(Regional) Climate Modeling

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Outline

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PIK

Potsdam-Institut für Klimafolgenforschung

Potsdam Institute for Climate Impact Research

"At PIK, researchers in the natural and social sciences from all over the world work closely together to study global change and its impacts on ecological, economic and social systems. Researchers examine the earth system's capacity for withstanding human interventions and devise strategies and options for a sustainable development of humankind and nature. Interdisciplinary and solution-oriented approaches are a distinctive characteristic of the institute."

`https://www.pik-potsdam.de`

PIK

Potsdam-Institut für Klimafolgenforschung

Potsdam Institute for Climate Impact Research

- more than 400 employees
- four research domains: Earth system analysis, climate resilience, transformation pathways, complexity science
- methods: system and scenario analysis, quantitative and qualitative modeling, computer simulations and data integration

Climate Impacts

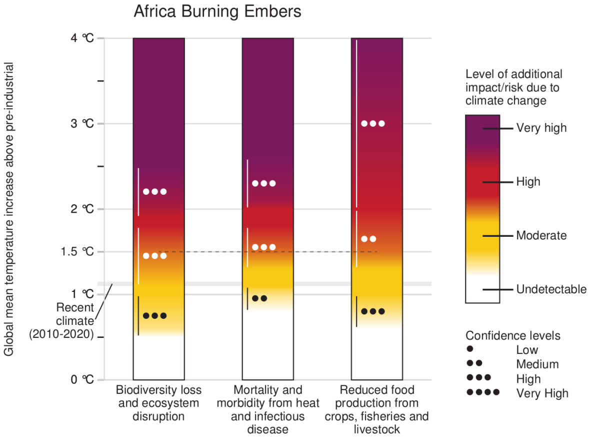
Potsdam Institute for Climate Impact Research

impacts: *consequences of climate change,* such as

- change in harvest yields (for better or worse)
- health issues
- increased/decreased floods and droughts
- death of coral reefs due to ocean acidification

etc.

Risks of Anthropogenic Climate Change, example Africa



source: IPCC AR6, WGII (2022)

Burning Embers showing increasing risk due to climate change for selected key risks in Africa. The temperature increase is relative to 1850 – 1900. All three risks are assessed to have already transitioned to moderate risk by the recent level of global warming 2010 – 2020 (1.09 °C). (Burning ember diagrams are iconic in climate impact science.)

Global and Regional Climate Modeling

- one of the most important tools for climate impact research: climate models
- one type of models simulates the whole world → *global climate model* (GCM)
- however, scale of impact research rather small (a few kilometers), since that is the size of fields, river basins, forest stands and so on
- cannot be modeled globally (yet) due to CPU constraints → *regional climate model* (RCM) which models only part of the globe
- most important variables for impact research: temperature and precipitation (this lecture focuses on these)

Regional Climate Modeling

1. assumption of some future socioeconomic / emission scenario

2. simulation of global atmosphere with a global model

3. simulation of region of interest with more highly resolved regional model (*"downscaling"*)

IPCC

Intergovernmental Panel on Climate Change (IPCC)

- founded in November 1988 by the United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO)
- assesses risks of global temperature increase
- gathers mitigation/adaptation strategies
- no own research but collects results from climate sciences
- Nobel Peace Prize 2007 (together with Al Gore)

IPCC Assessment Reports

- publishes *Assessment Reports:* FAR (1990), SAR (1995), TAR (2001), AR4 (2007), AR5 (2013), AR6 (2022)

- three working groups in AR6

  WG I *"The Physical Science Basis"*

  WG II *"Impacts, Adaptation and Vulnerability"*

  WG III *"Mitigation of Climate Change"*

- many climate simulations were carried out for WG I
  Coupled Model Intercomparison Project (CMIP) 6

- there is also an interactive atlas for AR6, see

  https://interactive-atlas.ipcc.ch

Outline

What is Climate?

IPCC

Climate in a narrow sense is usually defined as the "average weather", or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

What is Climate?

This means statistical properties of the meteorological variables are investigated

- mean
- variance
- extreme events (floods, droughts, heat waves, storm surges)

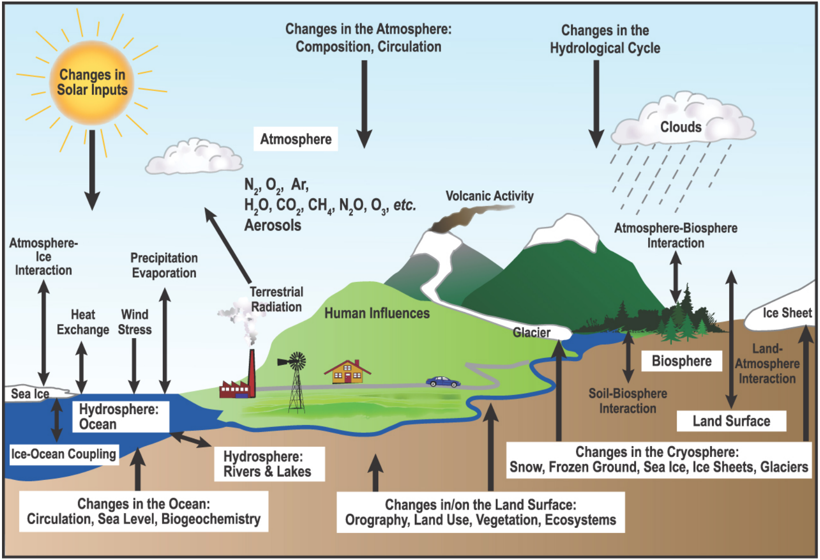
when doing a climate simulation, the question is not

~~*"What is the temperature in Tokyo on 4/2/2086?"*~~

but

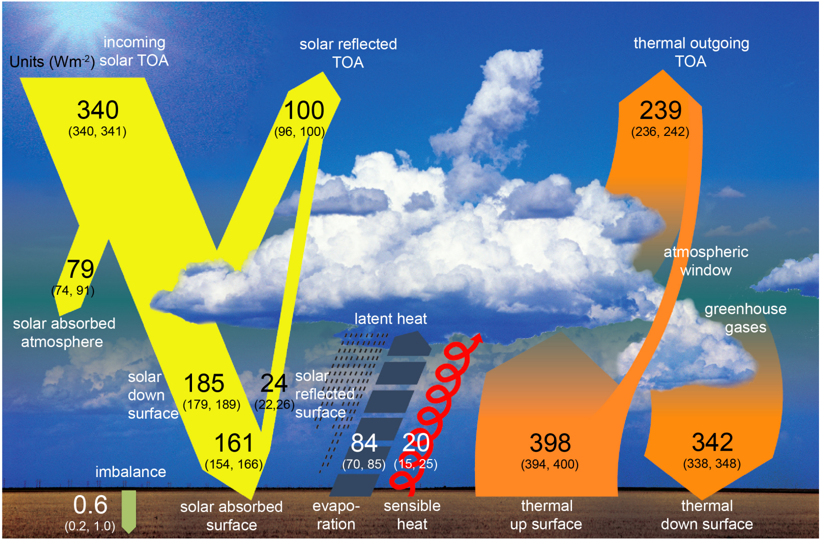
"What are the statistical properties of the temperature in Tokyo in the years 2071 to 2100 under a certain emission scenario?"

Climate System



source: IPCC AR4 2007

Energy budget / Radiation

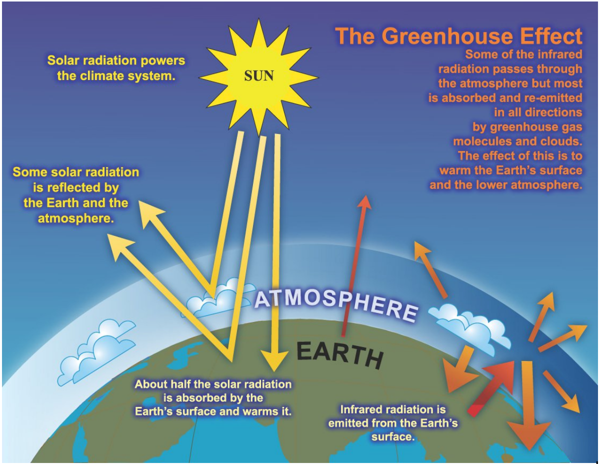


TOA – top of the atmosphere

source: IPCC AR5 (2013)

global mean energy budget under present-day climate conditions

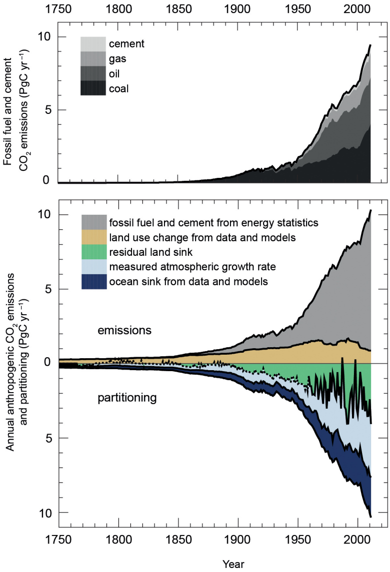
Greenhouse Effect



source: IPCC AR4 2007

average temperature without atmosphere but same albedo: -18 °C, with atmosphere 14 °C

CO_2 Emissions into the Atmosphere



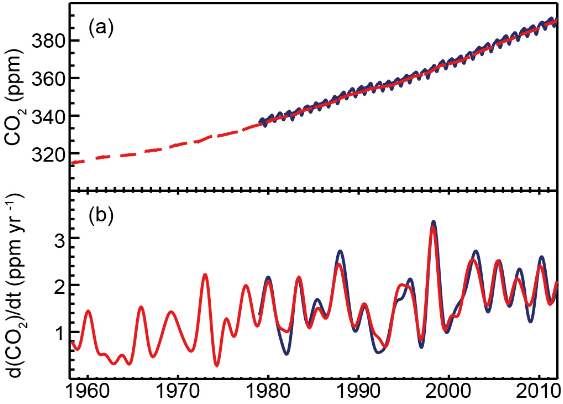
source: IPCC AR5 (2013)

- increased anthropogenic CO_2 emissions start in the 2nd half of 19th century
- largely due use to fossil fuels (coal, oil, gas) and cement production
- emitted CO_2 absorbed into biosphere, atmosphere and ocean

CO_2 Concentration in the Atmosphere

measured at Mauna Loa, Hawaii

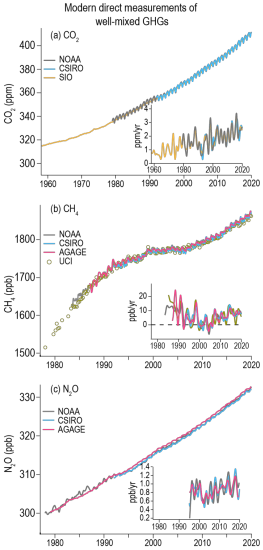
also known as *"Keeling curve"* after Charles David Keeling



annual cycle due to vegetation cycle

source: IPCC AR5

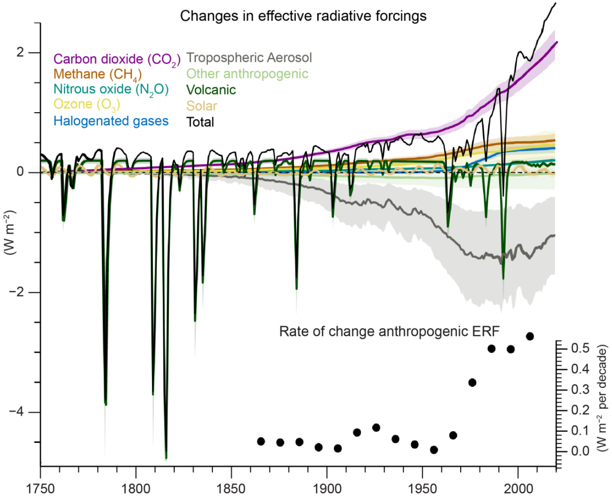
CO_2, Methane, Nitrous Oxides



source: IPCC AR6, WG1 (2021)

- CO_2 not the only important green house gas
- methane and nitrous oxides important as well
    - sources of methane emissions are ruminants, fossil fuel emissions and the expansion of rice paddy agriculture
    - a source of nitrous oxides emissions are changes in the nitrogen cycle

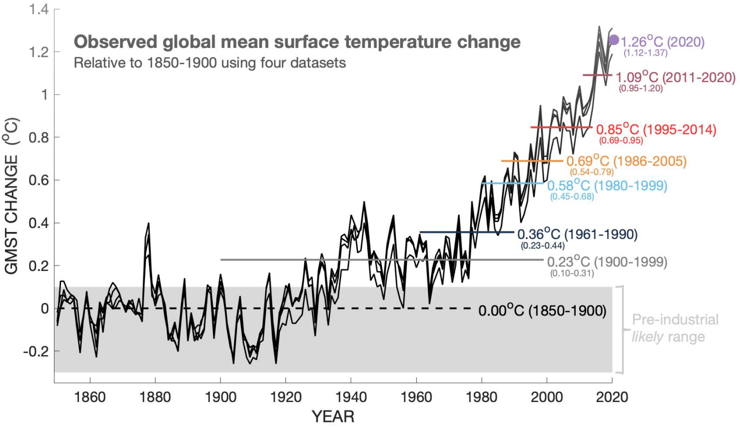
Radiative Forcing



source: IPCC AR6, WG1 (2021)

Temporal evolution of effective radiative forcing (ERF) related to individual drivers. Lines depict the mean, while the shading covers the 5 % to 95 % uncertainty range. The dots show the total anthropogenic ERF (no TSI and volcanic) for 30 year periods centered at the dot. TSI: total solar irradiance

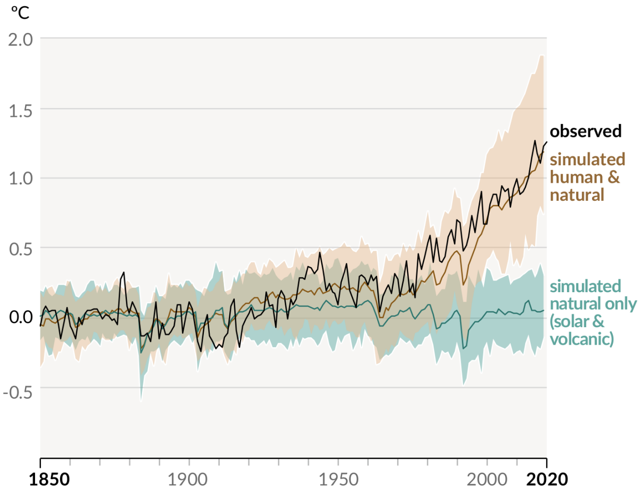
Climate Change – Global Surface Temperatures



source: IPCC AR6, WG1 (2021)

Global warming over the instrumental period: observed global mean surface temperature, relative to the average temperature of 1850 – 1900 in each dataset.

Climate Change – Global Surface Temperatures

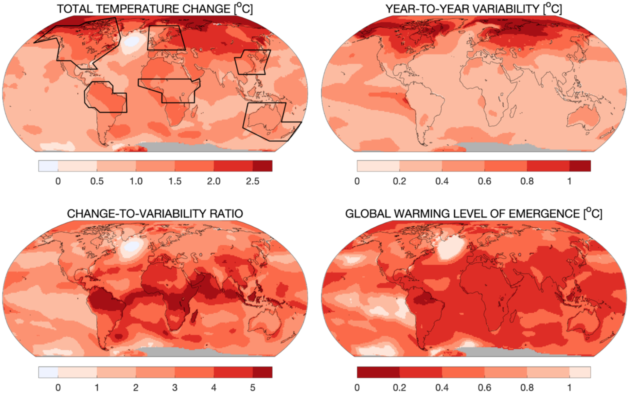


source: IPCC AR6, WG1 (2021)

Change in global surface temperature (annual average) as observed and simulated using human & natural and only natural factors (both 1850 – 2020).

Climate Change – Global Surface Temperatures

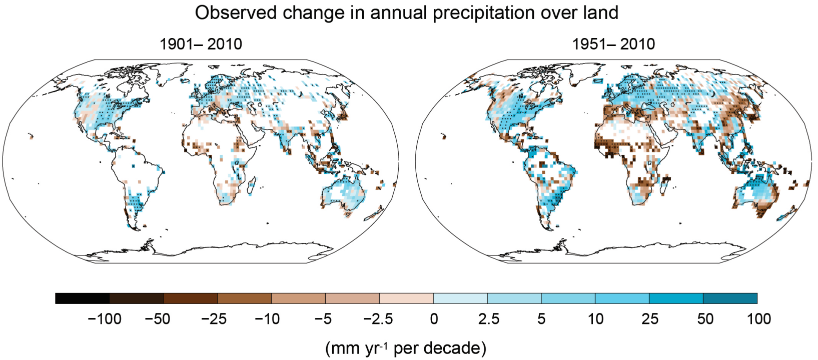
Observed changes in temperature have emerged in most regions



source: IPCC AR6, WG1 (2021)

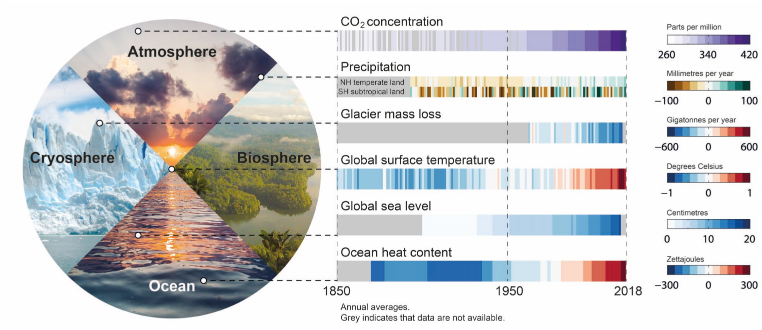
The observed emergence of changes in temperature. *top left:* the total change in temperature estimated for 2020 relative to 1850 – 1900 (following Hawkins et al. 2020), showing the largest warming in the Arctic. *top right:* the amplitude of estimated year-to-year variations in temperature. *bottom left:* the ratio of the observed total change in temperature and the amplitude of temperature variability (the 'signal-to-noise (S/N) ratio'), showing that the warming is most apparent in the tropical regions. *bottom right:* the global warming level at which the change in local temperature becomes larger than the local year-to-year variability.

Climate Change – Precipitation on Land



source: IPCC AR5 (2013)

Climate Change – further observations



source: IPCC AR6, WG1 (2021)

left: Main realms of the climate system: atmosphere, biosphere, cryosphere and ocean.
right: Six key indicators of ongoing changes since 1850, or the start of the observational or assessed record, through 2018. Each stripe indicates the global (precipitation: 2 latitude bands) annual mean anomaly of a single year, relative to a multiyear-baseline (CO_2 and glaciers are absolute values). Grey indicates missing values.

Observations

- observations are made at weather stations, density of weather stations quite low, especially in remote areas and underdeveloped regions
- data is quite often spurious and has gaps
- observations are made at weather stations, but often required on grids → interpolation
- depending on the algorithm, interpolation can change averages, minima, maxima …

Observations

Hellmann Rain Gauge

source:
http://de.wikipedia.org/wiki/Nieder-
schlagsmesser

- precipitation measurements furthermore skewed by *"undercatch"*
- due to wind, wetting of gauges, evaporation etc.
- depending on the correction scheme, measurements are off by 10 % or more
- effect most severe for snow
- all satellite precipitation products are calibrated with station data
- "observations" are usually highly processed data

Current State of the Climate

1. It is unequivocal that human influence has warmed the atmosphere, ocean and land. Widespread and rapid changes in the atmosphere, ocean, cryosphere and biosphere have occurred.
2. The scale of recent changes across the climate system as a whole and the present state of many aspects of the climate system are unprecedented over many centuries to many thousands of years.
3. Human-induced climate change is already affecting many weather and climate extremes in every region across the globe. Evidence of observed changes in extremes such as heatwaves, heavy precipitation, droughts, and tropical cyclones, and, in particular, their attribution to human influence, has strengthened since the Fifth Assessment Report (AR5).
4. Improved knowledge of climate processes, paleoclimate evidence and the response of the climate system to increasing radiative forcing gives a best estimate of equilibrium climate sensitivity of 3 °C, with a narrower range compared to AR5.

source: IPCC AR6, WG1 (2021)

Outline

Socioeconomic / emission scenarios

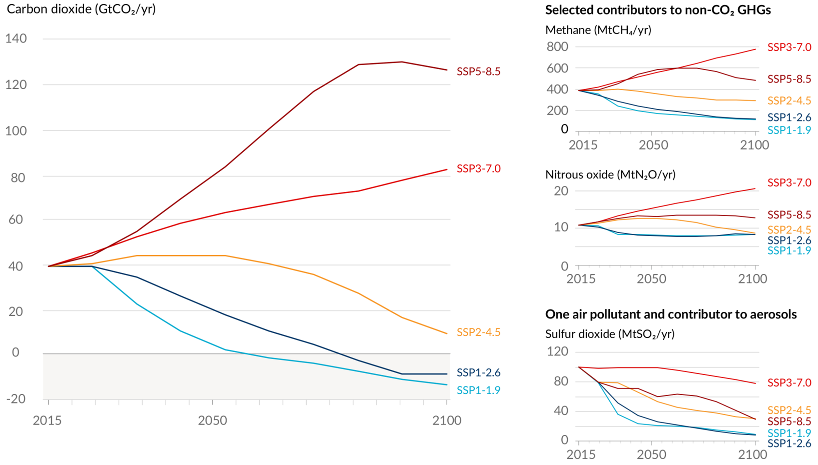
Regional Climate Modeling

1. assumption of some future socioeconomic / emission scenario
2. simulation of global atmosphere with a global model
3. simulation of region of interest with more highly resolved regional model (*"downscaling"*)

Representative Concentration Pathways (AR5, AR6)

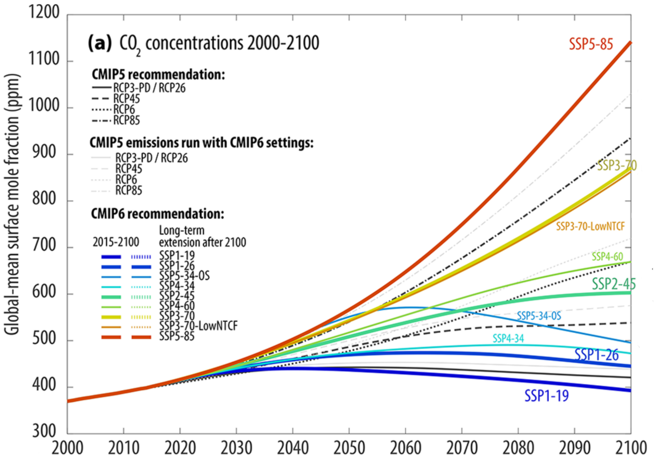
- improved scenarios were deemed necessary for AR5 because of increased demands by users, modelers and impact researchers (more consistent, higher spatial and temporal resolutions, longer time frames)
- in 2006 the IPCC decided not to commission another set of emission scenarios, left scenario development to research community
- they represent “the full of stabilization, mitigation, and reference emissions scenario available in the current scientific literature”
- well separated, even number (otherwise middle one is always picked)
- “representative” – each RCP provides only one of many possible scenarios leading to a specific radiative forcing
- number in scenario name: change in radiative forcing between 2100 and pre-industrial

Anthropogenic emissions (AR6)



source: IPCC AR6, WGI (2021)

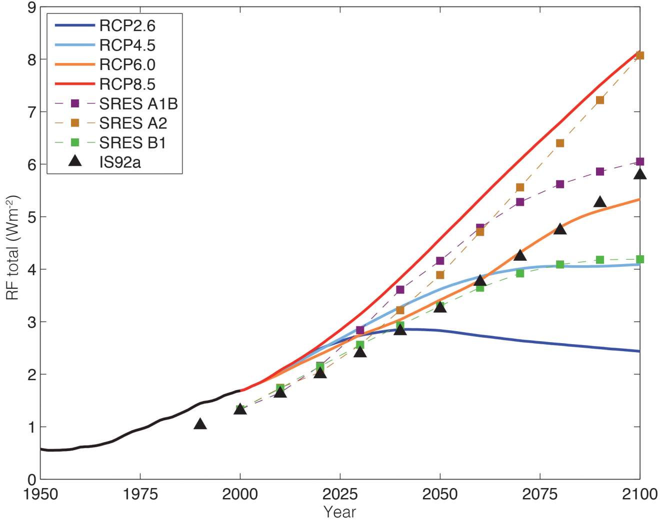
RCP, SSP (AR6, CMIP6)



source: Meinshausen *et al.,* (2020), DOI 10.5194/gmd-13-3571-2020

Interestingly, CMIP6 has higher CO_2 concentrations than CMIP5 for the same change in radiative forcing.

RCP Radiative Forcing (AR5, AR6)



source: IPCC AR5

(The SRES scenarios were used in TAR and AR4.)

RCP, SSP (AR6, CMIP6)

for CMIP6 the RCPs are still used, however, they are combined with SSPs (*"shared socio-economic pathways"*), e.g. SSP5-8.5

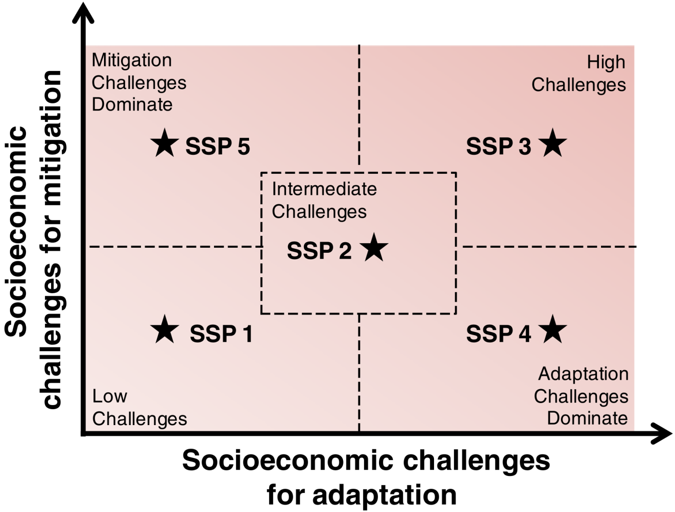
- set of five story lines that describe possible developments for human development and global environmental change during the 21st century
- describe various quantities such as population size, urbanization rates, income, energy use and production, agriculture, land use, emissions
- mirrors previous SRES scenarios (TAR, AR4)

SSP (AR6, CMIP6)

- SSP1 Sustainability low challenges for mitigation (resource efficiency) and adaptation (rapid development)
- SSP2 Middle of the road scenario, intermediate challenges
- SSP3 Regional Rivalry high challenges for mitigation (regionalized energy / land policies) and adaptation (slow development)
- SSP4 Inequality low challenges for mitigation (global high tech economy), high for adapt. (regional low tech economies)
- SSP5 Fossil-fueld development high challenges for mitigation (resource / fossil fuel intensive) and low for adapt. (rapid development)

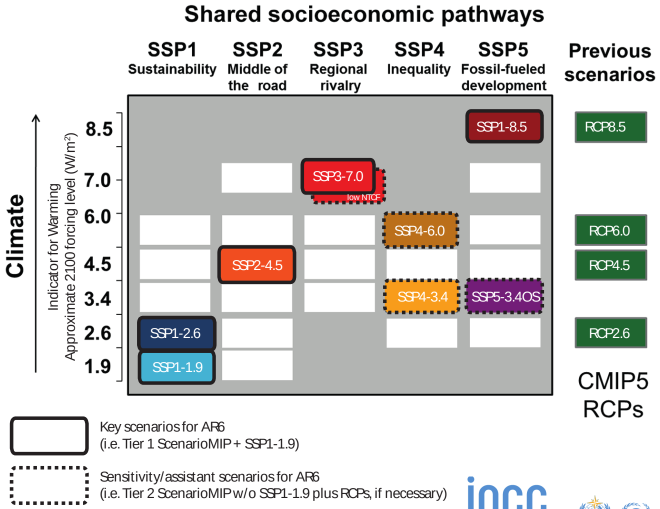
source: poster by Riahi *et al.*

SSP (AR6, CMIP6)



source: Neill *et al.*, DOI:https://doi.org/10.1007/s10584-013-0905-2

AR6, CMIP6 Scenarios



ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP

source: IPCC (2019)

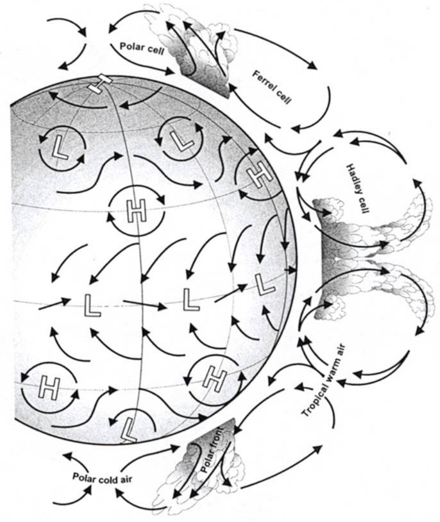
Outline

Earth System Models (ESM)

Regional Climate Modeling

1. assumption of some future socioeconomic / emission scenario
2. simulation of global atmosphere with a global model
3. simulation of region of interest with more highly resolved regional model (*"downscaling"*)

Aqua Planet



source: von Storch *et al.* (1999)

- *"Aqua Planet"* – simulation of climate on an Earth-like planet covered completely by water
- initial conditions: atmosphere at rest
- at about day 10: trade winds and tropical cells appear suddenly
- at about day 20: Ferrel cells appear
- after two months: large scale patterns similar to the ones actually observed on Earth have emerged

Fischer *et al.* (1991)

Global Climate Modeling

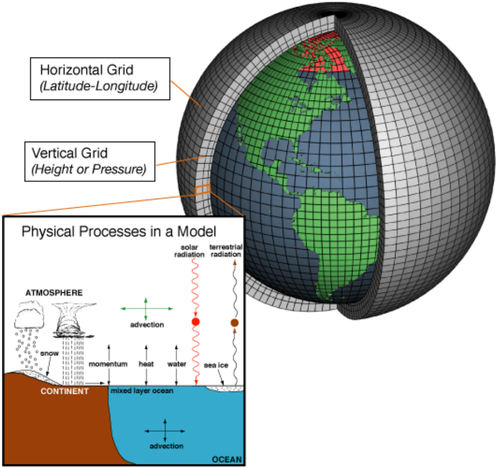
Global climate is not made up of regional climates.
Instead, regional climate should be understood as the result of an interplay of global climate and regional physiographic detail.

Implications:

- Planetary scale climate can be modeled with dynamical models with limited spatial resolution
- The success on planetary scales does not imply success on regional or local scales.
- The effect of smaller scales can be described summarily through parameterizations.

based on: von Storch, Lund 2014

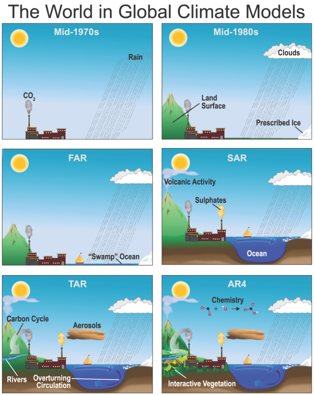
General Circulation Models



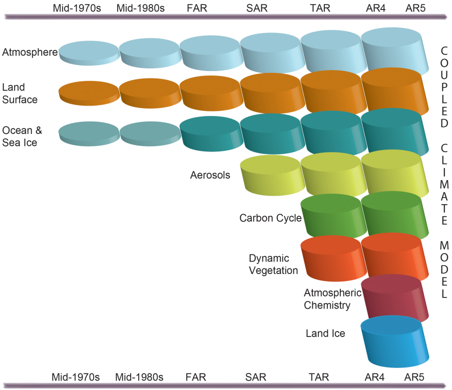
source: http://en.wikipedia.org/wiki/General_Circulation_Model

- *"General Circulation Model"* (GCM) simulates atmosphere
- for long term simulations usually an ocean model is coupled
- then the model is run with selected emission scenario

From GCM to ESM

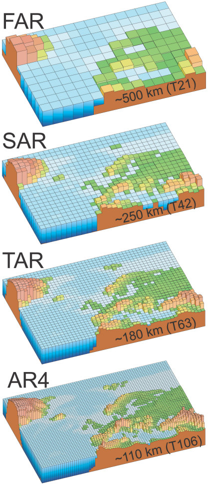


source: AR4 (2007)

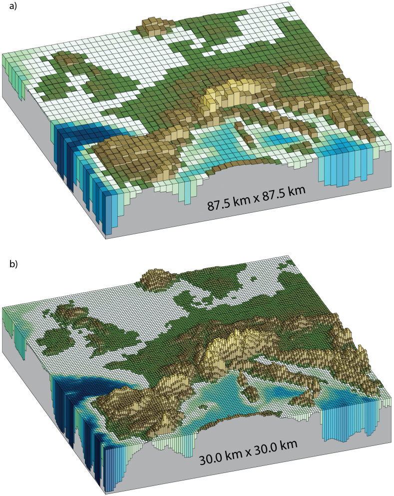


source: AR5 (2013)

ESM Resolution



source: IPCC AR4 (2007)

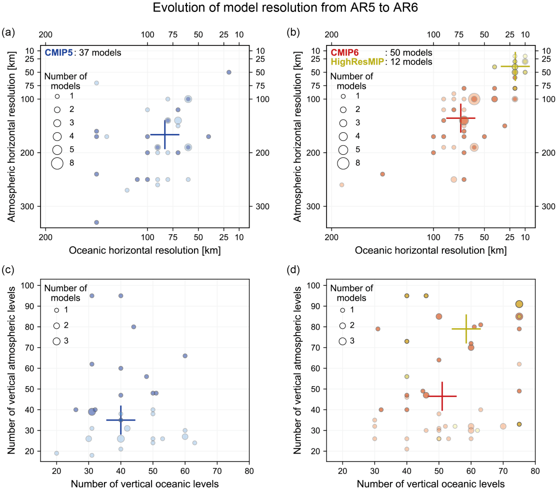


source: IPCC AR5 (2013)

left: ESM resolutions FAR to AR4
bottom right: current ESM resolutions

top right: AR5 ESM resolution

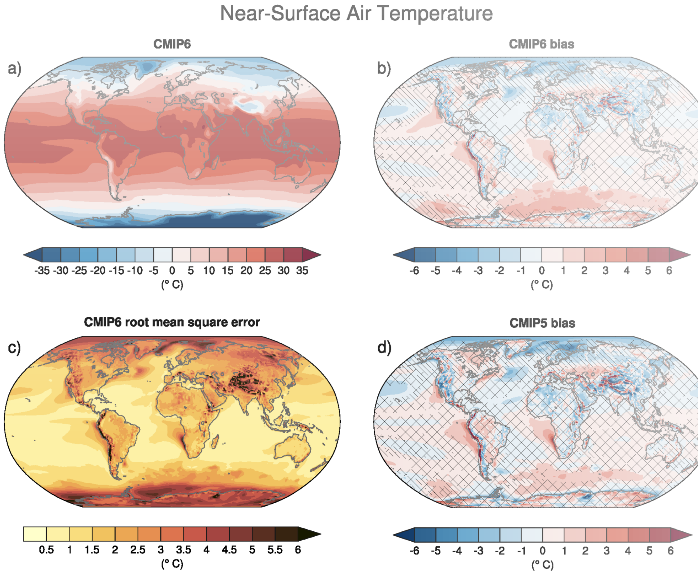
ESM Resolution



source: IPCC AR6, WGI (2021)

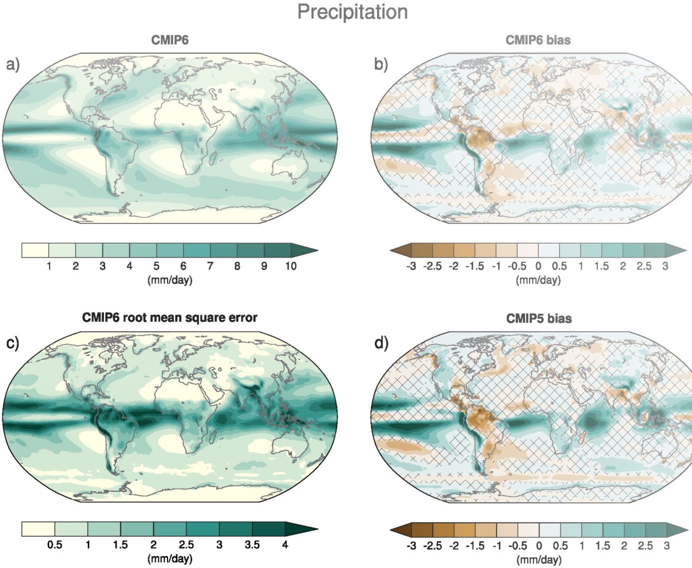
The resolution of the atmospheric and oceanic components of global climate modles participating in CMIP5, CMIP6 and HighResMIP. Darker colour circles indicate high-top models (TOA > 50 km). The crosses are the median values.

Performance of ESM: Annual Mean 2 m Temperature



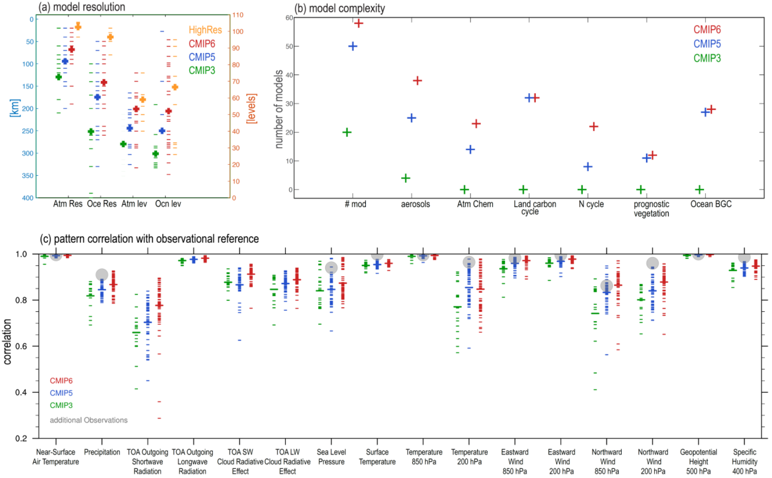
time frame: 1995 – 2014; a) CMIP6 multi-model mean; b) multi-model mean bias compared to ERA-5; c) multi-model rmse over all months; d) multi-model mean bias of CMIP5 vs ERA-5 source: AR6, WG1 (2021)

Performance of ESM: Annual Mean Precipitation



time frame: 1995 – 2014; a) multi-model mean; b) multi-model mean bias compared to GPCP v2.3; c) c) multi-model rmse over all months; d) multi-model mean bias of CMIP5 vs GPCP v2.3 source: AR6, WG1 (2021)

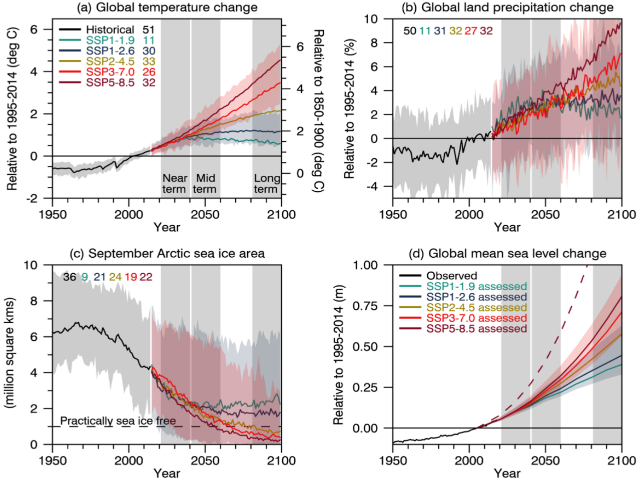
Progress of ESM



Centered pattern correlations (1.0 is perfect), time frame: 1980 – 1999; besides the steady progress also observe the discrepancies in various observation sets (grey dots).

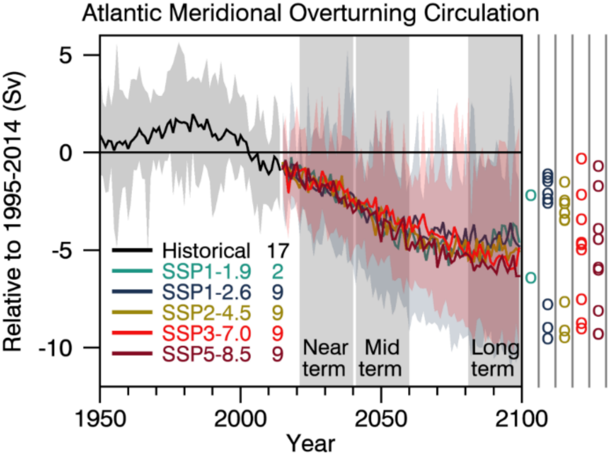
source: IPCC AR6, WG1 (2021)

ESM Long Term Projection Surface Temperature, Precipitation, Arctic Sea Ice and Sea Level



Multi-model means of CMIP6 for four quantities. a), b), d) are annual means, d) dashed curve is the low confidence and low likelihood outcome at the high end of SSP5-8.5 and reflects deep uncertainties arising from potential ice-sheet and ice-cliff instabilities; shadings around the SSP1-2.6 and SSP3-7.0 curves show 5 – 95 % ranges, numbers near the top show the number of model simulations source: IPCC AR6, WG1 (2021)

ESM Long Term Projection AMOC

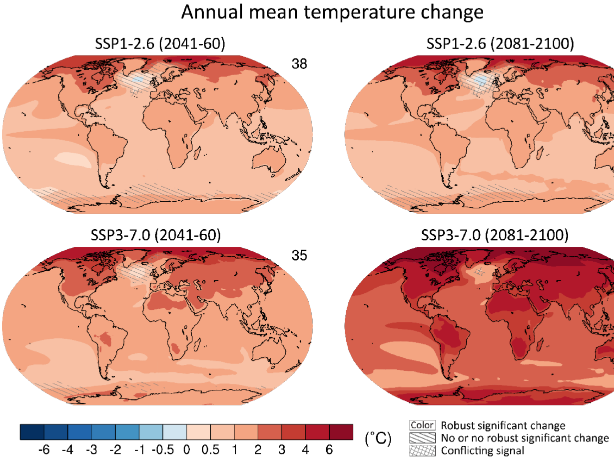


CMIP6 annual mean AMOC strength change in historical and scenario simulations. Changes are relative to averages from 1995 – 2014.

The curves show ensemble averages and the shadings the 5 – 95 % ranges across the SSP1-2.6 and SSP3-7.0 ensembles. The circles to the right of the panel show the anomalies averaged from 2081 – 2100 for each of the available model simulations. The numbers inside the panel are the number of model simulation. (1 Sverdrup = 10^6 m³/s)

source: AR6, WG1 (2021)

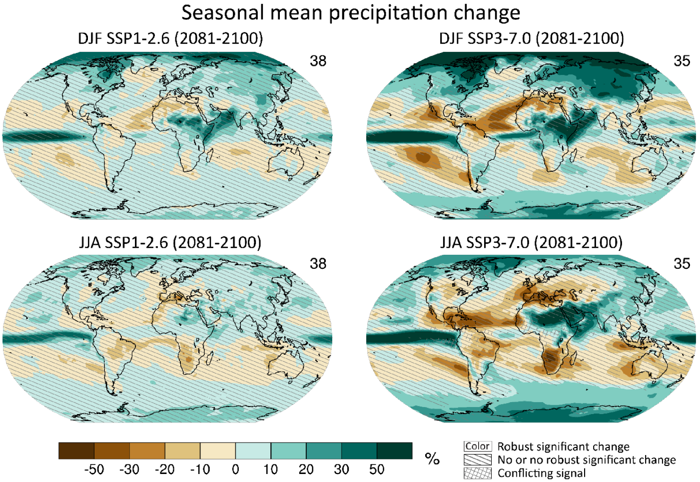
ESM Mid and Long Term Projection Surface Temperature



Multi-model mean change in annual mean near-surface air temperature (°C) in 2041 – 2060 (left) and 2081 – 2100 (right) relative to 1995–2014 for SSP1-2.6 (top) and SSP3-7.0 (bottom). The number of models used is indicated in the top right of the maps.

source: IPCC AR6, WG1 (2021)

ESM Long Term Projection Precipitation



CMIP6 multi model change in DJF (top) and JJA (bottom) for SSP1-2.6 (left) and SSP3-7.0 (right) Baseline is 1995 – 2014.The number of models used is indicated in the top right of the maps. source: IPCC AR6, WG1 (2021)

Possible Climate Futures

1. Global surface temperature will continue to increase until at least the mid-century under all emissions scenarios considered. Global warming of 1.5 °C and 2° C will be exceeded during the 21st century unless deep reductions in carbon dioxide (CO_2) and other greenhouse gas emissions occur in the coming decades.
2. Many changes in the climate system become larger in direct relation to increasing global warming. They include increases in the frequency and intensity of hot extremes, marine heatwaves, and heavy precipitation, agricultural and ecological droughts in some regions, and proportion of intense tropical cyclones, as well as reductions in Arctic sea ice, snow cover and permafrost.
3. Continued global warming is projected to further intensify the global water cycle, including its variability, global monsoon precipitation and the severity of wet and dry events.
4. Under scenarios with increasing CO_2 emissions, the ocean and land carbon sinks are projected to be less effective at slowing the accumulation of CO_2 in the atmosphere.
5. Many changes due to past and future greenhouse gas emissions are irreversible for centuries to millennia, especially changes in the ocean, ice sheets and global sea level.

source: IPCC AR6, WG1 (2021)

Outline

Regional Climate Modeling

Regional Climate Modeling

1. assumption of some future socioeconomic / emission scenario
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Scales and atmospheric processes (Orlanski 1975)

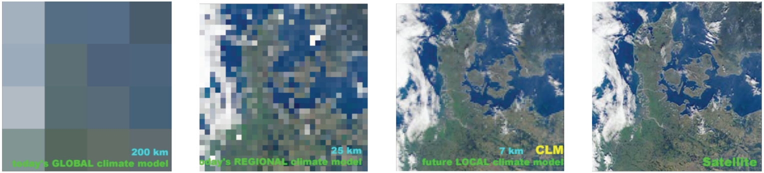
> 10 000 km	general circulations in the atmosphere (weeks to month)	macroscale α
10 000 – 2000 km	baroclinic waves (weeks to month)	macroscale β
2000 – 200 km	weather front and cyclones (days)	mesoscale α
200 – 20 km	orographic effects, land sea wind, urban effects (days)	mesoscale β
20 – 2 km	thunderstorms, urban effects (hours)	mesoscale γ
2 km – 200 m	convection, tornado (minutes to hours)	microscale α
200 – 20 m	thermals	microscale β
< 20 m	small scale turbulence (< seconds to minutes)	microscale γ

meteorologic phenomena occur at characteristic spatial / temporal scales

small / fast phenomena not resolved by too coarse resolutions / time steps

Regional Modeling

- global ESM capture only large scale drivers on planetary scale
- RCM resolves small/fast meteorologic phenomena through high resolutions / small time steps
- enable qualitatively improved modeling by dropping parametrizations (e.g. cloud resolving simulations instead of convection schemes)
- capture small-scale regional and local drivers (e.g. orography, difference land–sea)



IPCC TAR: regional scale covers an area between 10^4 km^2 and 10^7 km^2 (square with side length of 100 km to 3 160 km)

Goals of Regional Climate Modeling

- capture regional and local drivers
- description of structures at small and fast scales
- translation of results of global models to highly resolved regional scale (*"downscaling"*)
- bridge gap between scales of global ESM and climate impact research (e.g. fields, river basins, forest stands)
- reduction in CPU time compared to ESM simulations with the same resolution

Outline

Dynamical Regional Modeling

- idea: solve physical equations (differential equations, balance equations etc.), similar to ESM, on some region of the Earth
- requires
  - initial conditions,
  - time-dependent meteorological lateral boundary conditions (temperature, wind, humidity etc.)

  derived from ESM or observations/reanalysis data
- technology largely an offspring of numerical weather prediction

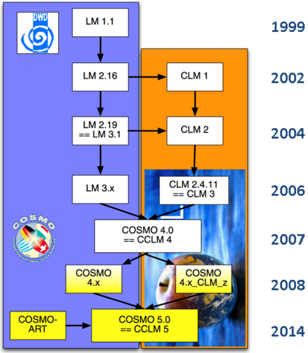
Dynamical Regional Modeling

- high resolutions (1 km … 50 km)
- simulations up to several decades possible
- typically one-way nesting: no feedback of regional model to driving global model
- atmospheric models can be coupled with other models (RCM $\rightarrow$ regional ESM [RESM]), such as
  - soil
  - hydrology
  - ocean
  - sea ice
  - chemistry and aerosol
  - biosphere
  - urban models

CCLM

- CCLM = COSMO-CLM, COSMO-Model in CLimate Mode
- homepage: http://www.clm-community.eu/
- COSMO: nonhydrostatic numerical weather prediction model originally by the German Weather Service (DWD)
- used and developed by national weather services that are members in the COnsortium for Small scale MOdeling (COSMO) (e.g. in Brazil INMET, DHN)
- CCLM is applied to time scales of decades to centuries
- resolution between 1 km and 50 km, applied to various regions in the world

CCLM History



source: www.clm-community.eu

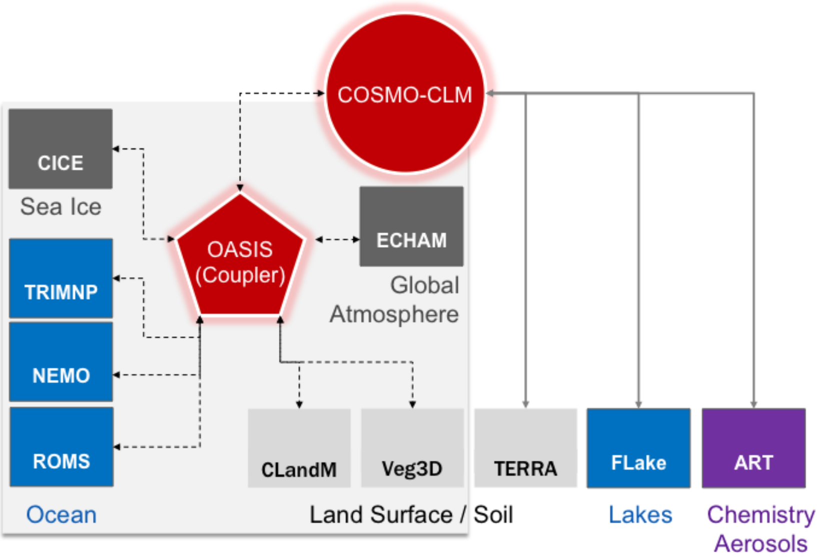
- first version of CCLM developed by PIK, HZG and BTU Cottbus on the basis of "Lokalmodell" (predecessor of COSMO), developed by DWD
- since 2005 community model of the German climate research
- 2007: unified model version for operational weather prediction and climate modeling
- current recommended version is COSMO_5.0_clm9
- approx. 400 000 … 500 000 lines of Fortran 90 Code
- currently phased out, successor: ICON

CLM Community

source: www.clm-community.eu

at the moment, 249 members from 77 institutions in Africa, Asia, Europe, North and South America member in CCLM consortium

CCLM as an RESM



source: www.clm-community.eu

Basic Equations of CCLM Atmosphere

I. Equations of Motion:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = g - 2\,\boldsymbol{\Omega} \times v - \frac{1}{\rho}\nabla p - \frac{1}{\rho}\nabla \cdot \mathbf{t}$$

v wind velocity, t time, g gravitational acceleration, $\boldsymbol{\Omega}$ angular velocity of the earth, ρ air density, p air pressure, $\mathbf{t}$ stress tensor

II. Continuity Equation:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} + \rho\,\nabla \cdot v = 0$$

t time, ρ air density, p air pressure, v wind velocity

III. Air Constituents:

$$\rho\,\frac{\mathrm{d}q^x}{\mathrm{d}t} = -\nabla \cdot J^x + I^x$$

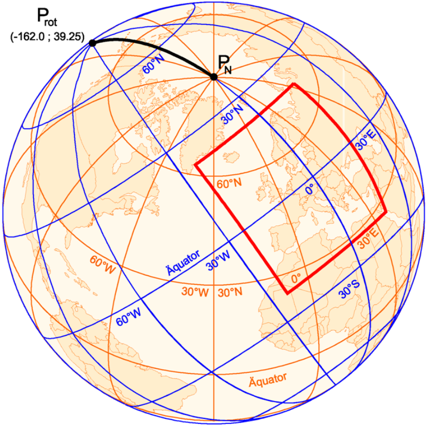
ρ air density, q mass fraction of x, t time, x constituent: d - dry air, v - water vapor, l - liquid water, f - ice, J diffusion flux of x, I source/sinks of x

IV. First Law of Thermodynamics (Conservation of Energy):

$$\rho\,\frac{\mathrm{d}e}{\mathrm{d}t} = -p\,\nabla \cdot v\; - \nabla \cdot (J_e + R) + \varepsilon$$

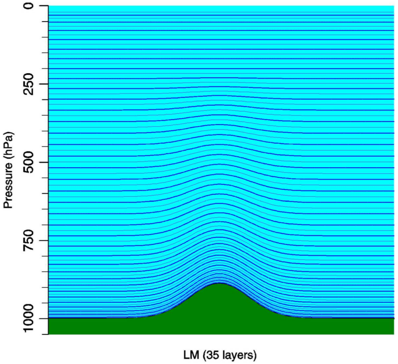
ρ air density, e specific internal energy, t time, p air pressure, v wind velocity, J_e heat flux, R flux density of solar/heat radiation, ε dissipation of kinetic energy due to viscosity

Coordinate system: horizontal



- rotated geographic coordinate system (latitude, longitude)
- new equator in the simulated region → grid cells approximately equally sized
- simplifies numerics
- again, user defined grid spacing (approx. 1 km … 50 km)

Coordinate system: vertical



- terrain following height coordinates with user defined grid spacing
- simplifies formulation of equations near the surface
- height levels become flat at a certain height (approx. 12 km)
- typical maximum height: approx. 22 km

CCLM – Prognostic variables

directly calculated from differential equations:

- horizontal and vertical wind
- temperature
- pressure
- specific humidity
- specific cloud water content

optional:

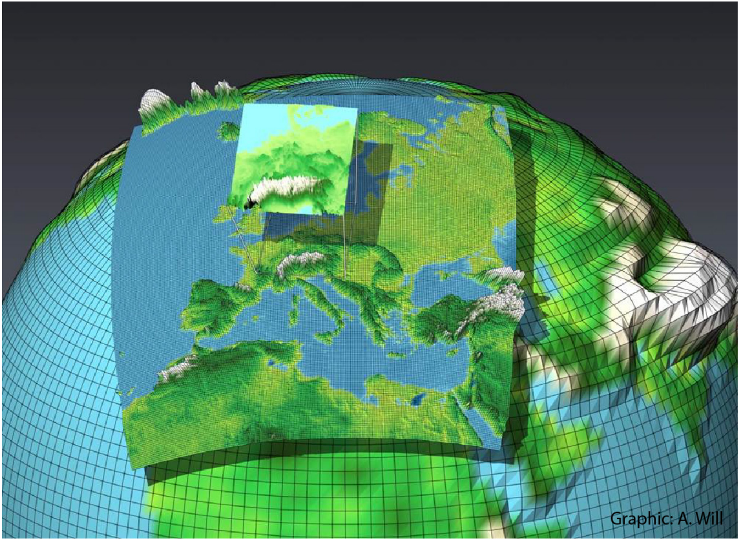
- specific cloud ice content
- turbulent kinetic energy
- specific rain, snow and graupel water content

CCLM – Diagnostic variables (examples)

calculated from prognostic variables e.g.

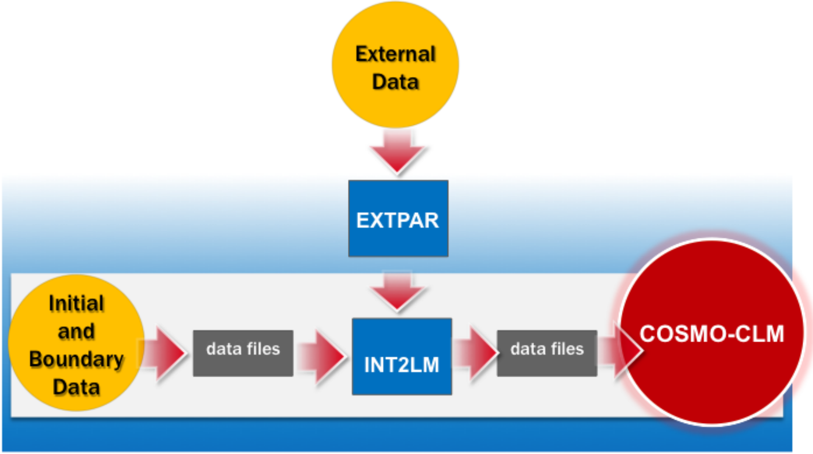
- air density
- cloud cover
- heat fluxes
- moist fluxes
- 2 m temperature
- 10 m wind

CCLM Setup



source: www.clm-community.eu

Preprocessing



source: www.clm-community.eu

CCLM Validation South America

simulation area: South America (CORDEX)

coordinate system: rotated north pole: λ=56.06°W, ϕ=70.6°N

horizontal resolution: 0.44°× 0.44° (about 50 km × 50 km),
166 × 187 grid points

vertical resolution: 40 layers

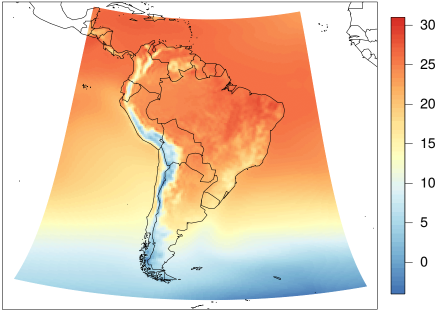
simulation period: 1 / 1 / 1979 – 12 / 31 / 2009

initial and boundary conditions: ECMWF Reanalysis
ERA-Interim, every 6 hours

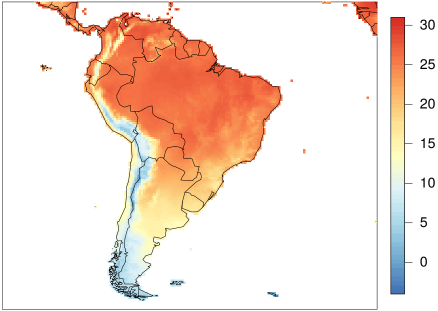
model version: CCLM 4.25_clm3 (setup by S. Lange)

S. Lange *et al.*, *"Regional climate model sensitivities to parametrizations of convection and non-precipitating subgrid-scale clouds over South America,"* Climate Dynamics (2014), DOI: 10.1007/s00382-014-2199-0.

Validation: Annual Average 2 m Temperature 1985–2009

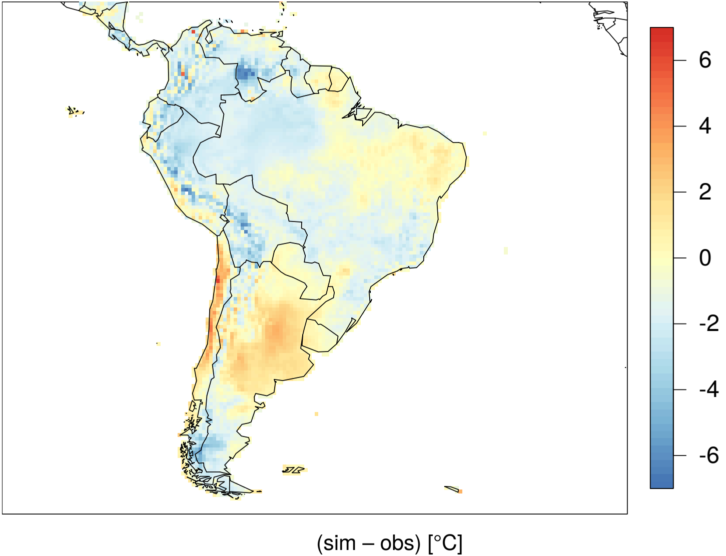


CCLM 4.25_clm3 (sim) [°C]

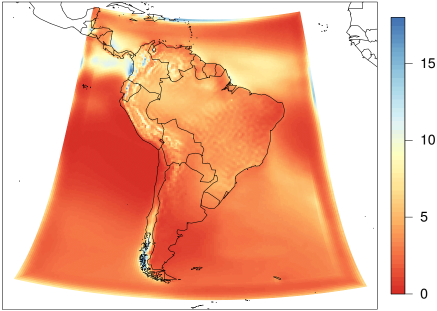


CRU TS 3.21 (obs) [°C]

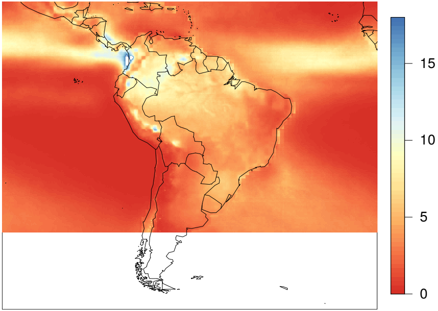
Validation: Annual Average 2 m Temperature 1985–2009



Validation: Annual Average Precipitation 1998–2009

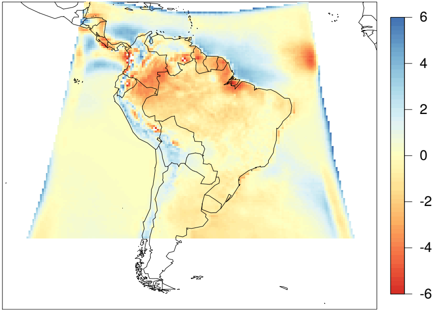


CCLM 4.25_clm3 (sim) [mm]

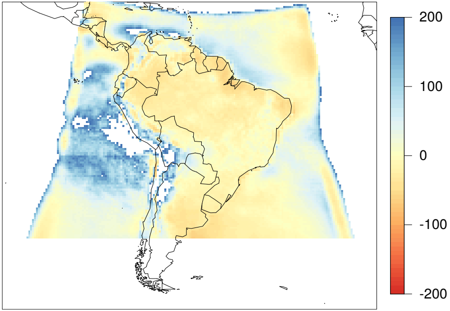


TRMM 3B42v7 (obs) [mm]

Validation: Annual Average Precipitation 1998–2009



(sim-obs) [mm]



(obs-abs)/obs [%]

Outline

Summary

- climate and climate change are to a large part determined by green house gases in the atmosphere
- climate change has severe impacts in some regions and sectors
- steps in climate modeling:
  1. chose a scenario
  2. model the global climate with an earth system model (ESM)
  3. downscale with a regional climate model (RCM)