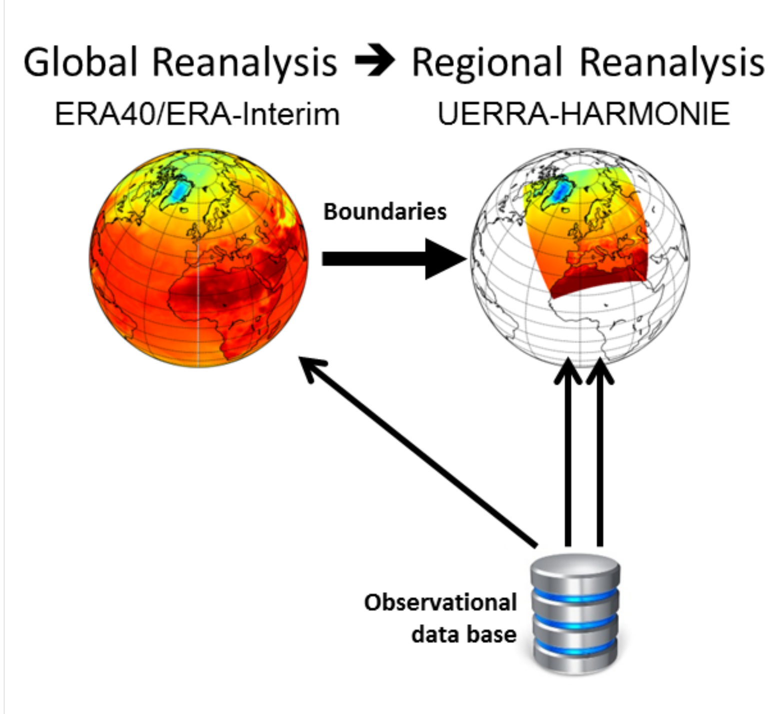

Figure 10.2: global-to-regional

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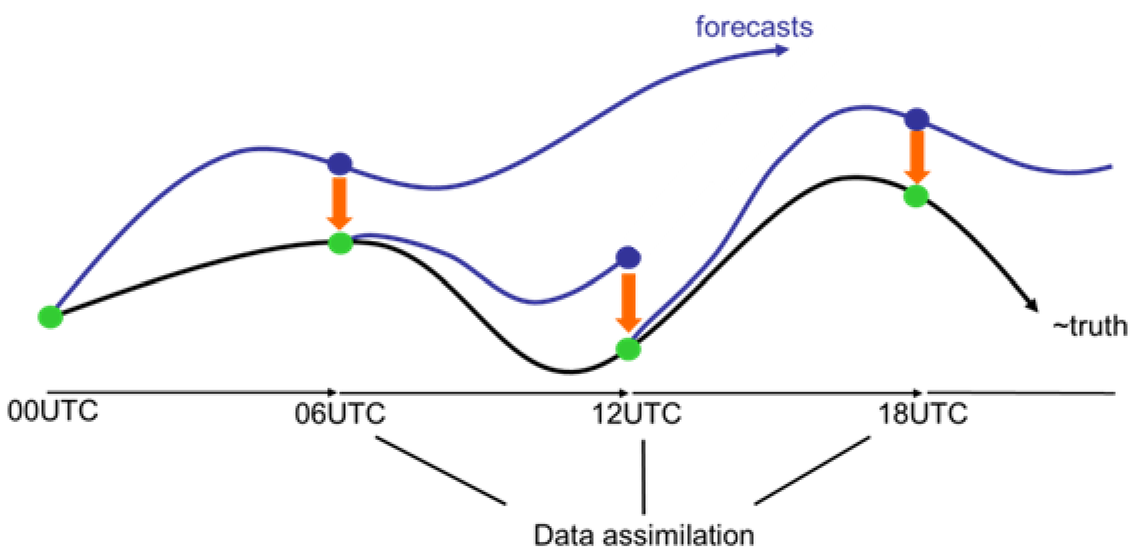

Figure 10.3: uerra-harmonie

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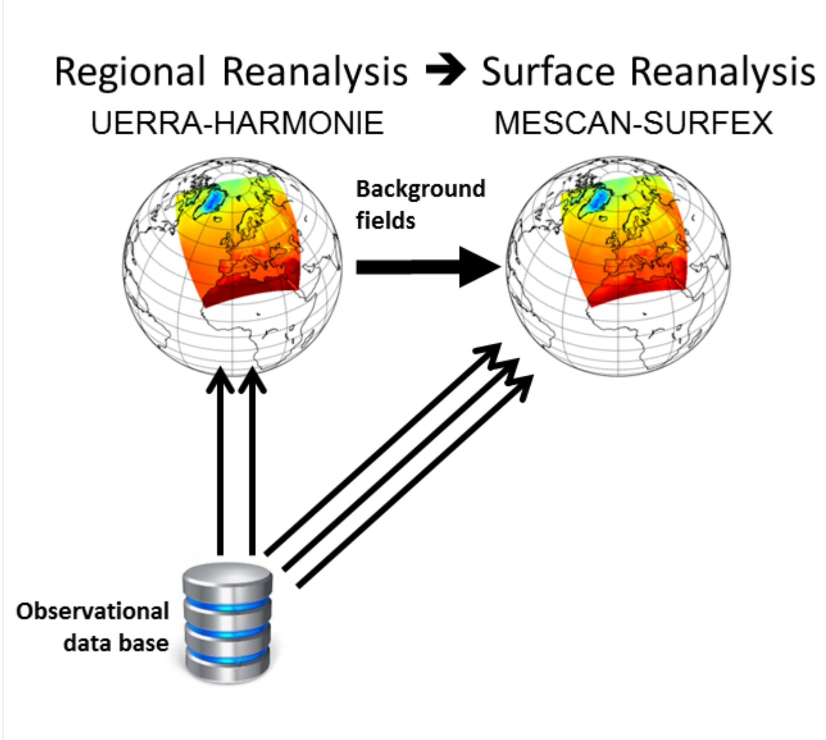

Figure 10.4: regional-to-surface

performing analyses at 00UTC, 06UTC, 12UTC and 18UTC. The **forecast lengths vary between 6 and 30 hours**.

10.4.2 Regional Reanalysis (UERRA-HARMONIE) —> Surface Reanalysis (MESCAN-SURFEX)

The MESCAN-SURFEX system analysis uses the **2D-analysis system MESCAN** and the **land surface platform SURFEX** to **generate a coherent surface and soil analysis**. The system combines downscaled UERRA-HARMONIE reanalysis fields and additional surface observation (especially for precipitation), to make a **high resolution (5.5 km) 2-dimensional analysis over Europe for every 6th hour**.

MESCAN is a surface analysis system using an **optimal interpolation algorithm for the 2m temperature and relative humidity and for the 24h-accumulated rainfall**. SURFEX is a **land surface platform,** which is driven by **temperature**, **humidity**, **precipitation**, wind and **radiative fluxes**.

10.5 Guidelines on using UERRA-HARMONIE & MESCAN-SURFEX data

This is a summary of some important features of the models and results that the user needs to be aware of when using the UERRA datasets. More information is available in the user guide.

Although UERRA provides consistent and coherent datasets there are **weaknesses and limitations**. Some of these are common for reanalyses in general, other are model/version dependent. The user has to decide whether the data is fit for their specific purpose.

Vast amount of data are available from the UERRA system. For the UERRA-HARMONIE system, a **complete set of parameters including all available time steps take up ca. 8 TB** (TB = terabyte, 1 terabyte of data could fill about 1500 CD:s) per model year and hence almost **500 TB for the entire time period**. The MESCAN-SURFEX surface analysis is not included in this estimation. However, it needs less storage place than the 3D-reanalysis – in total 47 TB.

For the UERRA-HARMONIE data, the user might choose among **more than 50 parameters for different heights and time steps**. In addition, the MESCAN-SURFEX analysis offers roughly 30 parameters for the surface and the soil (down to 12m).

10.5.1 Spatial Resolution

Horizontal resolution All parameters are computed for grid boxes. This means the parameter values reflect a mean over the grid box area. This needs to be considered when for instance UERRA data are compared with observations.

Having a horizontal resolution of **11km** for the **UERRA-HARMONIE** system implies that each value reflects the **mean over an area of 121km²** (11km*11km).

The resolution of the **MESCAN-SURFEX** surface analysis is **5.5km***5.5km. Hence, a grid box has an **area of roughly 30km²**.

Vertical resolution The **UERRA-HARMONIE** system has **65 vertical levels** but the major part of the data is stored on **selected pressure levels**. Pressure levels are available **between 1000-10hPa** with a **higher resolution at lower altitudes**. In addition, some parameters are stored on height levels. **11 height levels are available between 15-500m.**

The UERRA-HARMONIE **soil model** has **3 vertical levels**. The three levels represent approximately the **surface**, the **soil at root depth** and the **deep soil**. Due to the used force-restore scheme in the soil model it is not possible to relate the levels with a certain depth in meters.

The **MESCAN-SURFEX soil model** has **14 vertical levels**, which range **from the surface to a depth of 12m.** The edges between different levels are at 0.01m, 0.04m, 0.1m, 0.2m, 0.4m, 0.6m, 0.8m, 1.0m, 1.5m, 2m, 3m, 5m, 8m, and 12m. Values for a certain level reflect the **mean value over the level thickness**.

10.5.2 Temporal Resolution

The figure below gives an overview on available time steps for the **UERRA-HARMONIE system**. First, there are the **four analyses at 00UTC, 06UTC, 12UTC, and 18UTC** highlighted in red. These time steps should be of **highest quality** since the observations are assimilated directly. However, they are available only every sixth hour and not all parameters are available for the analyses.

Forecasts are then started from the analyses and the **output is saved hourly for the first six hours** as indicated by the **dark blue boxes** in the figure below. Forecasts initiated at 06UTC and 18UTC stop after six hours while forecasts initiated at 00UTC and 12UTC continue until forecast hour 30. However, the output frequency is reduced to **three hourly** until forecast hour 24 and the last output is then saved six hours later (blue boxes)

Different forecasts lengths have different **strengths and weaknesses**. Whereas the short-term forecasts are affected by spin-up issues after the initialization of the model the long-term forecasts might veer away from the real weather due to shortcomings in the model. It is not possible to give a general recommendation for which time steps should be used. The user needs to decide which selection should give the best result for the application.

The **MESCAN-SURFEX** output is essentially **hourly** except for the driving variables used as input by SURFEX. The analyzed variables are **2m temperature** and **relative humidity**, radiative fluxes and **wind** with a **frequency of 6h** and **24h precipitation**** only available at 6h UTC.

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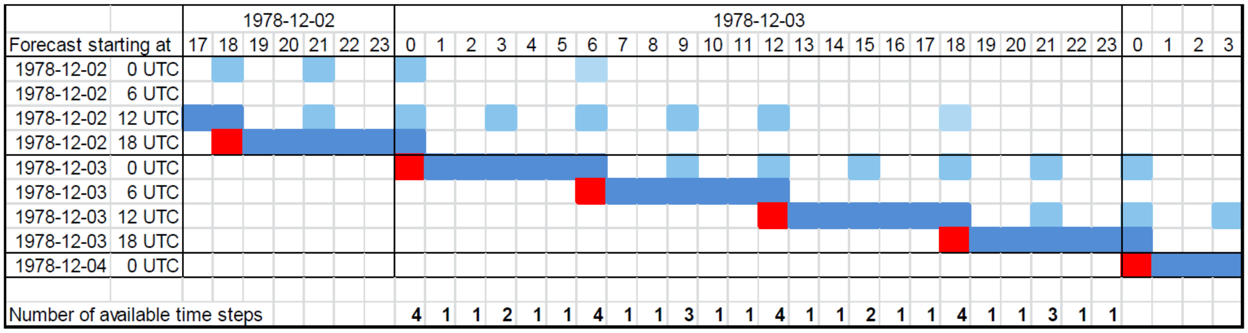

Figure 10.5: forecast-time

10.6 Limitations of reanalysis

Generally it is **challenging for a reanalysis system to correctly reconstruct variables that have large space and time variability**, such as **precipitation**. Therefore, for some applications, e.g. in hydrology, it is quite **common to bias correct precipitation data**. Other variables, like surface temperature, are generally less variable in space and time and easier to reconstruct by the reanalysis system.

Similarly, **results in complex terrain**, such as mountainous regions or coastal areas, are generally **less reliable than results over a more homogeneous terrain**. The current models cannot represent the strong gradients that sometimes are caused by the variable terrain.

The figure below illustrates this behavior. The **best (blue) and worst (red) correlations** between the **UERRA-HARMONIE 2m-temperature** and **observational sites** is illustrated for Swedish locations. A total of 853 measurement sites have been investigated and the 50 with highest and lowest correlation are shown. Mountains higher than 500 m are coloured gray in the map. Clearly, **correlations are lowest in the Swedish mountain areas** (north-west) and **along the (east) coast**.

10.7 Model specific issues

In the UERRA reanalyses some problems have been noticed that users need to be aware of. The most important issues currently known are listed here, for more information please read section 2.3 of the UERRA product user guide.

10.7.1 UERRA-HARMONIE spin-up issues (and effects on wind, temperature and precipitation data)

Spin-up issues are a general problem for data assimilation and Numerical Weather Prediction systems. Spin-ups **occur at the beginning of model runs**. **Due to the assimilation of observational data the model becomes slightly out of balance.** Then, the model needs some time to ramp up and stabilize. In the UERRA-HARMONIE system, observations are assimilated four times a day and each time the model needs to adjust to the observations causing a spin-up.

Unfortunately **this particular issue is in the UERRA-HARMONIE case somewhat extreme**. But the issue causing the problem is located and **the next RRA should not be affected as much by spin-up problems as the current version**.

The largest spin-up issues occurs during the **first 1-2 hours of the forecast**. It is therefore **recommended to primarily use the 6 hourly analysis fields whenever this is possible**. Also, it seems that **three hourly values can be used without larger restriction**. The spin-up problems are most pronounced

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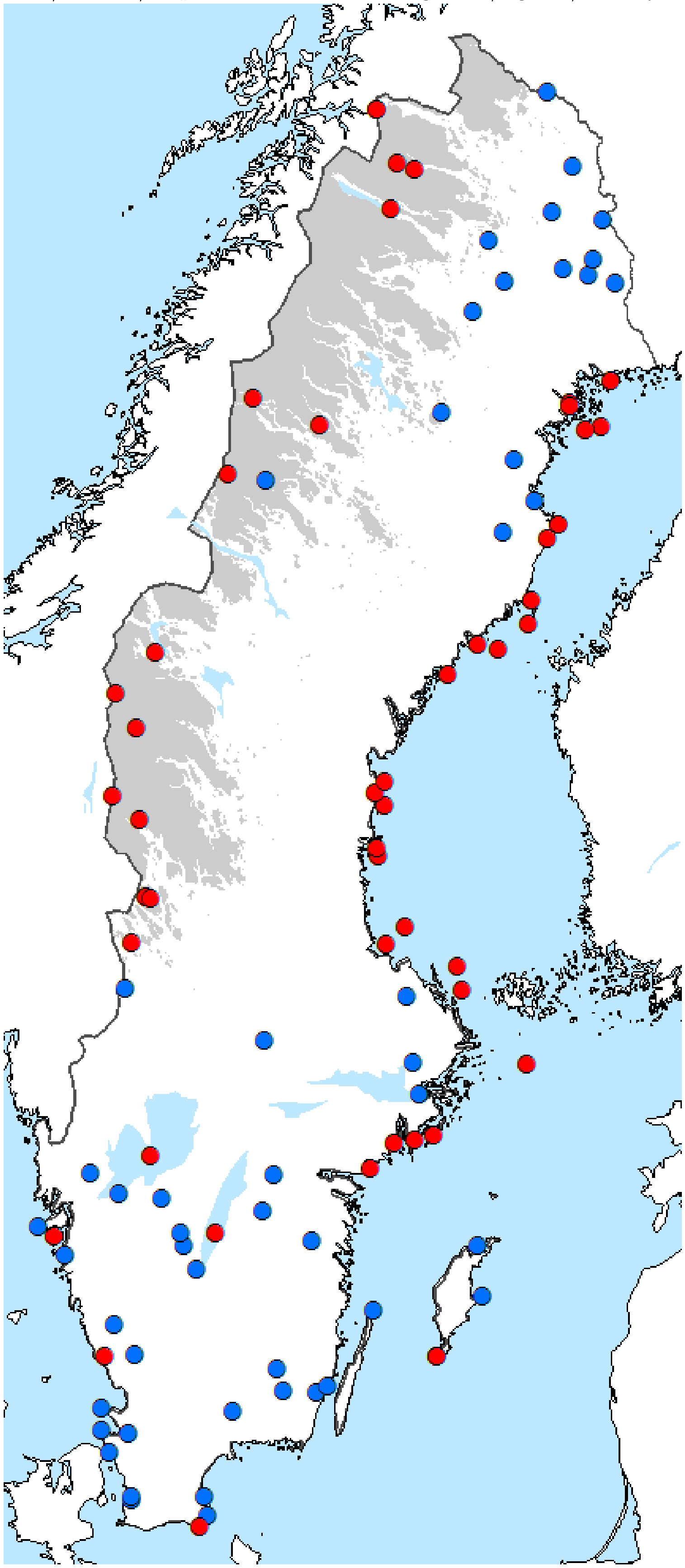

Figure 10.6: reanalysis-limitations

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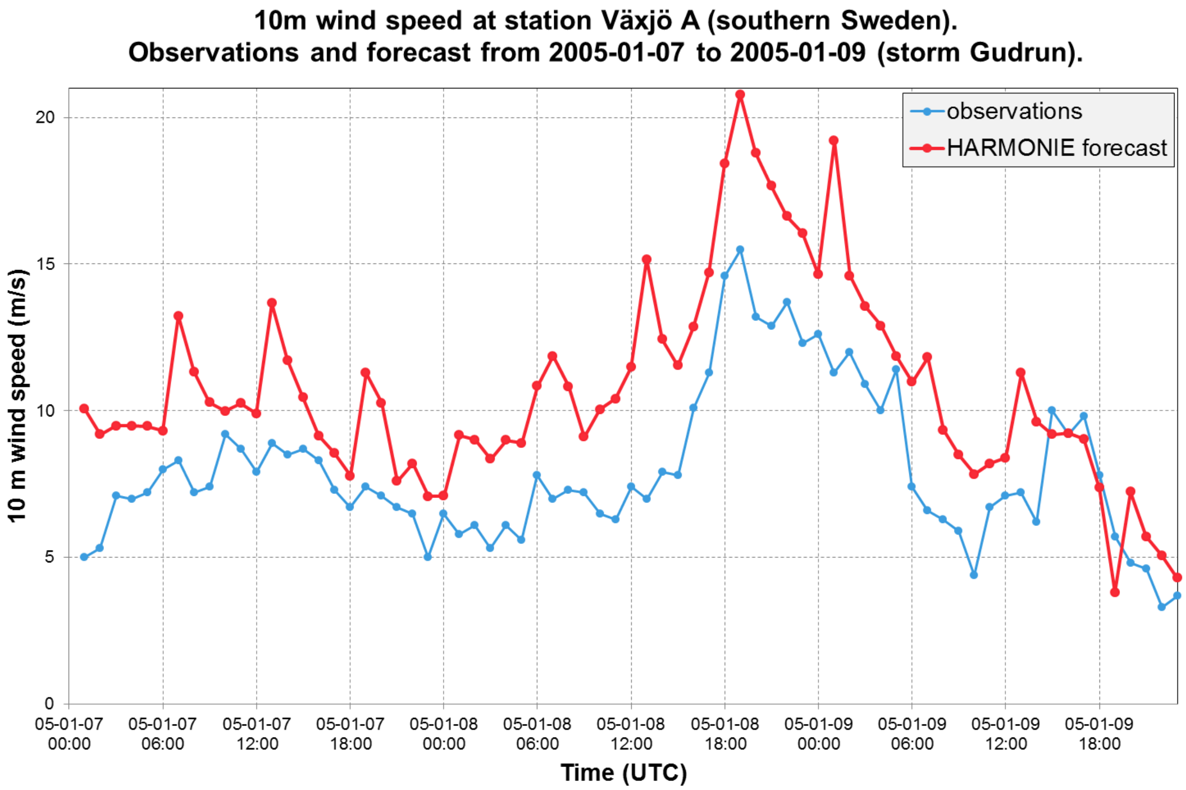

Figure 10.7: spin-up

during turbulent conditions, for example connected to deep low pressure systems, and should therefore be limited in space and time.

Wind

Spin-up problems are **in some situations causing wind speeds for the first 1-2 hour forecasts being too high**. This is most pronounced in the wind gust but the problem also occurs for the mean wind at 10 meter altitude, see the figure below.

Figure: *10m wind speed during a storm in southern Sweden January 2005. The blue line and dots are hourly observations from station Växjo A. Red line and dots are the hourly UERRA-HARMONIE forecast for the closest grid point. Note the reoccurring leaps in wind speed during forecast hours 1-2. Also note that this rather extreme case is picked as an example.*

Temperature

Similar spin-up problems can be seen for **maximum/minimum temperature**. This can in turn cause errors in the cold/warm extremes which affect climate indices such as frost days, tropical nights, ice days and summer days.

Precipitation

Models have usually **longer spin-up times** for **precipitation**. For the UERRA-HARMONIE case, we **do not recommended to use the first 6 hours of the forecasts for precipitation**. Tests have shown that you get **best daily precipitation (24h accumulated precipitation) if you use data from the long forecasts**. For example, **take a 30h forecast and subtract the 6h forecast to get precipitation for a 24h period**. This way you can avoid using the initial most spin-up affected forecast steps.

10.7.2 MESCAN-SURFEX precipitation observations

In the MESCAN-SURFEX surface analysis **errors have been noticed in the precipitation fields for some areas and time periods**. These errors are most likely **due to erroneous observations**, which did enter the assimilation procedure. It remains a **challenge for the next system to solve this type of weaknesses – especially for "old" and validated data where precipitation is equal to zero for long period**.

Since the errors are restricted in time and space, the user has to evaluate if the studied time period or region is affected.

10.8 Download and processing of UERRA-HARMONIE or MESCAN-SURFEX data

10.8.1 Copernicus Climate Data Store Website

The recommended way of handling the UERRA datasets is via the Copernicus Climate Data Store (CDS), located at climate.copernicus.eu. The CDS provides user friendly access to documentation and datasets download. There is also a toolbox for web based processing and plotting of the data.

10.8.2 Copernicus Climate Data Store API

The CDS download form and toolbox should cover most user needs for data access and processing. But users who need to download large amounts of data or need data that are not yet listed in the CDS should use the CDS API for programmatic access of the UERRA datasets. The CDS API provides access to all the data that is published within the service.

Data access via the CDS API **requires installation of the python based API client** and **execution of python extraction scripts** on the users computer. A guide for the installation process and some example scripts are available at the API how-to page.

Some **UERRA-specific example extraction scripts** are provided on the user examples GitHub. There are separate folders containing **example scripts** for data that are listed in the CDS and for data that are not yet listed in the CDS.

The request syntax for unlisted data is based on the **ECMWF MARS retrieval system**. Before running these scripts it is recommended to explore the available data and the corresponding MARS requests via Web-MARS: UERRA-HARMONIE data in Web-MARS MESCAN-SURFEX data in Web-MARS Then modify the time, parameters, levels etc. in the scripts to match your specific needs.

Chapter 11

Using climate models for climate scenarios

11.1 Definition climate scenario

A **climate scenario** is a ***plausible*** **image of a future climate based on knowledge of the past climate and *assumptions* on future change** (on **increase of greenhouse gas (GHG) concentrations**). They are constructed to **estimate the impact** of climate change. Usually they are constructed with the help of climate model information.

The terms "climate scenario" and "climate change scenario" are often used interchangeably. The term "climate change scenario" refers to a representation of *the difference* between the plausible future climate and the current or reference climate. A climate change scenario can be viewed as an *interim step* towards constructing a climate scenario.

The scenarios **should not be treated as predictions of what will happen in the future, since they are based on assumptions on increases in GHG concentrations** (plausible does not mean that the scenario is probable!).

11.1.1 Cascade of scenarios

A cascade of scenarios (based on uncertainties) **has to be considered in developing climate and related scenarios for climate change impact**, **adaptation** and **mitigation** assessment.

See also the UNFCCC webinar on approaches for developing climate scenarios (especially from minute 18:30)

11.2 Why do we use scenarios?

- By constructing scenarios based on different assumptions, we can **quantify the impact of *uncertainties*** about climate change. This can be uncertainties about the emissions of GHG, but also uncertainties about how the climate will react to an increase in GHG.
- Scenarios are ***plausible and consistent*** **images of the future,** based on our current knowledge of the climate system and about potential changes in GHG concentrations.
- Scenarios **help us to *understand climate change impacts*** and **determine key vulnerabilities**. They can also be used to *evaluate adaptation strategies.*

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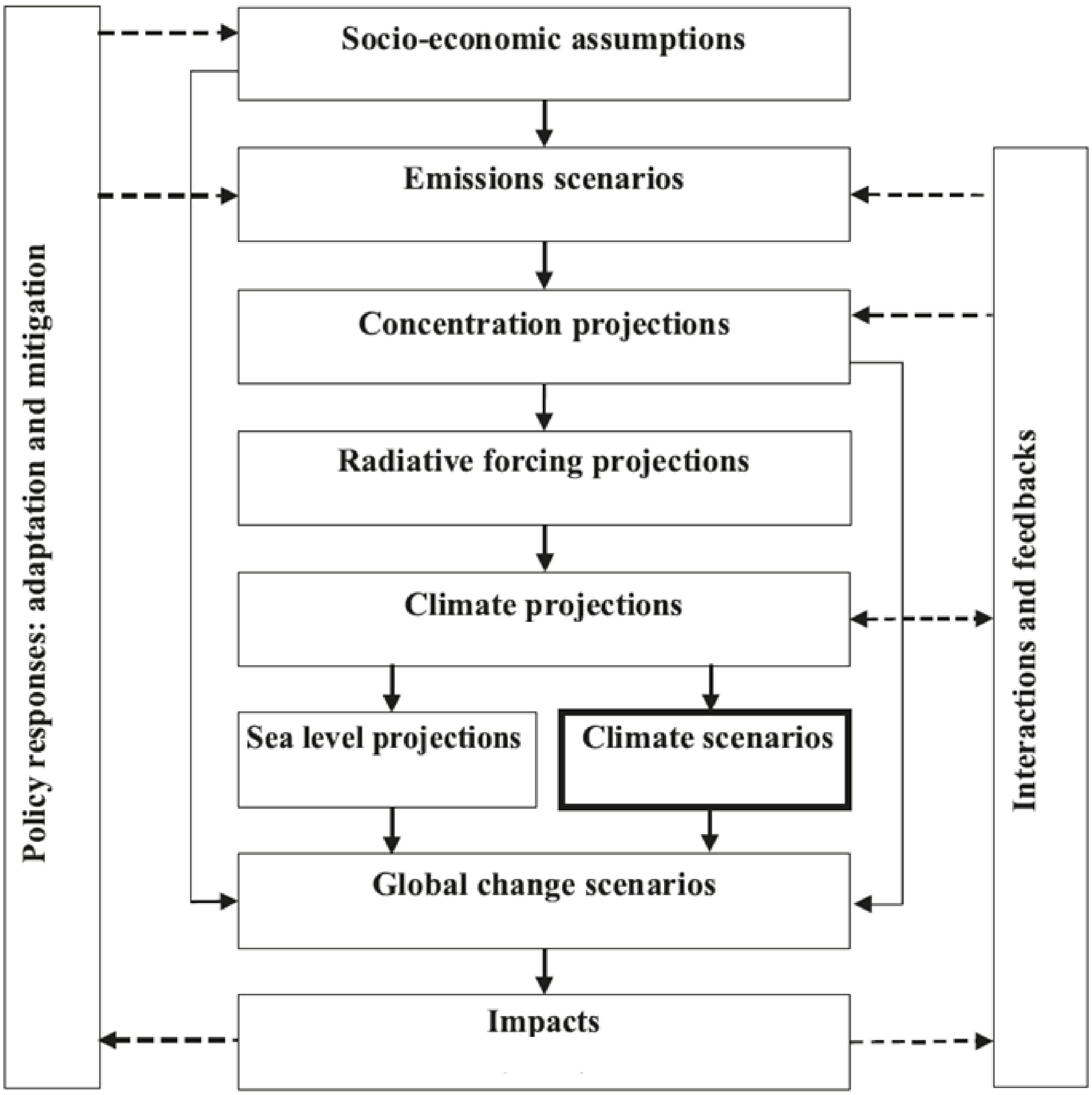

Figure 11.1: cascade

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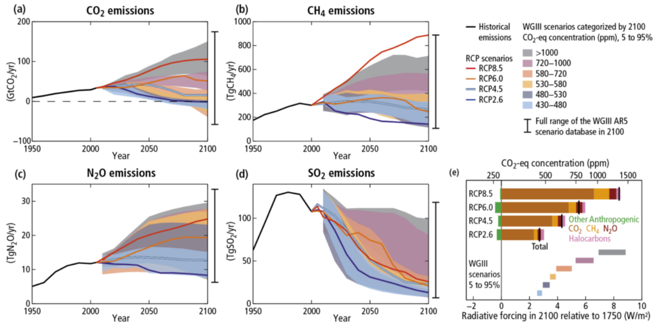

Figure 11.2: ipcc-scenarios

11.3 Constrution of IPCC scenarios

11.3.1 Types of scenarios

The Intergovernmental Panel on Climate Change - Task Group on Data and Scenario Support for Impact and Climate Assessment (IPCC-TGICA) classified climate scenarios into three main types (IPCC-TGICA, 2007), based on how they are constructed. These are:

- **synthetic scenarios**: particular climate elements are changed by a realistic arbitrary amount, for example, adjustment of temperature variable by +1, +2, and +3°C from a reference state, without the use of climate models.
- **analogue scenarios**: using a temporal analogue (using past climate record) or a spatial analogue to represent the possible future climate.
- **climate model based scenarios**: use outputs from Global Climate Models (**GCM**) or Regional Climate Models (**RCM**). They usually are constructed by **adjusting a baseline climate** (typically based on regional observations of climate over a reference period) by the absolute or proportional change between the simulated present and future climates.

The IPCC scenarios and the national climate scenarios that will be discussed later are all climate model based scenarios.

11.3.2 Steps in producing scenarios

The three main steps for developing IPCC climate change scenarios for the Fifth Assessment Report (AR5) in 2013 were:

- **Developing emission scenarios** and translating them to **Representative Concentration Pathways (RCP)** using **Integrated Assessment Models (IAMs).** The RCPs were designed in such a way that they represent a wide range of radiative forcing of the climate system at year 2100 and thus GreenHouse Gas (GHG) concentrations.
- **Simulating the effect of different RCP's** on the climate with a large number of **dynamical Earth System Models** (ESMs).
- The **IPCC climate scenarios are the difference of these projections compared to the reference climate**, in the AR5 report the period 1986-2005 (mean changes per RCP are determined and the probable range).

For several socio-economic development pathways the emissions of the various GHGs are determined (figures a-d).

Some GHGs have a stronger radiative forcing than others. The **radiative forcing of all GHG's is summed and expressed as the CO 2 -equivalent concentration** (figure e; the CO 2 concentration that would give this radiative forcing).

The names of the RCP's indicate the radiative forcing of each scenario around year 2100.

For **IPCC** especially the **climate model runs from the Coupled Model Intercomparison Project (CMIP) are used**. The range in model results for each RCP gives an indication of the uncertainties associated to the climate system reaction to the increase of GHG concentrations. **Up to about year 2050 the ranges of the 4 RCP's greatly overlap**.

The **mean change in global temperature** (and other climate variables) over the results of the large number of climate model simulations for each RCP is **calculated and compared to the reference period 1986-2005**. The probable range covering about two-thirds of the range of the climate model simulations is represented by the bands around the thick lines.

11.4 National climate scenarios: why constructing them? and why are there differences?

National climate scenarios, in addition to the global IPCC climate scenarios, are developed in order to:

- **Translate IPCC reports to the national scale**: IPCC reports do not provide results for individual countries.
- Support the **national climate adaptation policy**, for which regional or local climate change information is needed.
- Provide a **common framework for adaptation planning** in **different sectors** of society.
- **Support impact studies** or develop adaptation options and strategies. With this information questions from various sectors in society can be answered. Moreover, national climate scenarios can be **used for long-term planning of public and private sector organisations**, to reduce exposure to climate risks and exploit potential new opportunities.
- Provide **more relevant and appealing information on the national (or regional) scale in order to raise awareness**.

11.4.1 Overview of national scenarios (January 2019)

Below links to national climate scenarios in various European countries (latest updated Jan. 2019). The timing for translating the global scenarios to national climate scenarios differs in each country. Methods used, the reference period, the time horizons, etc. may also differ.

Source: updated from Bessembinder et al., 2018

11.4.2 Reasons for differences between national scenarios

National climate scenarios of European countries differ in many aspects. Although they generally use the global climate models adopted in the IPCC reports, **they also use results form large European projects on climate modelling for which downscaling of results from GCMs is done with RCMs**, for example **PRUDENCE**, **ENSEMBLES**, **EUROCORDEX**.

Factors

Which **global and regional climate models** are used, **reference** period, **RCPs**, **time horizons**, climate **variables** are included may depend on the availability and accessibility of the climate model output in a country. Moreover, the climate models that the organisation(s) developing the national/regional climate scenarios can run, the **purpose of the development** of climate scenarios, the **relevant areas** for the country/region and the **sectors included** may also influence the way national climate scenarios are developed.

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Country	Website with regional climate scenarios	Year publication
Austria	www.bmlfuw.gv.at/umwelt/klimaschutz/klimapolitik national/anpassungsstrategie/klimaszenarien.html	2015
Belgium	www.kuleuven.be/hydr/cci/CCI-HYDR rp.htm	2015
Denmark	www.dmi.dk/fileadmin/user upload/Rapporter/DKC/2014/Klimaforandringer dmi.pdf	2014
France	www.drias-climat.fr/decouverte	2014?
Finland	www.geophysica.fi/pdf/geophysica 2016 51 1-2 017 ruosteenoja.pdf	2016
Germany	www.kliwas.de/	2015
	www.klimaatlas.de/	?
	reklies.hlnug.de/home/	2017
Ireland	www.epa.ie/pubs/reports/research/climate/Research Report 244.pdf	2018
Netherlands	www.climatescenarios.nl/	2014
Norway	klimaservicesenter.no/faces/desktop/scenarios.xhtml	2017
Portugal	portaldoclima.pt/pt/	2015?
Spain	www.aemet.es/es/serviciosclimaticos/cambio climat	2014?
Sweden	www.smhi.se/en/climate/climate-scenarios	2014
Switzerland	www.meteoswiss.admin.ch/home/latest-news/news/climate-scenarios-ch2018.html	2018
United Kingdom	www.metoffice.gov.uk/research/collaboration/ukcp	2018

Figure 11.3: national-scenarios

11.4.3 Examples of differences between national scenarios

Some differences between the national climate scenarios in some European countries (for the scenarios per country mentioned in the table on slide 16).:

Source: updated from Bessembinder et al., 2018

11.4.4 RCPs used in national scenarios

Although there are 4 RCPs they are not always used for the construction of national/regional climate scenarios. **In almost all cases of the table in the previous slide RCP8.5 and RCP4.5 were used**.

- RCP**8.5** represents the **highest emissions and consequently the largest change in climate** (it was often refered to as business-as-usual or worst-case).
- RCP**4.5** is often used to indicate the **lower probable climate change**. Although RCP2.6 is possible, it is not considered very likely. Moreover, there are also less climate model runs with RCP2.6.
- **In some scenarios RCP2.6 is used to construct the climate scenario with the lowest climate change and RCP8.5 for the higest climate change, leaving out the others.**
- RCP**6.0** is not used much in the scenarios as **it does not necessarily add much additional information when showing the range of possible climate change.**

In older national climate scenarios, the SRES (Special Report on Emission Scenarios) emission scenarios may still be used.

Example: national scenario of the Netherlands

In the figure below the selection of climate scenarios is **based on information from RCP8.5 and RCP4.5**. RCP8.5 represents high levels of climate change when few mitigation measurements are taken, and RCP4.5 low levels of climate change when many mitigation measurements are taken. RCP2.6 was considered less relevant.

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Country	Reference period	Time horizons	RCPs or emissions scenarios
Austria	1971-2000	2021-2050, 2071-2100	RCP4.5, RCP8.5
Belgium	Not defined explicitly	30, 50 and 100 years ahead	Low, medium, high (RCP4.5 and RCP8.5 used)
Denmark	1986-2005	2046-2065, 2081-2100	RCP2.6, RCP4.5, RCP6.0, RCP8.5
France	1976-2005	2021-2050, 2041-2070, 2071-2100	RCP 2.6, RCP4.5, RCP8.5
Germany (Kliwas)	1961-1990	2021-2050, 2071-2100	Range of models (A1B model runs used)
Ireland	1971-2000	2021-2050, 2071-2100	RCP2.6 and RCP8.5 (also runs for RCP4.5 used)
Netherlands	1981-2010	2016-2045, 2036-2065, 2071-2100	4 based on range of change of global temperature + circulation (runs for RCP4.5-8.5 used)
Norway	1971-2000	2031-2060, 2071-2100	RCP4.5, RCP8.5
Portugal	1971-2000	2011-2040, 2041-2070, 2071-2100	RCP4.5, RCP8.5
Spain	1961-1990, 1961-2000	2046-2065, 2081-2100	RCP4.5, RCP6.0, RCP8.5
Sweden	1971-2000	2011-2040, 2041-2070, 2071-2100	RCP2.6, RCP4.5, RCP8.5 (A1B)
Switzerland	1981-2010	2020 - 2049, 2045 - 2074, 2070 - 2099	RCP2.6, RCP4.5, RCP8.5
United Kingdom	1981-2010, 1961-1990	2020-2039 to 2080-2099 (subsequent 20-year periods)	RCP2.6, RCP4.5, RCP6.0, RCP8.5

Figure 11.4: differences-scenarios

Example: national scenario of Switzerland

Range of climate change ("Starke der Anderung") in the CH2018 climate scenarios for Switzeland compared to what is currently used to describe the climate ("Bisherige Norm"). For RCP8.5 and RCP2.6 the mean change in an **ensemble of EUROCORDEX models** is shown ("erwartet") and the possible range ("moglich") (Source: CH2018, 2018)

In the figure below shows the Swiss CH2018 climate scenarios RCP8.5 and RCP2.6 used to describe the range of levels of climate change for the future. RCP8.5 represents high levels of climate change when few mitigation measures are taken ("Ohne Klimaschutz"), and RCP2.6 represents what the levels of climate change may look like when many mitigation measures are taken ("Mit Klimaschutz"). The RCPs selection for the Swiss case differs from that in the Netherlands.

11.4.5 Selection of reference period

Diverse criteria drive the selection of the reference period:

- Same reference period as the **former national climate scenarios to make comparison easier**.
- Two reference periods may be used: a recent period (e.g. 1981-2010) and a previous climate scenarios (e.g. 1961-1990) reference period. This makes **comparison with earlier scenarios easier**.
- Same reference period as that used in IPCC to **make comparison with IPCC easier**.
- Same reference period used for the "climate normals" (to describe whether the weather is above or below normal). The **availability of the description of these normals (and the ranges) makes it easier to understand what will be the future climate**.
- **Most recent period of 30 years, since that comes closest to what society will consider the "current climate"**.

In most cases a **period of 30 years is used as reference period**. However, since there maybe a considerable trend in climate in 30 years, a period of 20 years may be used as reference. For example **IPCC used 1986-2005 as reference period in the Fifth assessment report**.

Example selection of reference period (Switzerland):

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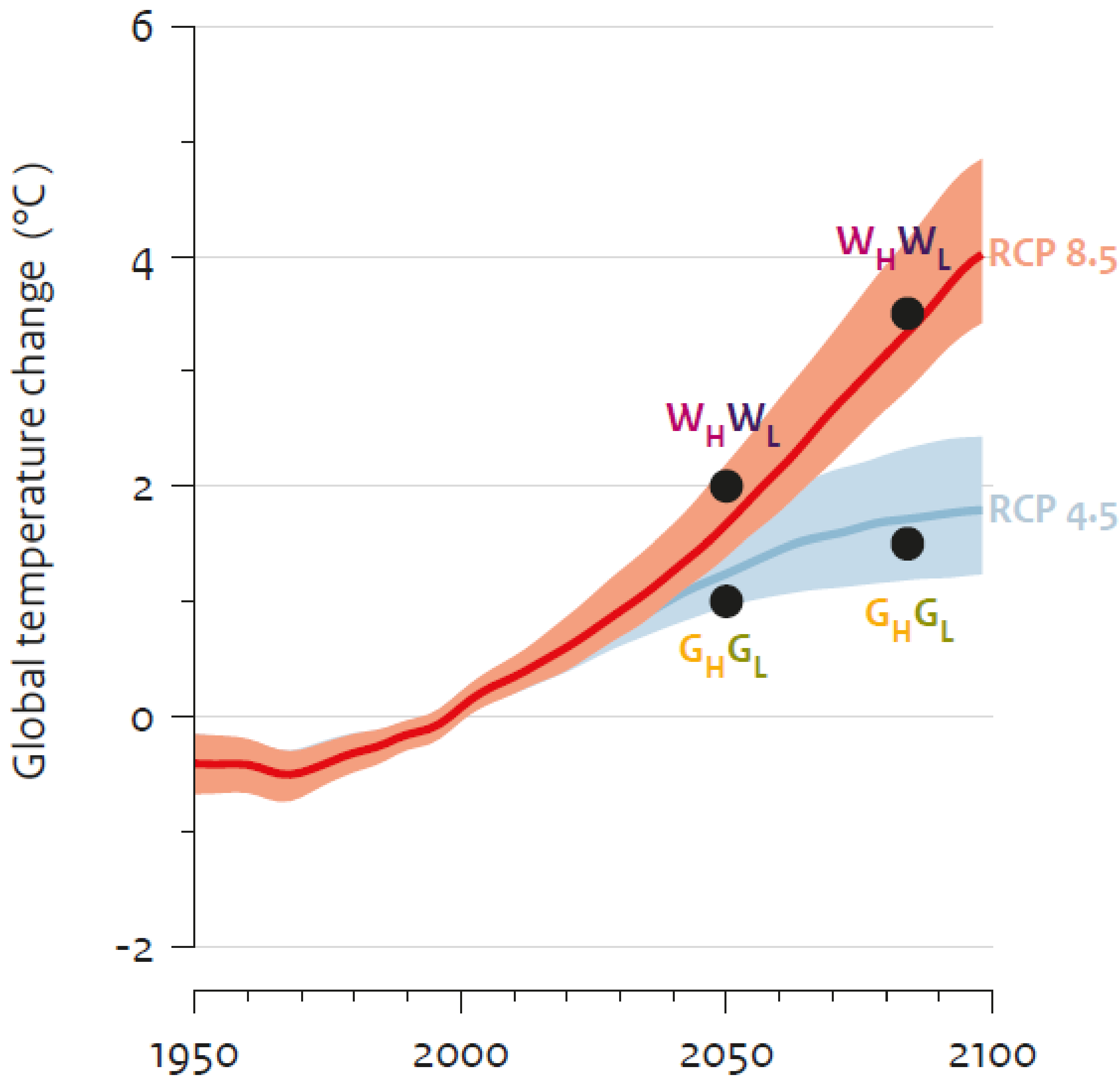

Figure 11.5: netherlands2

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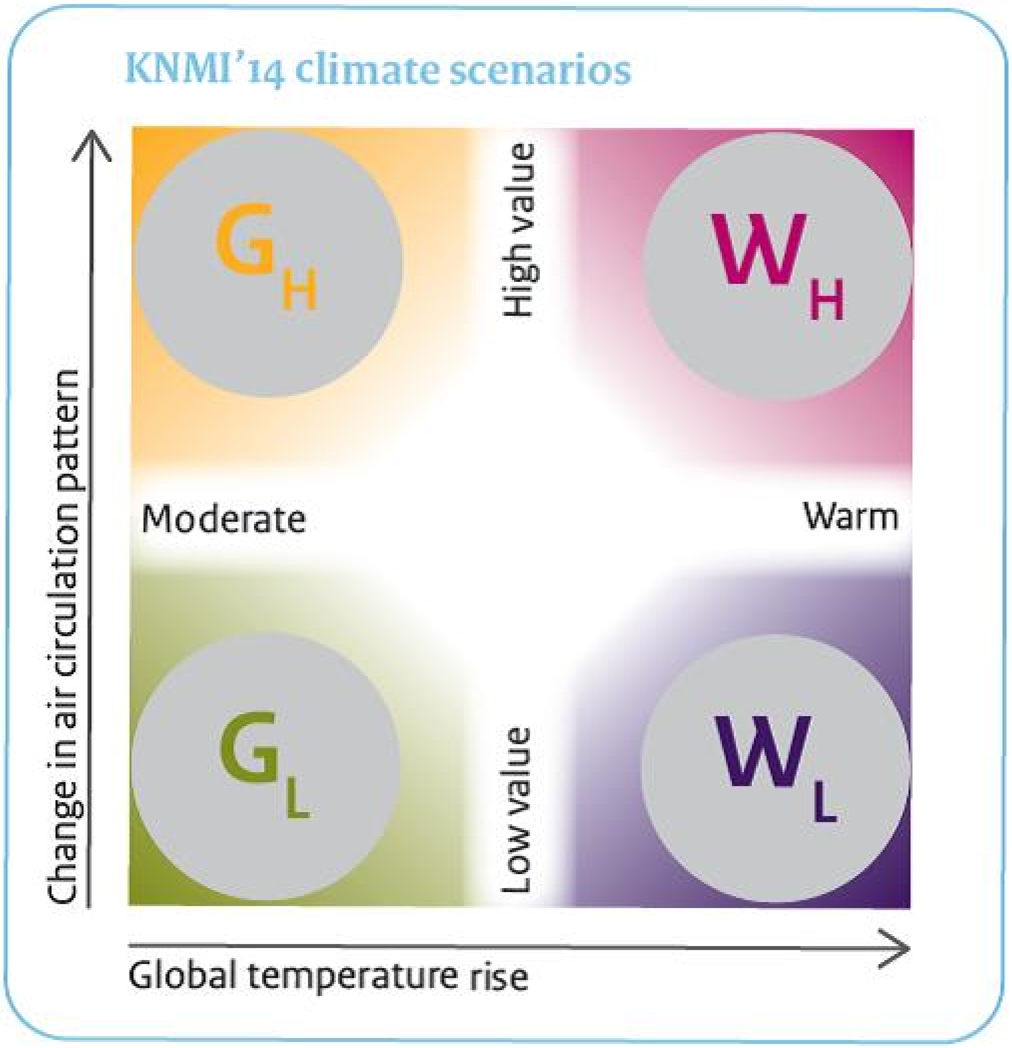

Figure 11.6: netherlands1

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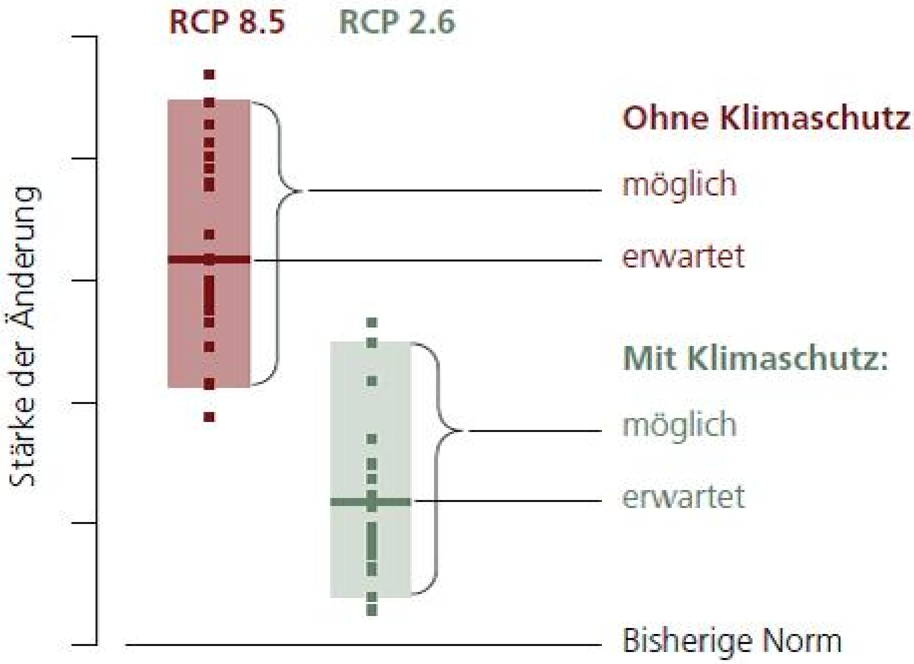

Figure 11.7: switzerland

The table below shows that the **reference period (last row) used in Switzerland has changed somewhat with the various sets of climate scenarios publised in 2007, 2011 and 2018**. For the CH2018 scenarios the most recent "normal period" 1981-2010 is used. This dataset may have not been available in 2011 therefore, the most recent 30 year period 1980-2009 was used in CH2011. For the CH2007 scenarios, "1990" is mentioned as reference (probably meaning the 30 year period around this year, 1976-2005). This shows that **criteria to choose a reference period selection may change over time**.

Source: CH2018, 2018

11.4.6 Selection of time horizon

The selection of the future time horizons greatly differs for each country:

- In most cases a time horizon around the **middle of this century** is chosen, as well as a time horizon at the end of the 21st century.
- In some countries a **"near-future" time horizon is also used, for example 2021-2050**. The change in this period, compared with the reference period is often not significant and differences between scenarios are often not significant.
- **Most countries use 30 year time slices** but **20 year time slices are not uncommon**. A 30 year period is commonly used to describe the climate. However, since a 30 year period can contain clear trends, especially for temperature, 20 year time slices are also used regularly nowadays.

Example of time horizon selection: the Netherlands & Switzerland

In the figures below year 2050 (2036-2065) and 2085 (2071-2100) are chosen as time horizons for the KNMI14 scenarios in the Netherlands. In Switzerland the time horizons 2035 (2020-2049), 2060 (2035-2074) and 2085 (2070-2099) for the CH2018 scenarios are used.

Average summer temperature in the Bilt, ***Netherlands****: observations (three 30-year averages in blue),* Drive/AdaptEconII/courses/Copernicus Basic Learning Path/figures/switzerland-reference.bb

	CH2018	CH2011	CH2007
Model Ensemble	Euro-CORDEX [177, 198]	EU FP6 ENSEMBLES [352]	EU FP5 PRUDENCE [59]
Resolution	12 km (0.11°) and 50 km	25 km (0.22°)	50 km (0.44°)
Number of Simulations	26 (12 at 12 km, 14 at 50 km)	14	16
Number of GCMs	13	6	2
Number of RCMs	9	10	8
Simulation Period	1971 - 2100	1951 - 2100	1961 - 1990 and 2071 - 2100
Scenario Periods	2020-2049 (“2035”), 2045 - 2074 (“2060”), 2070 - 2099 (“2085”)	2020-2049 (“2035”), 2045 - 2074 (“2060”), 2070 - 2099 (“2085”)	2030, 2050, 2070
Reference Period	1981 - 2010	1980 - 2009	1990

Figure 11.8: switzerland-reference

KNMI’14 scenarios (2050 and 2085, in four colours) and natural variations (in grey, for 30-year averages; Source: KNMI, 2015)

The reference period and time horizons used in the CH2018 climate scenarios for ***Switzerland*** *(Source: CH2018, 2018)*

11.4.7 Selection of global climate models (GCMs)

Often during the development of national (or regional) climate scenarios the **most recent GCMs** (or the more sophisticated Earth System Models) are first analysed to discover the **range of change** they show for, among others, temperature and precipitation. Various approaches can be used:

- **Use all**: use the majority of available GCMs and leave out only the models that perform the worst for the country of interest. In practice this means that the **majority of GCMs used in the IPCC reports or the CMIP projects are taken into account**. Hardly any of these models perform poorly for all climate variables for the country of interest.
- **Only use the best**: only select the **GCMs that perform the best for the region or country of interest,** i.e. the climate models that simulate better the current climate and past trends (small bias, correct amplitude of temperature and precipitation throughout the year, good air circulation patterns, etc.).

The choice of climate models is also partly determined by the **ease and availability of data** (CMIP5 data are available through the Climate Data Store). For further downscaling a selection of RCMs may be used.

Example of selection of climate models: the Netherlands

For the development of the **KNMI14 climate scenarios** (Netherlands) a **large range of GCMs (and RCPs)** was used to determine the range of potential global temperature change and the related local temperature range in the Netherlands. In the **former KNMI06 climate scenarios only the best performing GCMs** for air circulation were used (however, this **covered more or less the range of all available GCMs**).

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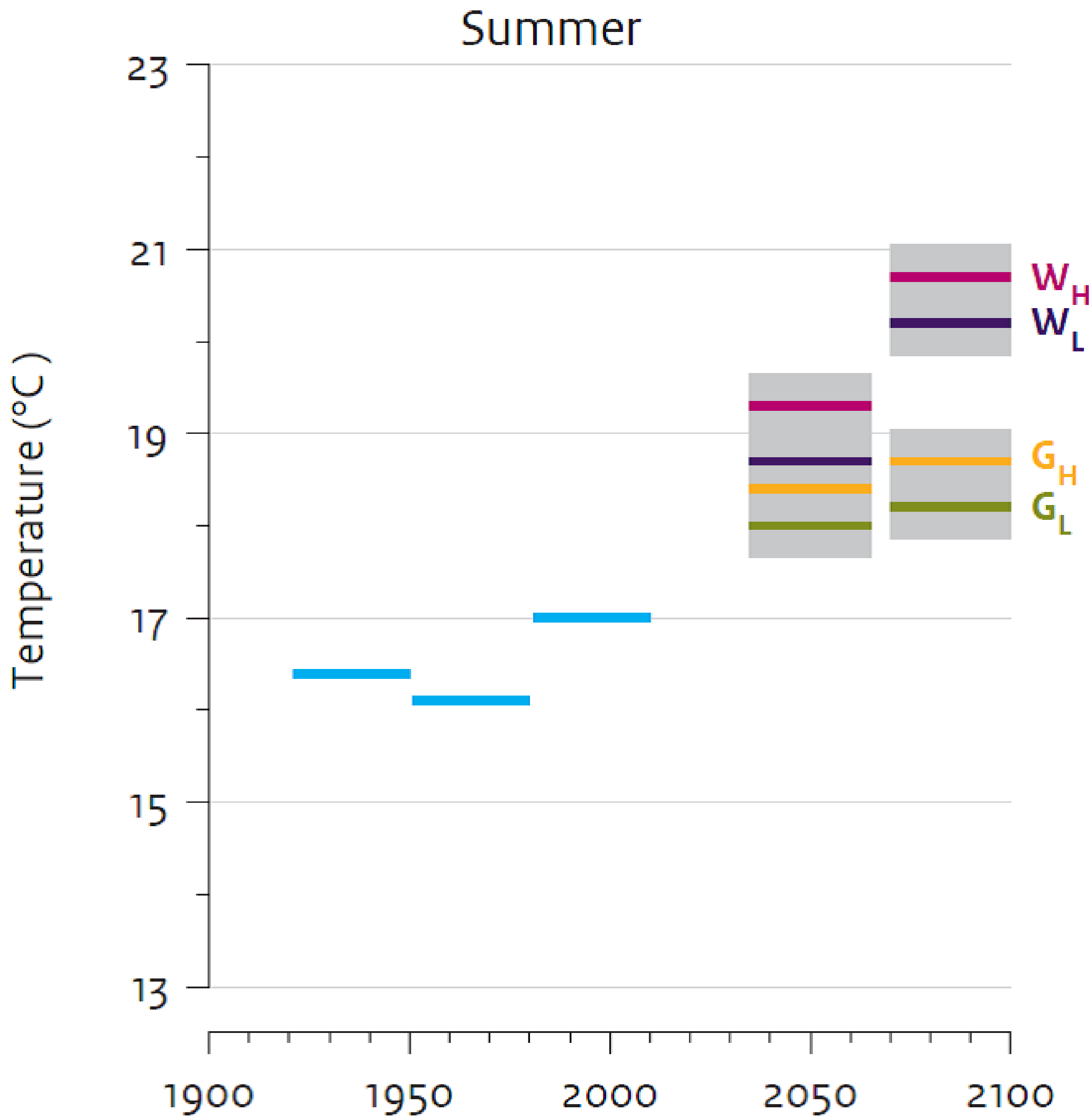

Figure 11.9: horizon-netherlands

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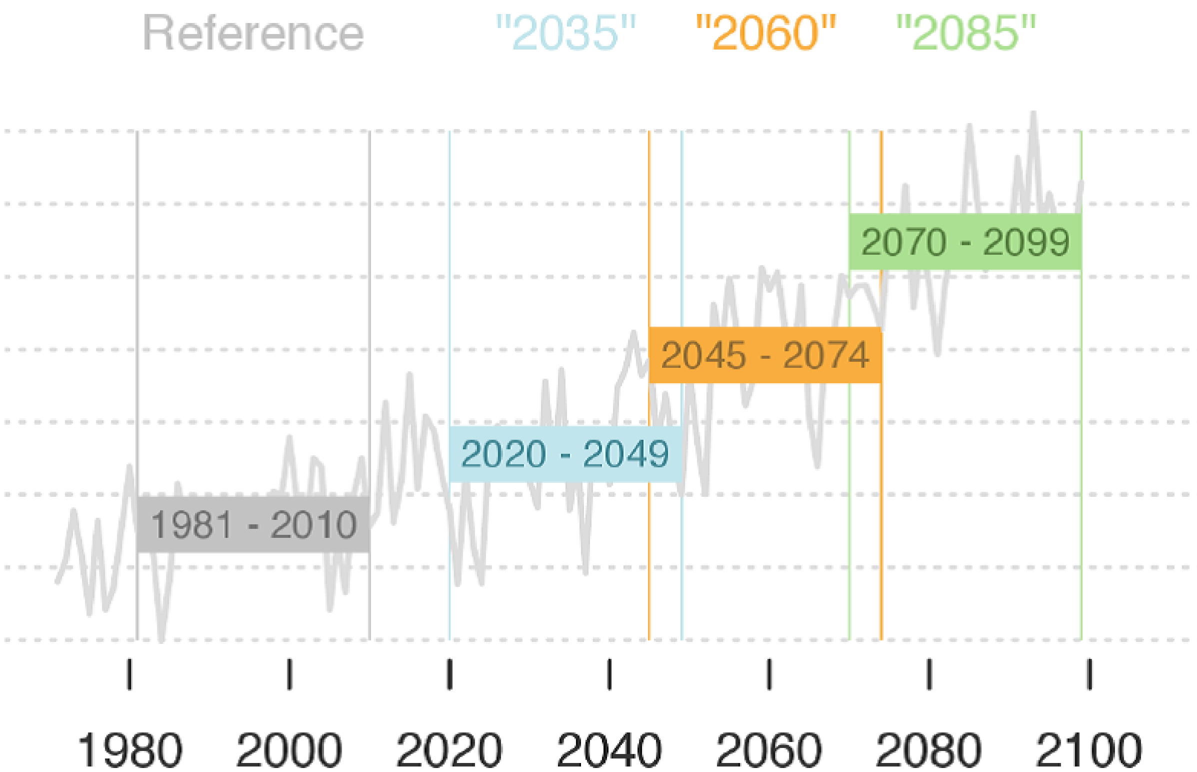

Figure 11.10: horizon-switzerland

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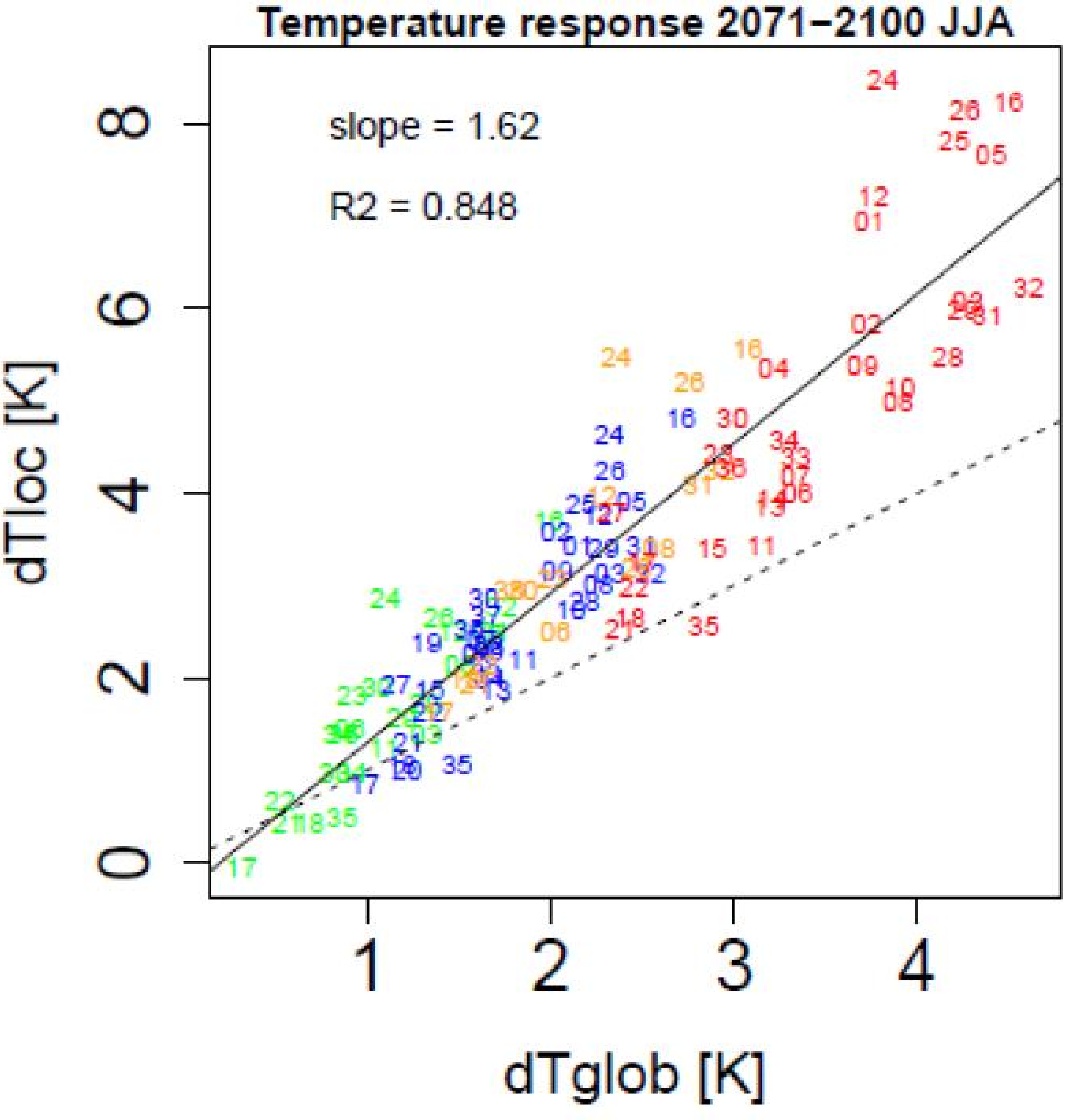

Figure 11.11: netherlands-gcm

Figure: Temperature change in the Rhine basin (dTloc) per GCM/RCP combination in 2071-2100 relative to 1976-2005 as function of global temperature change (dTglob). Numbers= GCMs; green=RCP2.6, blue=RCP4.5, orange=RCP6.0, red=RCP8.5; dotted line 1:1. (Source: KNMI, 2014)

Example of selection of climate models: Switzerland

For the development of the CH2018 climate scenarios (Switzerland), the range of seasonal temperature change in the used **CORDEX-GCMs and CORDEX-RCMs** was compared with the range in temperature change for the IPCC AR5 GCM's for Switzerland. Although the used GCM's (CORDEX) do not always cover the same range as the IPCC GCMs, the **chosen RCMs cover most of the range presented by the IPCC GCMs**.

Figure: Temperature change per season for Switzerland around 2085 and RCP8.5, based on various model ensembles. Quantile-based uncertainty ranges (colored bars 5-95%) and individual models (points) are shown. Green bars=CORDEX RCMs, left grey bars=CORDEX-GCMs, right grey bars=IPCC-AR5-GCMs (Source: CH2018, 2018)

Example selection of Global Climate Models

Climate scenarios generally aim to show the possible range of changes in the future or a large part of this range. Therefore, looking at the range of changes in an ensemble of GCMs is a useful first step. **If certain GCMs show a decrease in seasonal precipitation and others show an increase in annual precipitation, it may be good to have this expressed in the national climate scenarios**. The **figures below show the percentiles in such an ensemble**. They show that for the UK and Netherlands some GCMs have an increase (75% percentile) and others a decrease of precipitation in the summer half year (50% and 25% percentiles).

Figure: Change in precipitation sum in 2081-2100 in April-September relative to 1986-2005 for North and Central Europe. Middle: average of the GCM ensemble, left 25% percentile, right: 75% percentile. Hatching: 20-year mean differences less than the standard deviation of model-estimated present-day natural variability (Source: IPCC AR5 (2013) WG1 Annex1)

11.4.8 Selection of RCMs for downscaling

Although there are several methods for downscaling (statistical and dynamical) often **dynamical downscaling with the help of RCMs** is used. These models help to get a more detailed view on the effects of global climate change for a country and its regional differences. Either an **ensemble of RCMs** is used to construct the national climate scenarios or **one RCM** is used to downscale the changes represented by various GCMs.

In Switzerland the ensemble of EURO-CORDEX RCMs is used (see table:various GCM-RCM combinations), whereas in the Netherlands an ensemble of various runs with the GCM-RCM combination EC-Earth (GCM) and RACMO (RCM) was used for downscaling.

Figure: EURO-CORDEX runs used for CH2018 climate scenarios. Checkmarks indicate existing simulations, circles mark the simulations used for multi-model combination, and empty dashed circles show the simulations substituted by pattern scaling (source: CH2018, 2018)

11.4.9 Approaches to use ensembles of climate models

Different approaches can be used to construct climate scenarios:

- From the ensemble of available climate models, **individual model runs** can be chosen to represent one scenario (for various time horizons), e.g. for high and for low emissions. Often they are chosen so that they span a considerable part of the uncertainty in the ensemble.
- On the basis of the ensemble of climate model runs **for all used RCPs** the mean change in all model runs is calculated together with specific percentiles (e.g. 25% and 75%). The percentiles are than considered scenarios. Often such percentiles are interpreted as probabilities however, they only give an indication on how often a certain change is observed in the ensemble used.

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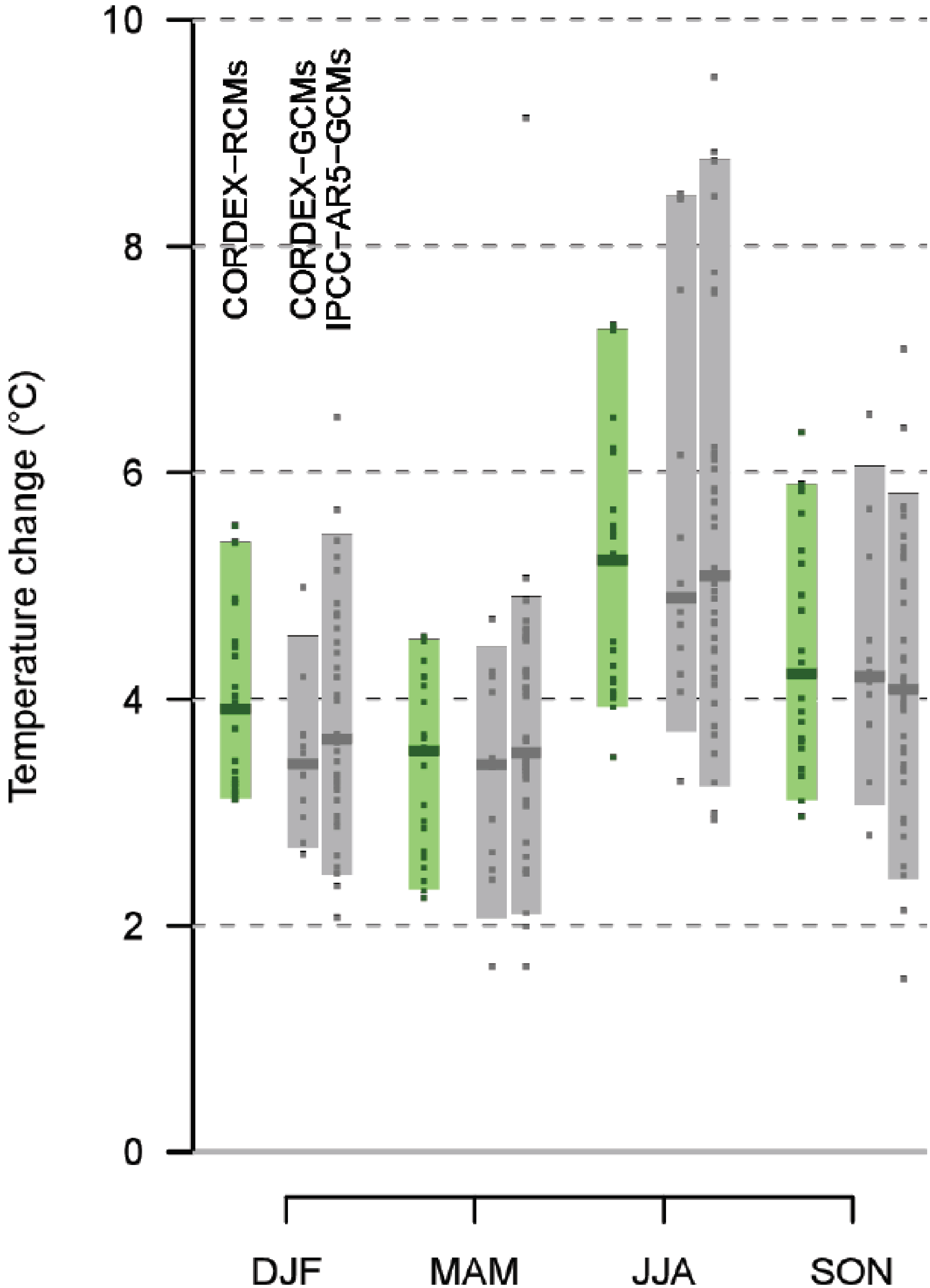

Figure 11.12: switzerland-gcm

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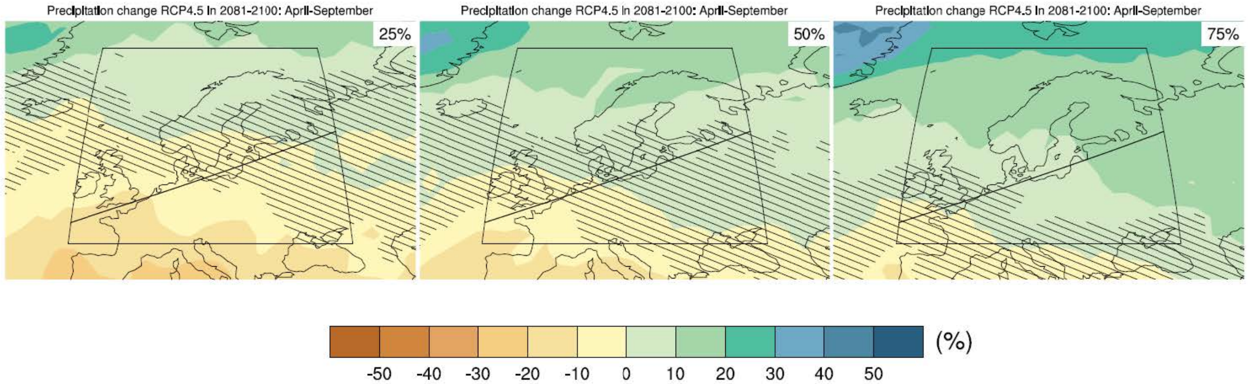

Figure 11.13: selection-global-gcm

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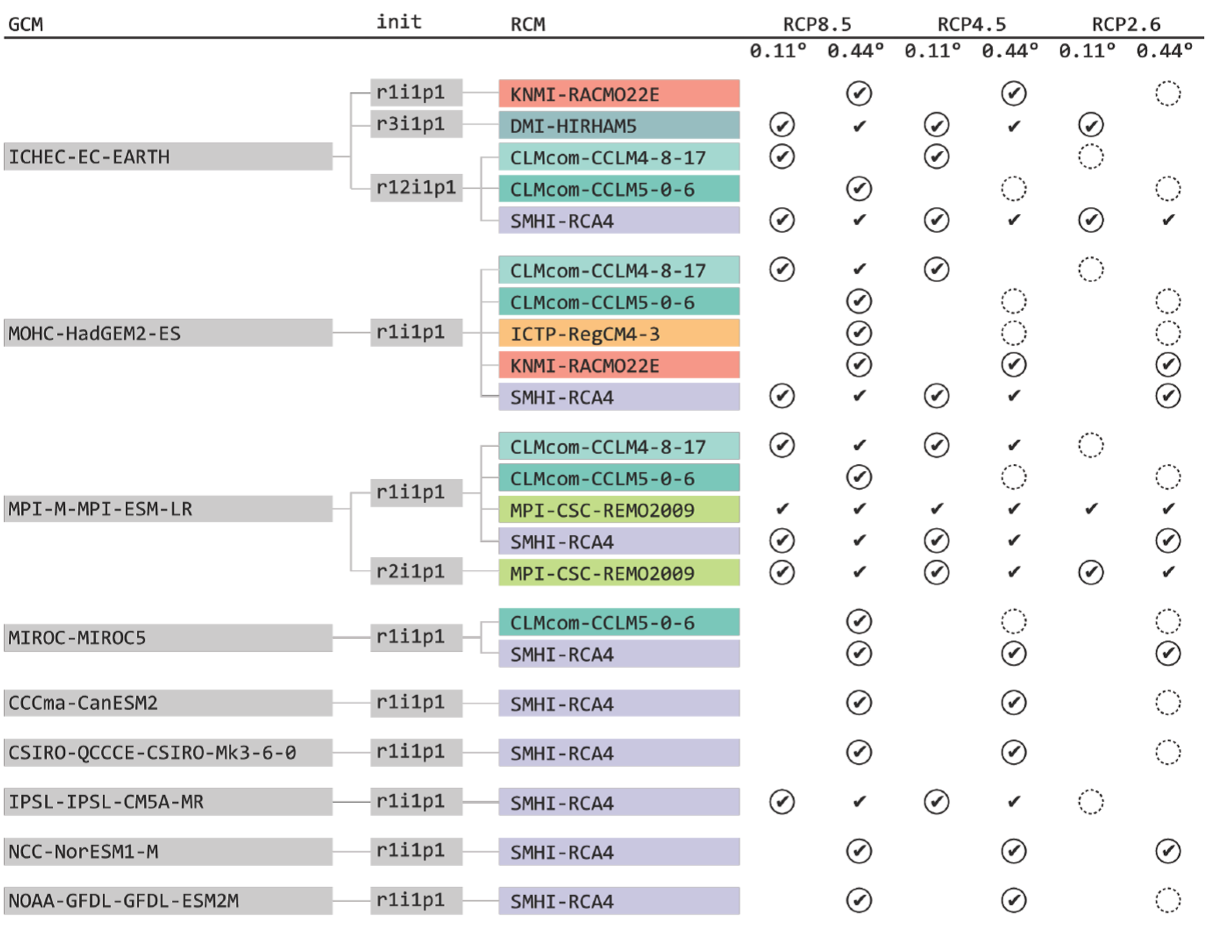

GCM	init	RCM	RCP8.5 0.11°	RCP8.5 0.44°	RCP4.5 0.11°	RCP4.5 0.44°	RCP2.6 0.11°	RCP2.6 0.44°
ICHEC-EC-EARTH	r1i1p1	KNMI-RACMO22E		(✔)		(✔)		◌
	r3i1p1	DMI-HIRHAM5	(✔)	✔	(✔)	✔	(✔)	
	r12i1p1	CLMcom-CCLM4-8-17	(✔)		(✔)		◌	
		CLMcom-CCLM5-0-6		(✔)		◌		◌
		SMHI-RCA4	(✔)	✔	(✔)	✔	(✔)	✔
MOHC-HadGEM2-ES	r1i1p1	CLMcom-CCLM4-8-17	(✔)	✔	(✔)		◌	
		CLMcom-CCLM5-0-6		(✔)		◌		◌
		ICTP-RegCM4-3		(✔)		◌		◌
		KNMI-RACMO22E		(✔)		(✔)		(✔)
		SMHI-RCA4	(✔)	✔	(✔)	✔		(✔)
MPI-M-MPI-ESM-LR	r1i1p1	CLMcom-CCLM4-8-17	(✔)	✔	(✔)	✔	◌	
		CLMcom-CCLM5-0-6		(✔)		◌		◌
		MPI-CSC-REMO2009	✔	✔	✔	✔	✔	✔
		SMHI-RCA4	(✔)	✔	(✔)	✔		(✔)
	r2i1p1	MPI-CSC-REMO2009	(✔)	✔	(✔)	✔	(✔)	✔
MIROC-MIROC5	r1i1p1	CLMcom-CCLM5-0-6		(✔)		◌		◌
		SMHI-RCA4		(✔)		(✔)		(✔)
CCCma-CanESM2	r1i1p1	SMHI-RCA4		(✔)		(✔)		◌
CSIRO-QCCCE-CSIRO-Mk3-6-0	r1i1p1	SMHI-RCA4		(✔)		(✔)		◌
IPSL-IPSL-CM5A-MR	r1i1p1	SMHI-RCA4	(✔)	✔	(✔)	✔	◌	
NCC-NorESM1-M	r1i1p1	SMHI-RCA4		(✔)		(✔)		(✔)
NOAA-GFDL-GFDL-ESM2M	r1i1p1	SMHI-RCA4		(✔)		(✔)		◌

Figure 11.14: euro-cordex-runs

- The mean change of the ensemble of model runs **for each RCP** is calculated together with specific percentiles (e.g. 25% and 75%). In this way "probabilistic" estimates of climate change per RCP are constructed.

Example of climate model construction: UK and Switzerland

Probabilistic estimates of climate change for each RCP are constructed for both the UKCP18 (UK) and CH2018 (Switzerland) climate scenarios.

Figure: Range (5-95%) of air temperature change per season compared to 1981-2010 for RCP8.5 for around 2035 (blue), 2060 (orange) and 2085 (green) for the northwestern part of Switzerland (Source: CH2018, 2018)

Figure: Projected change in temperature for the UK region per RCP or SRES scenario from 1981-2000 to 2080-2099 using the probabilistic projections (Source: UKCP18, 2018)

11.4.10 Level of detail in climate scenarios

The level of details and amount of information in the national climate scenarios in the various European countries **differ considerably**. In some countries only the information on annual or seasonal average changes in temperature and precipitation is presented. In other countries information is presented for a large number of climate variables also including extremes. In general, **more detailed information is given in countries where there is a strong interaction with users and where climate scenarios are used to estimate the impact of climate change on several sectors**.

Figure: Example of precipitation indices that are calculated for the Swiss CH2018 climate scenarios (Source: CH2018, 2018)

11.4.11 Additional information delivered with the climate scenarios

In some countries the national climate scenarios consist of a table with changes relative to each climate scenario. In other countries additional information is provided to help users to carry out further impact studies. For example **daily time series**, representative of the various climate scenarios for certain time horizons, can be provided. These time series are often obtained with the help of the underlying climate model runs for the climate scenarios, although **different methods may be used to generate this information** (statistical downscaling, bias correction, delta methods).

Figure: Downscaling and bias removal methods (Source: Bessembinder, 2015)

Example: Switzerland

In Switzerland additional **high resolution gridded datasets** are provided in addition to presenting the changes in various climate variables for various time horizons and RCPs. The figure below shows information on the current and future climate at various weather stations, as well as high resolution gridded datasets for further impact studies. Here **Quantile Mapping (QM, bias-correction method) is used to provide the additional information**:

Figure: Quantile mapping methods and related data products. All variants produced for the entire CH2018 RCM ensemble but for different sets of meteorological variables (Source: CH2018, 2018)

11.4.12 Consistency between climate variables

Depending on the method used, the changes in various climate variables may show more or less consistency. **For further impact analysis consistency among climate variables is often important**, since the impact is determined by various climate variables.

- Climate scenarios that are based on **individual climate model runs** will show **consistency** between the various climate variables, since the climate models have internal consistency (note that statistical downscaling or bias-correction methods may affect the consistency somewhat).

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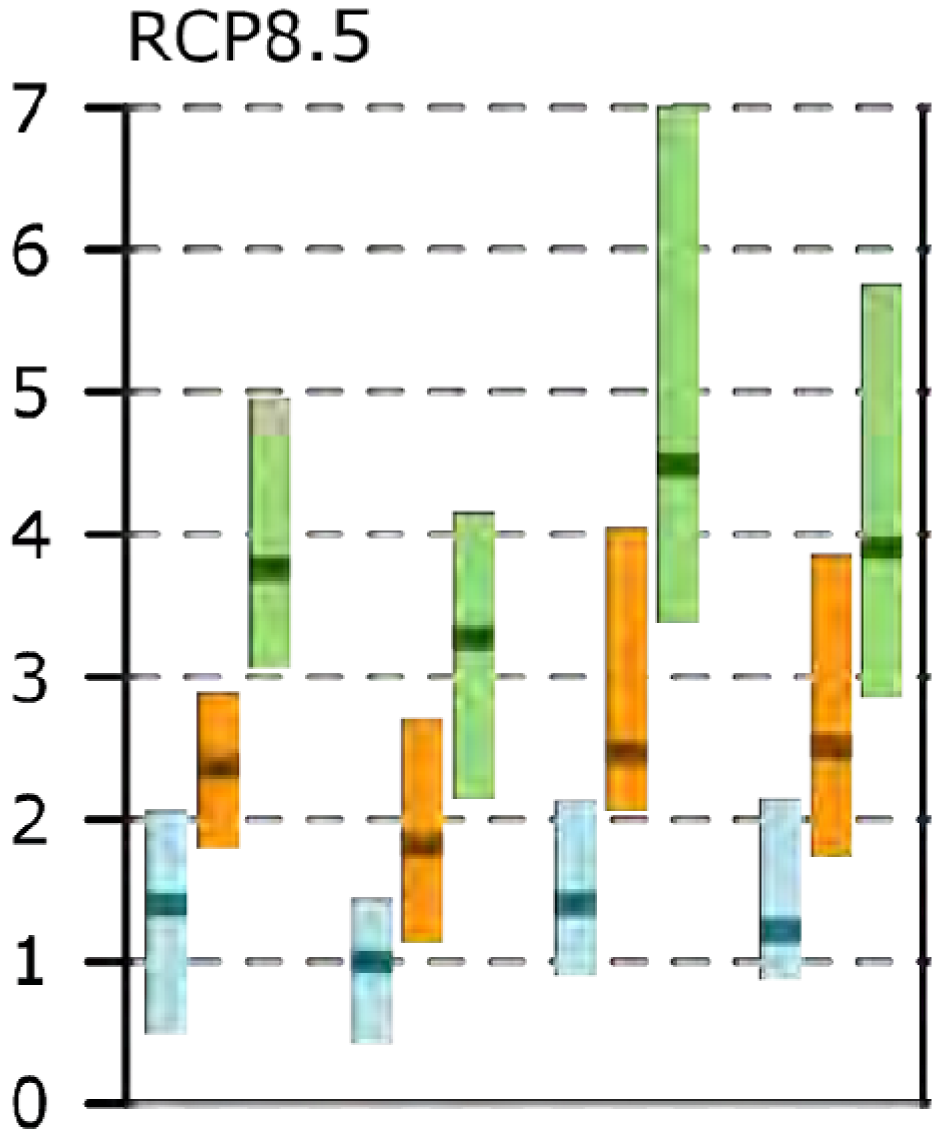

Figure 11.15: temperature-change-0

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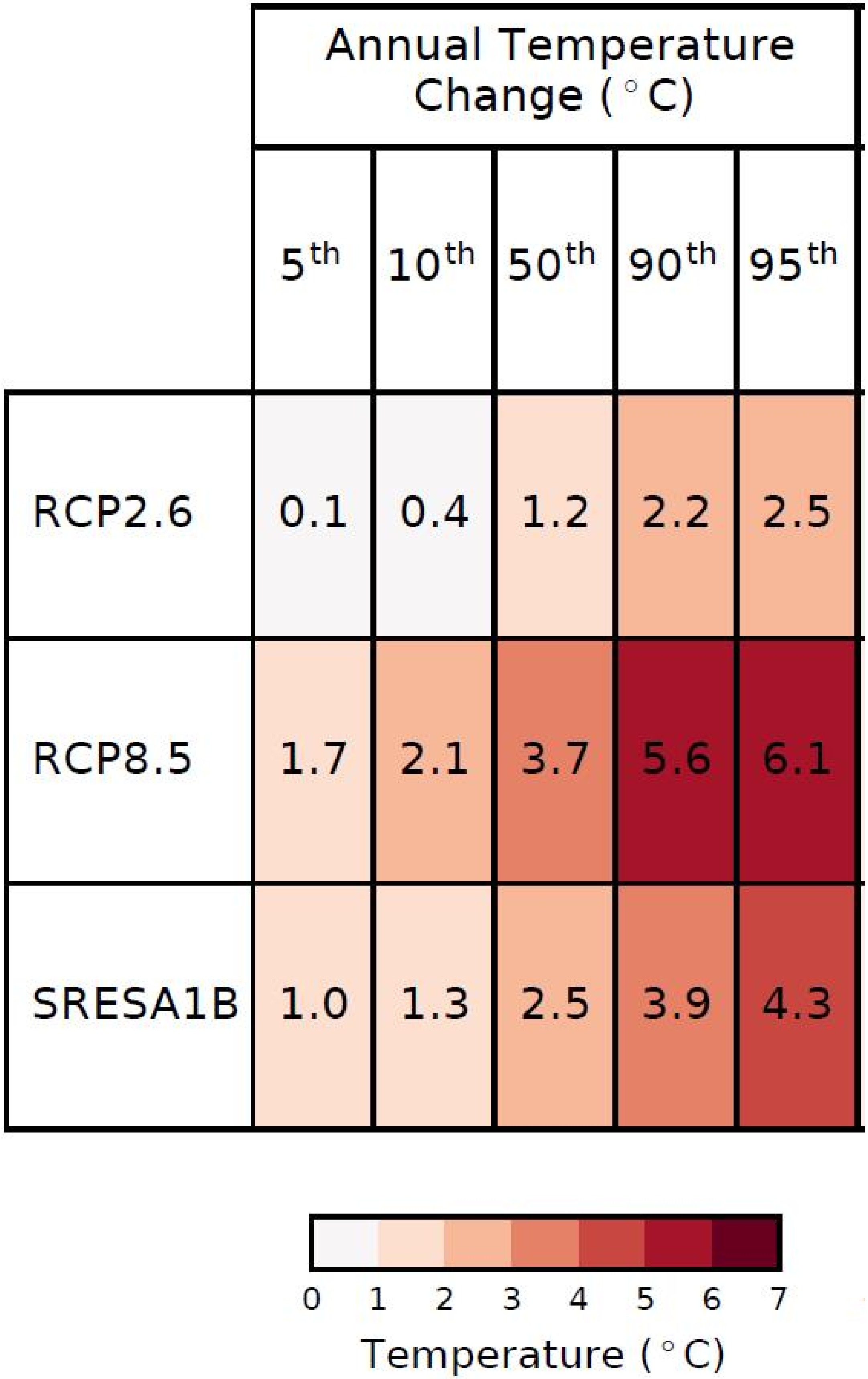

Figure 11.16: temperature-change

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Precipitation indices			
MEA	Mean daily precipitation	mm/d	Seasonal 30yr mean
FRE	Wet-day frequency: frequency of wet days (R>1mm/day)	fraction	Seasonal 30yr mean
INT	Wet-day intensity: mean precipitation amout on wet days	mm/d	Seasonal 30yr mean
Rx1d	Maximum of 1-day precipitation	mm/d	Seasonal 30yr mean
Rx5d	Maximum of 5-day accumulated precipitation	mm/d	Seasonal 30yr mean
Precipitation Percentiles			
Rp90%	90th all-day percentile of daily precipitation	mm/d	Seasonal percentile
Rp95%	95th all-day percentile of daily precipitation	mm/d	Seasonal percentile
Rp99%	99th all-day percentile of daily precipitation	mm/d	Seasonal percentile

Figure 11.17: detail-level

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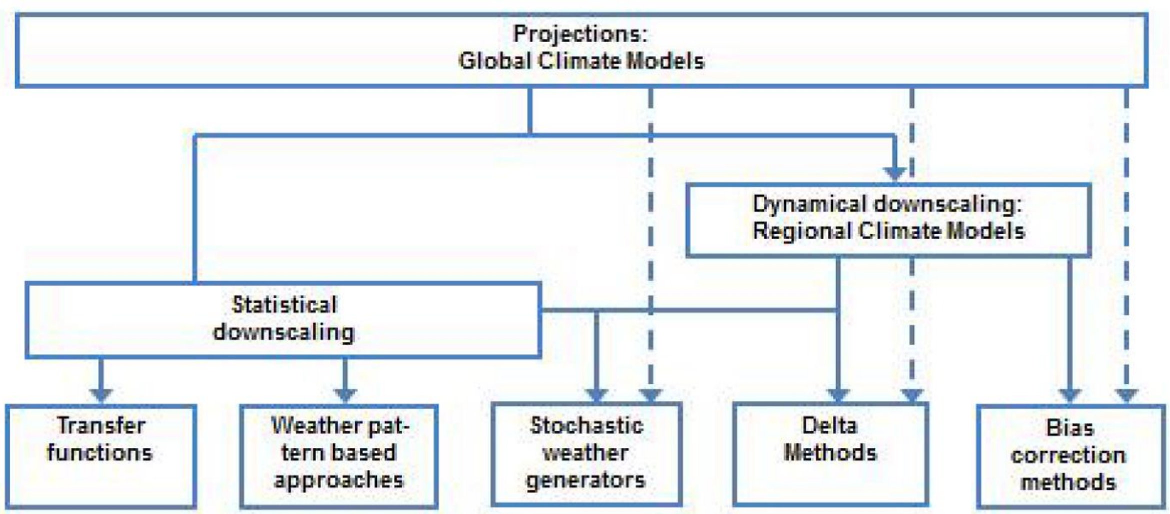

Figure 11.18: additional-data

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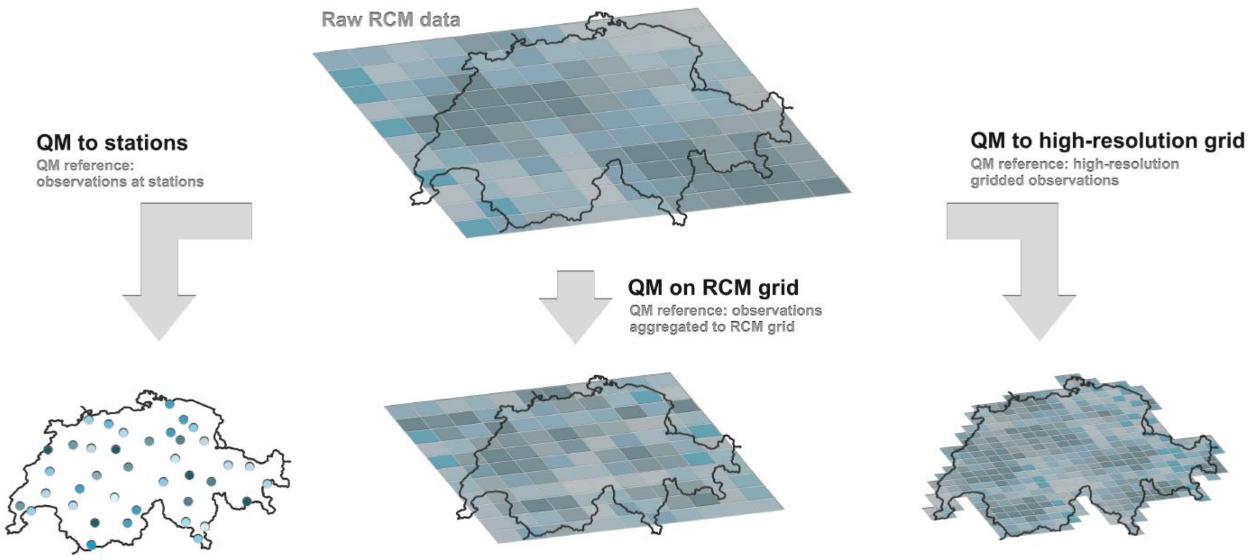

Figure 11.19: quantile-mapping

- An **ensemble of climate model runs** may show a **range of change in for example summer precipitation and summer temperature**. The **highest increase for summer temperature likely does not occur at the same time as the highest increase for summer precipitation**.

11.4.13 Representation of uncertainties

- **Model uncertainty** is represented by the spread of climate model output for each RCP. Some countries use the mean change per RCP (no model uncertainty), whereas others show also extreme percentiles for each RCP. The more climate models are used, the more the model uncertainty is represented. The more extreme the percentiles (e.g. 5-95%) the more of the model uncertainty is represented. Up to 2050, model uncertainty is relatively the most important uncertainty (see figure).
- **Natural or internal variability**: Not all countries present information on natural variability.
- **Scenario uncertainty** is represented by the differences between the RCPs means. Countries may differ in the RCP's they use for the development of their national climate scenarios. Countries that use RCP8.5 and RCP2.6 present the largest part of the scenario uncertainty. This uncertainty is especially important in the second half of the 21st century (see figure).

How much of the various sources of uncertainties is presented in the national climate scenarios varies for each country (for types of uncertainties see the dedicated chapter on uncertainties.

Example of uncertainty representation: the Netherlands & Switzerland

Figure: In the KNMI14 climate scenarios the temperature of the IPCC 10-90% range for the RCP8.5-RCP4.5 is used instead of the mean of the RCPs. In this way both scenario and model uncertainty are taken into account. This is especially important for the period up to 2050, which is of most relevance to users.

Figure: Range (5-95% of the EURO-CORDEX models used) of air temperature change for each season compared to 1981-2010 for RCP8.5. Around 2035 (blue), 2060 (orange) and 2085 (green) for the northwestern part of Switzerland (Source: CH2018, 2018). Source: KNMI, 2014

Examples of natural variability representation: the Netherlands and the UK:

*Figure: Change of average summer temperature in the Netherlands in the KNMI'14 climate scenarios. The **grey bands** represent the **30-year** natural variability based on the variability in the current climate (Source:*

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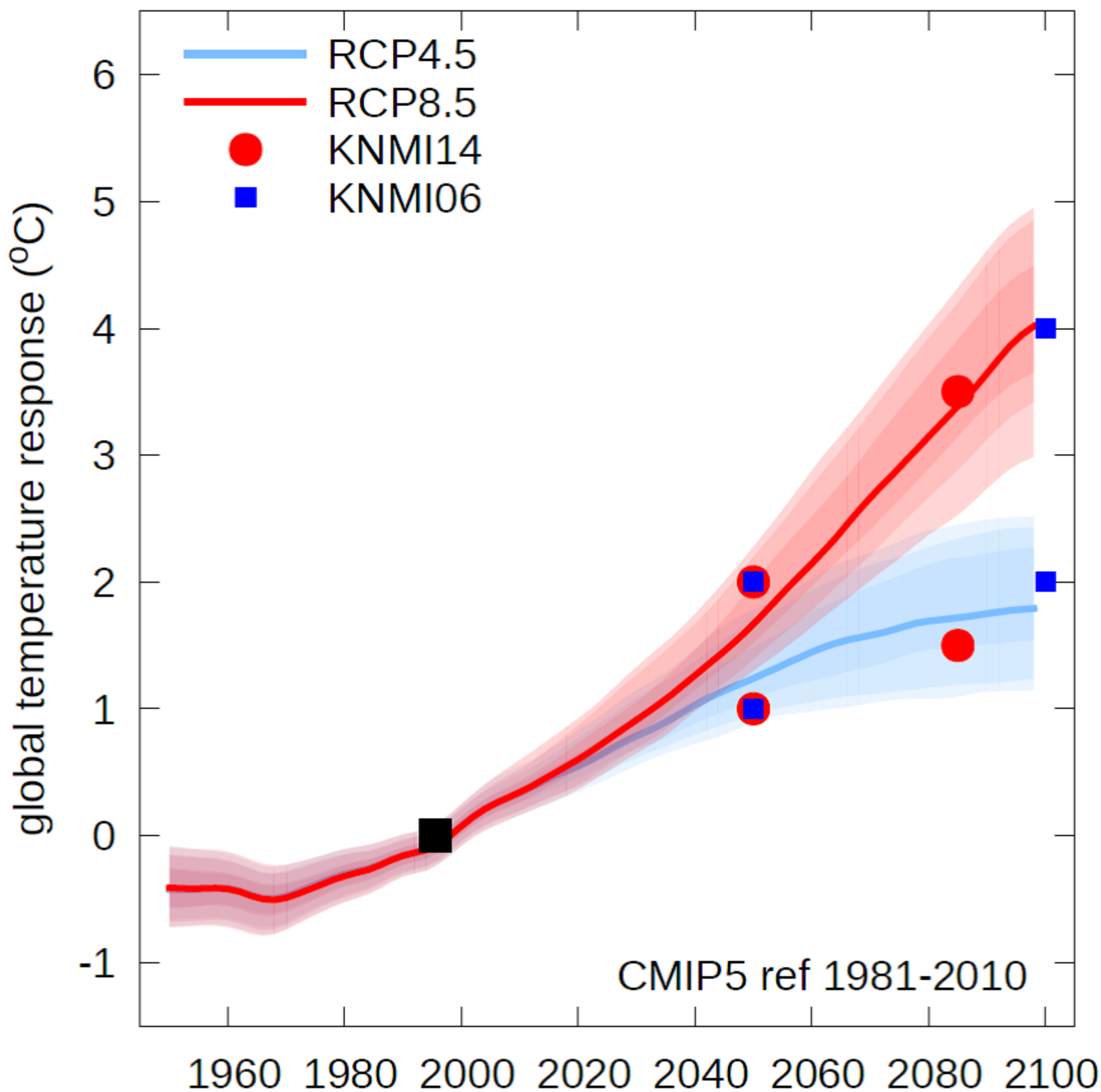

Figure 11.20: uncertainty-netherlands

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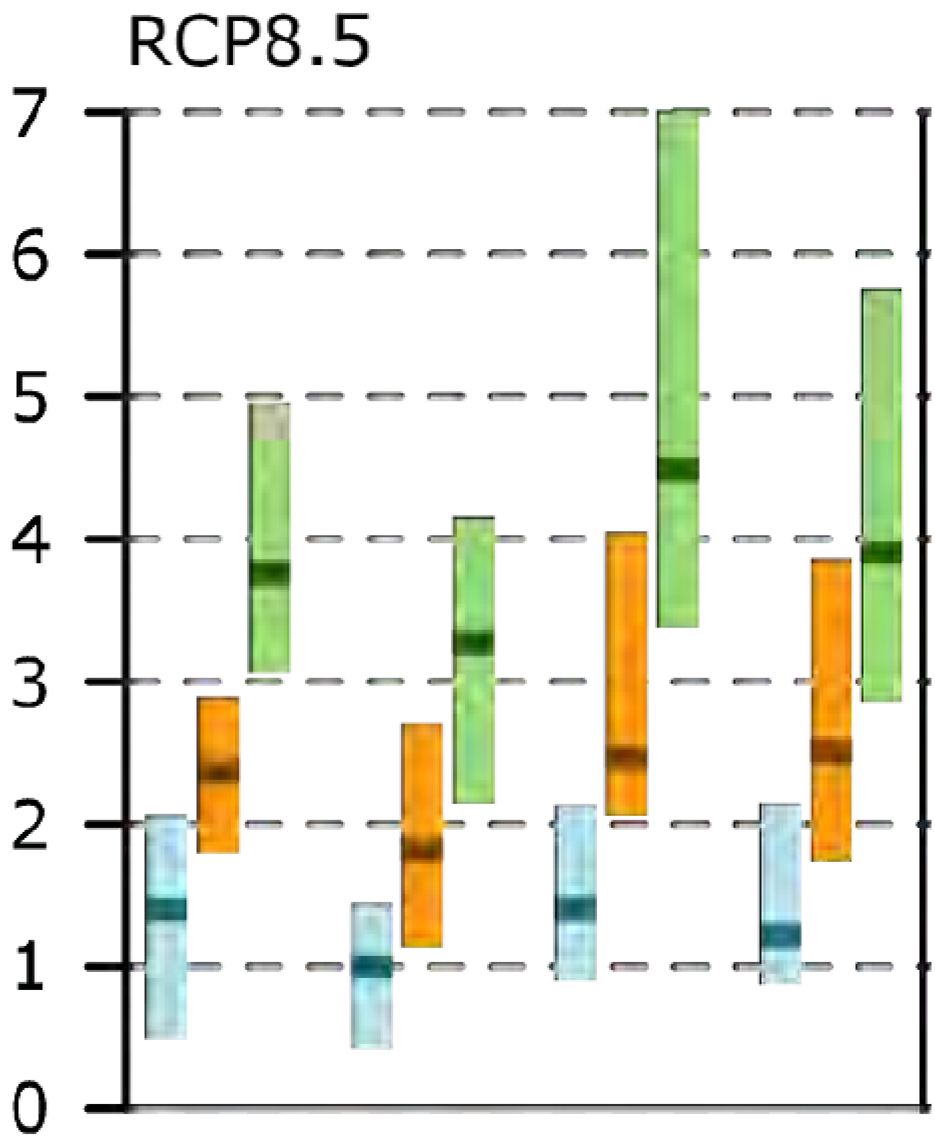

Figure 11.21: uncertainty-switzerland

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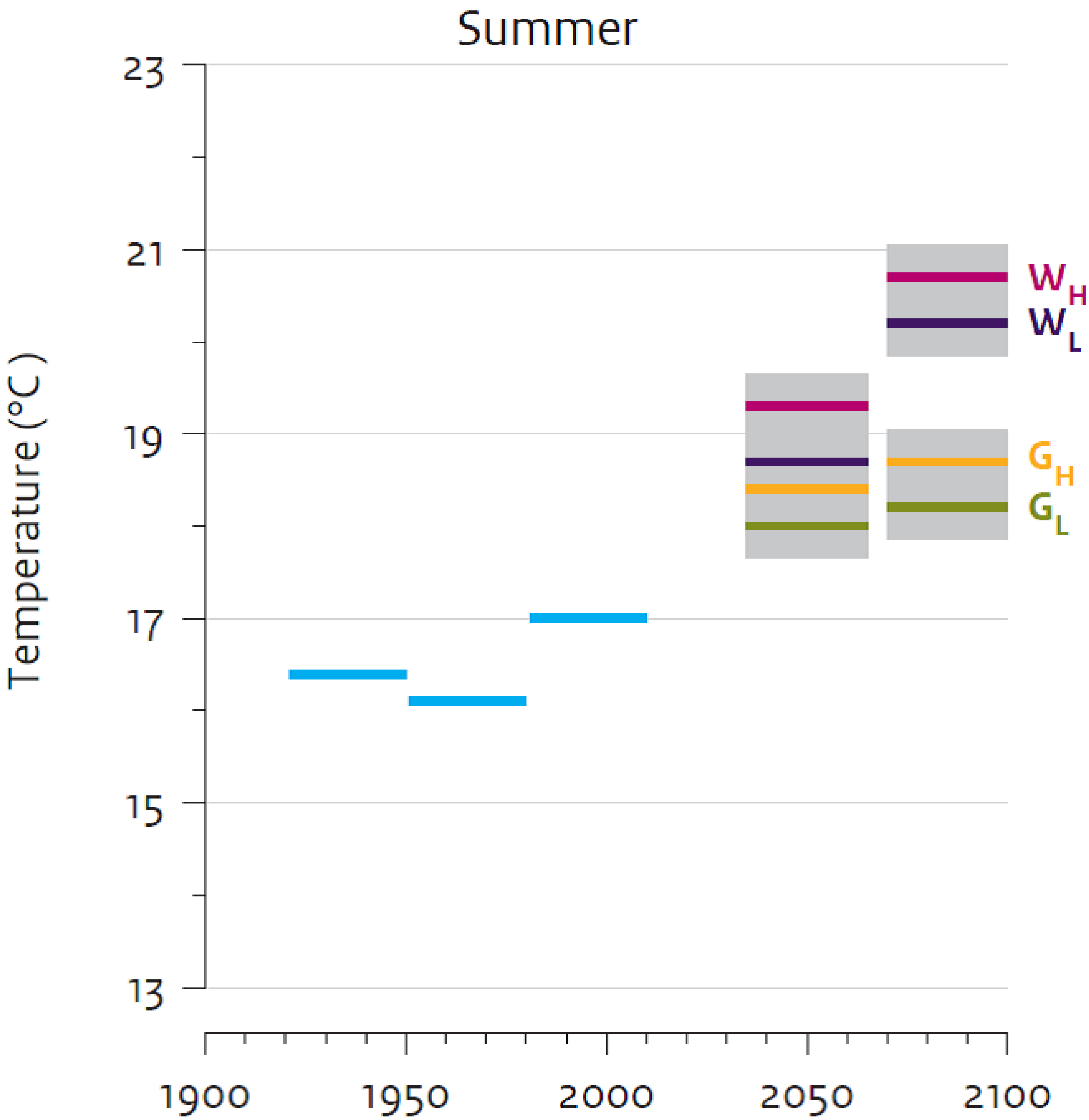

Figure 11.22: natural-variability-netherlands

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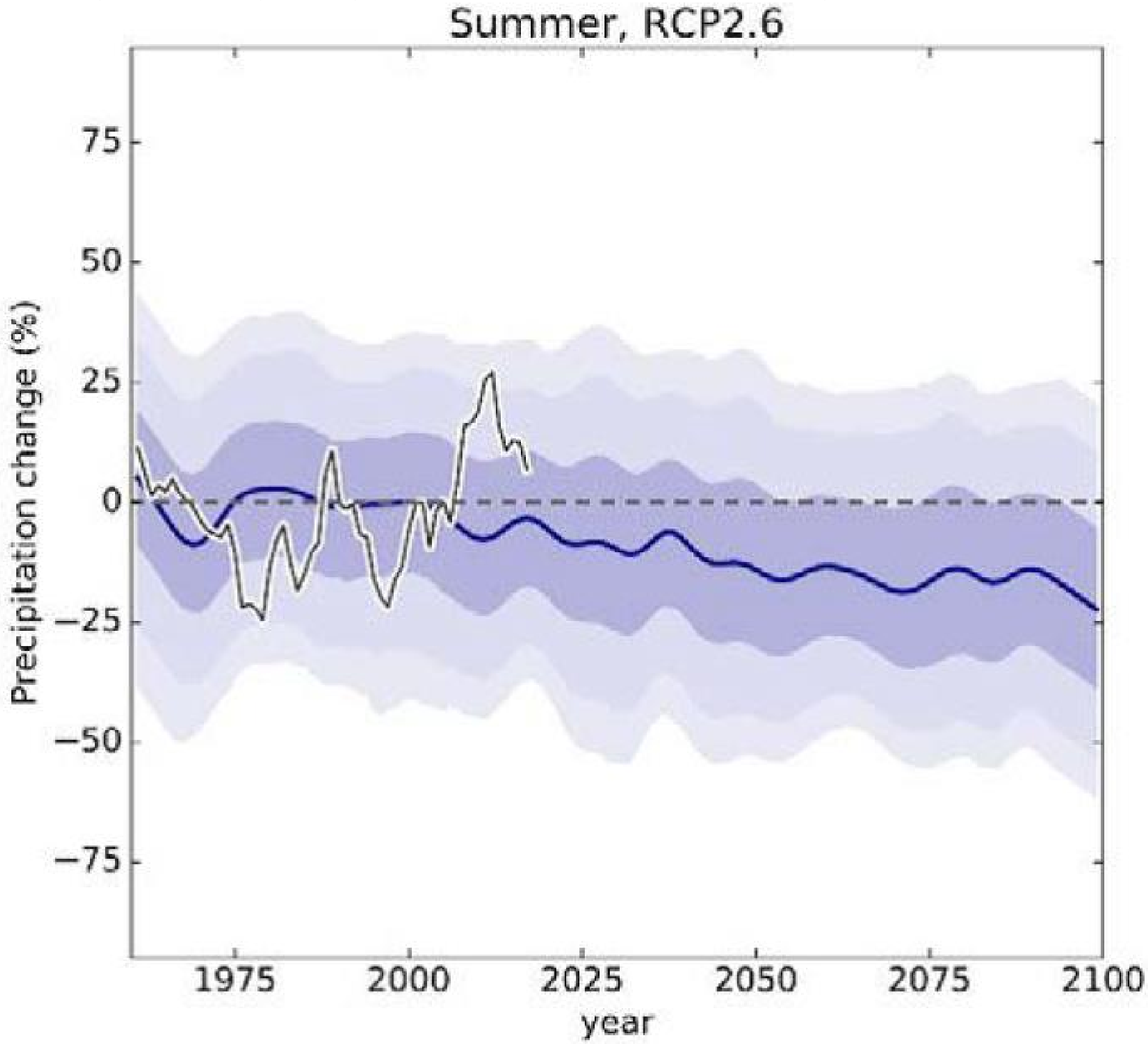

Figure 11.23: natural-variability-uk

KNMI, 2015).

*Figure: Change of average summer precipitation in the UK under the RCP2.6 in the UKCP18 climate scenarios. The **bands** around the thick line represent various percentiles for the **year to year**natural variability for the past and future climate (Source: UKCP, 2018).*

11.5 References