(Regional) Climate Modeling

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Outline

Outline

PIK

Potsdam-Institut für Klimafolgenforschung

Potsdam Institute for Climate Impact Research

- more than 350 employees
- four research domains: Earth system analysis, climate impacts and vulnerabilities, sustainable solutions, transdisciplinary concepts and methods
- investigates scientific and social questions regarding global change, climate impact and sustainability
- methods: system and scenario analysis, quantitative and qualitative modeling, computer simulations and data integration

Climate Impacts

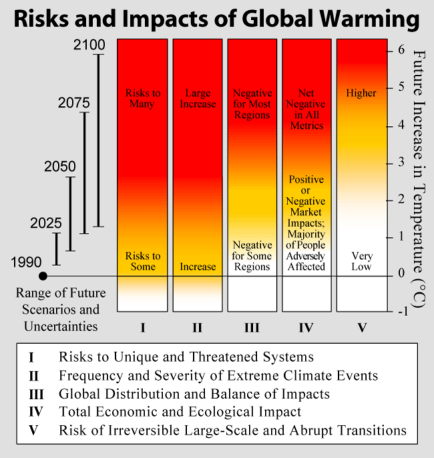
Potsdam Institute for Climate Impact Research

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 and Impacts of Anthropogenic Climate Change



source: http://www.globalwarmingart.com/

This is an iconinc plot in climate impact science and it is called the burning ember diagram.

Regional Climate Modeling

- one of the most important tools for climate impact research: climate models
- 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 (will concentrate on these in this lecture)

Regional Climate Modeling

1. assumption of some future development / 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 of AR5

  WG I *"The Physical Science Basis"*
  (259 authors, 39 countries, 54 677 comments)

  WG II *"Impacts, Adaptation and Vulnerability"*
  (309 authors, 70 countries, 50 444 comments)

  WG III *"Mitigation of Climate Change"*
  (235 authors, 57 countries, 38 315 comments)

- many climate simulations were carried out for WG I (CMIP5 with 42 global models)
- for AR6 a similar exercise was carried out, CMIP6 (about 40 models)

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 (heavy rainfall, dry spell, heat waves, storm surges)

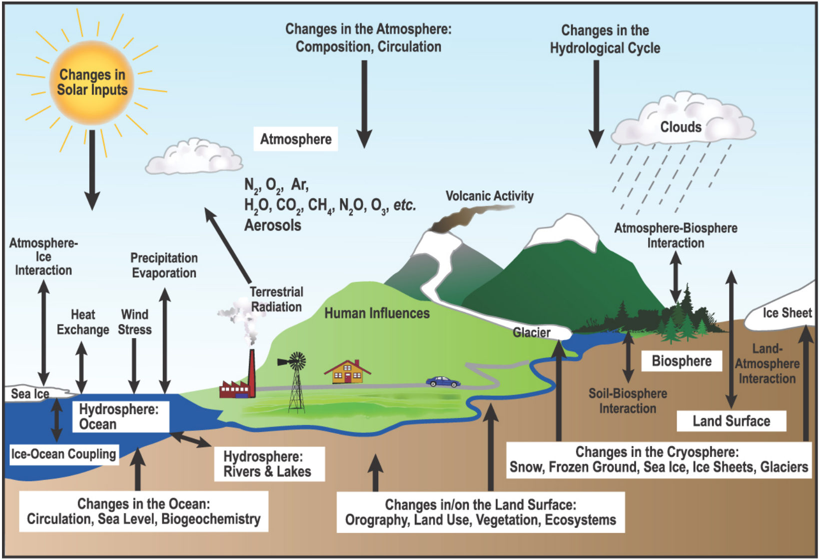
when doing a climate simulation, the question is not

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

but

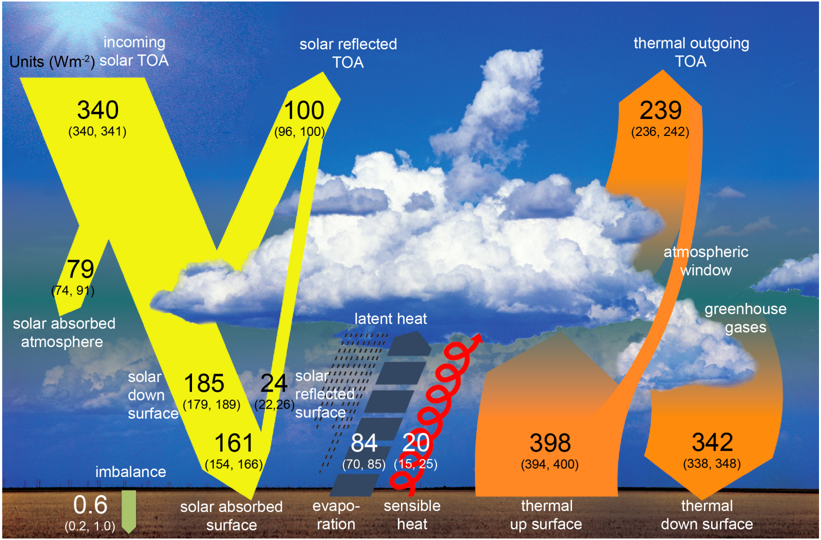
“What are the statistical properties of the temperature in Tokyo in the years 2071 to 2100 under a certain emission scenario?”

Climate System



source: IPCC AR4 2007

Energy budget / Radiation

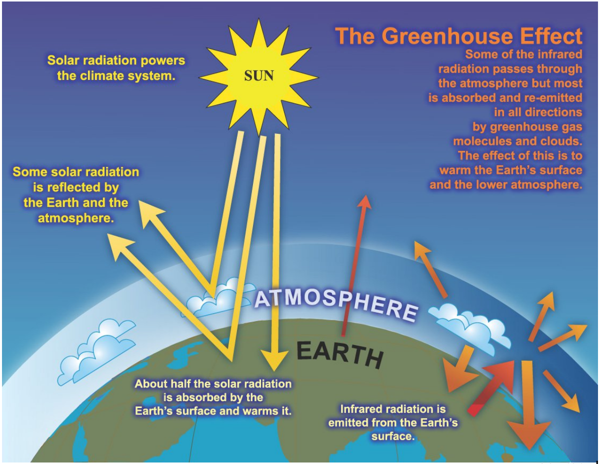


TOA – top of the atmosphere

source: IPCC AR5 (2013)

global mean energy budget under present-day climate conditions

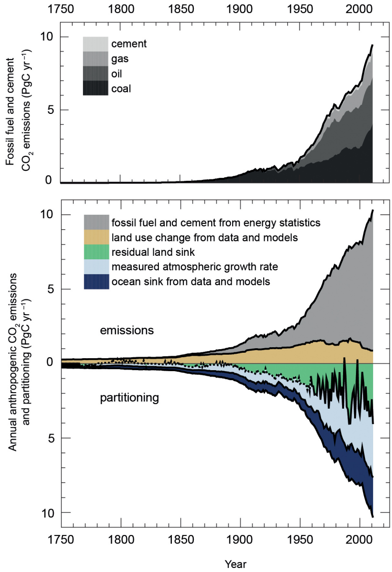
Greenhouse Effect



source: IPCC AR4 2007

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

CO_2 Emissions into the Atmosphere



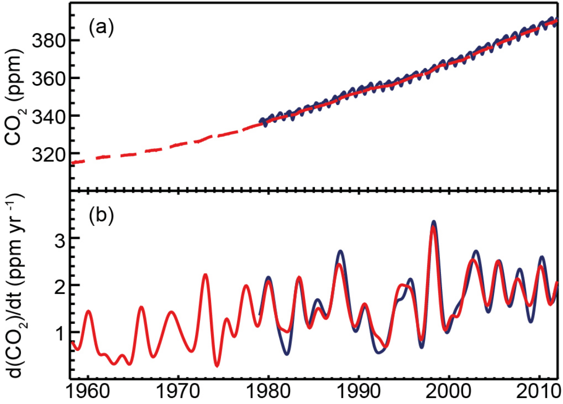
source: IPCC AR5 (2013)

- increased anthropogenic CO_2 emissions start in the 2nd half of 19th century (industrial age)
- 2002–2011 +3.2 % / a
  1990s +1 % / a
- 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

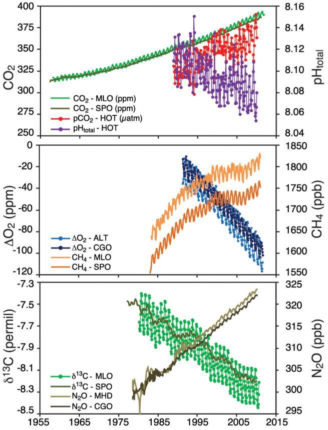
also known as *"Keeling curve"* after Charles David Keeling



annual cycle due to vegetation cycle

source: IPCC AR5

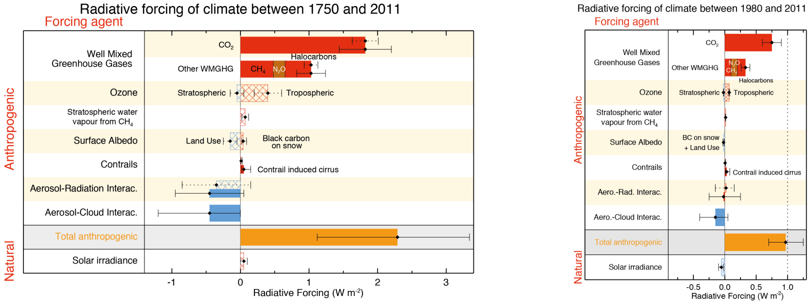
CO_2, Methane, Nitrous Oxides



source: IPCC AR5 (2013)

- CO_2 not the only important green house gas
- methane and nitrous oxides important as well
    - methane increased by a factor of 2.5 compared to preindustrial, largely due to increased number of ruminants, fossil fuel emissions and expansion of rice paddy agriculture
    - nitrous oxides increased by a factor of 1.2 compared to preindustrial, largely due to changes in the nitrogen cycle

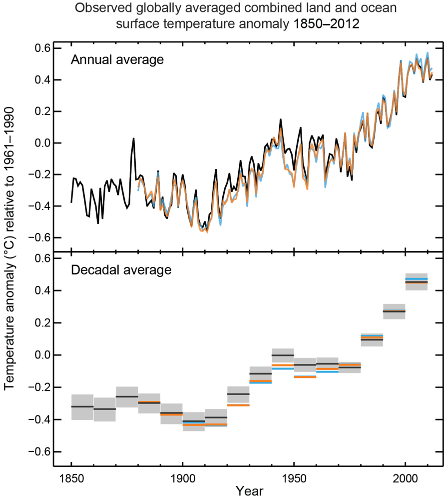
Radiative Forcing



source: IPCC AR5 (2013)

almost half of the additional radiative forcing is due to the last 35 / 40 years

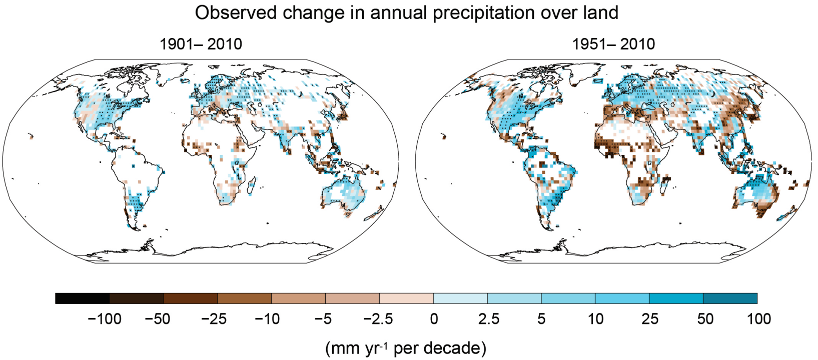
Climate Change – Global Surface Temperatures



source: IPCC AR5 (2013)

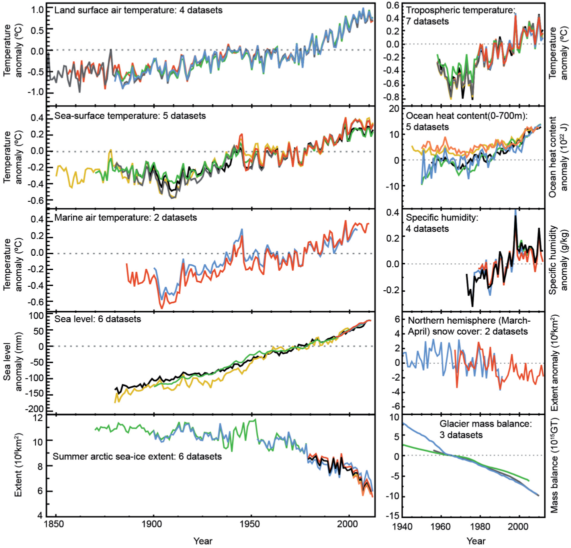
top: annual average global surface temperature anomalies (three data sets)
bottom: decadal (1850–1859, … , 2000–2009) global means with uncertatinty for black data set

Climate Change – Precipitation on Land



source: IPCC AR5 (2013)

Climate Change – further observations



source: IPCC AR5 (2013)

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
- the number of stations is decreasing world wide (exception China)
- 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

Outline

Preliminaries

Climate and Climate Change

Emission Scenarios

Earth System Models

Regional Climate Modeling

The Dynamical Model CCLM

Summary

Emission scenarios

Regional Climate Modeling

1. assumption of some future development/
   emission scenario

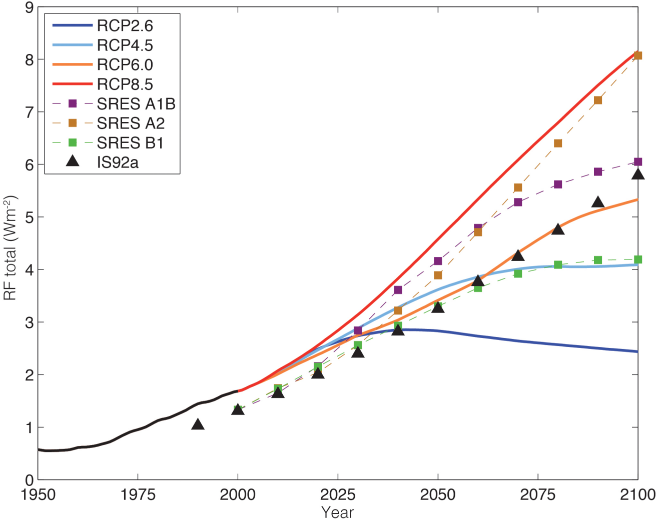
2. simulation of global atmosphere with a global model

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 b/c 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
- unlike SRES, are to 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

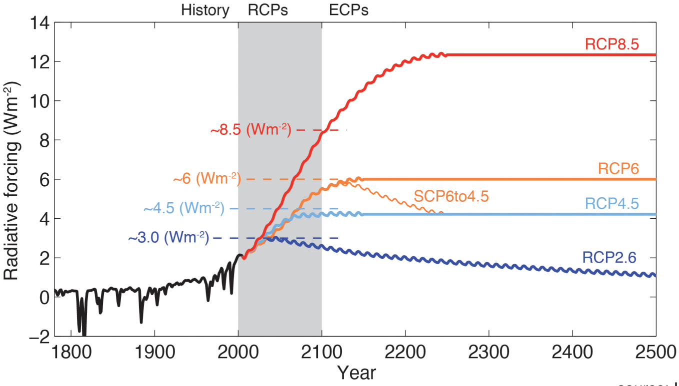
RCP Radiative Forcing (AR5, AR6)



source: IPCC AR5

The SRES scenarios were used in TAR and AR4.

Extended Concentration Pathways (ECP)



source: IPCC AR5

in order to investigate even longer term questions, *“Extended Concentration Pathways”* (ECP) were introduced

mainly linear extensions

RCP, SSP (AR6, CMIP6)

for CMIP6 the RCPs are still used, however, they are combined with SSPs (*"shared socio-economic pathways"*), e.g. SSP1-8.5

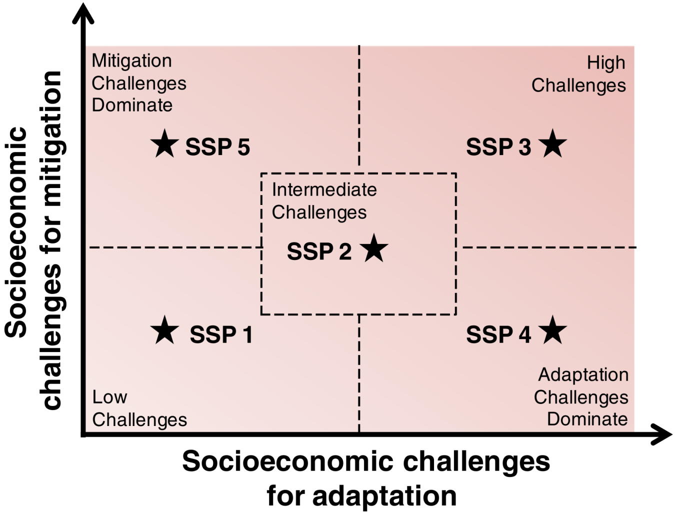
- set of five story lines that describe possible developments for human development and global environmental change during the 21st century
- describe various quantities such as population size, urbanization rates, income, energy use and production, agriculture, land use, emissions
- mirrors previous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

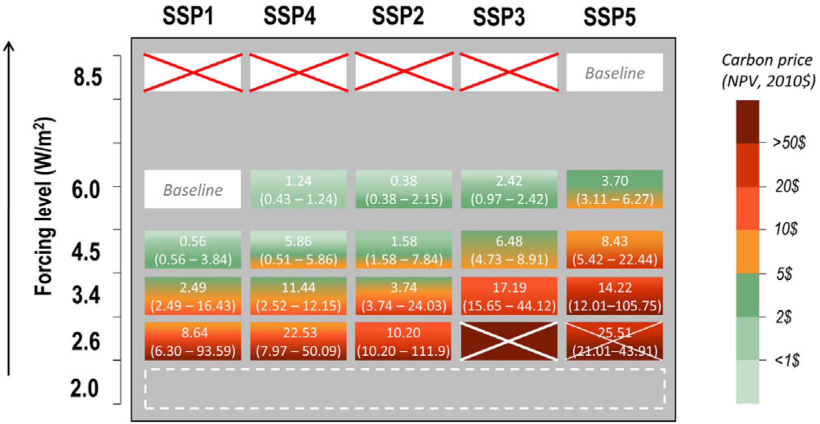
source: poster by Riahi *et al.*

SSP (AR6, CMIP6)



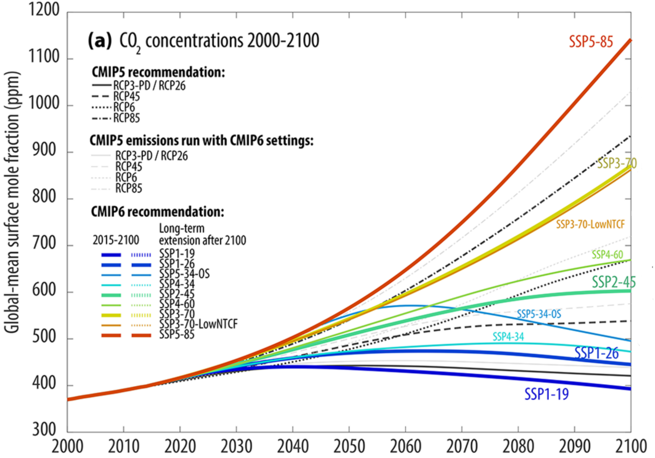
source: Neill *et al.*, DOI:https://doi.org/10.1007/s10584-013-0905-2

RCP, SSP (AR6, CMIP6)



source: Riahi *et al.,* DOI https://doi.org/10.1016/j.gloenvcha.2016.05.009

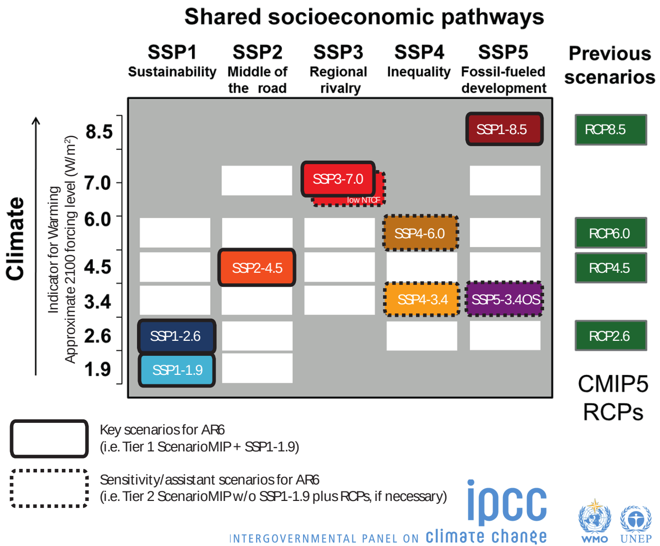
RCP, SSP (AR6, CMIP6)



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

AR6, CMIP6 Scenarios



source: IPCC (2019)

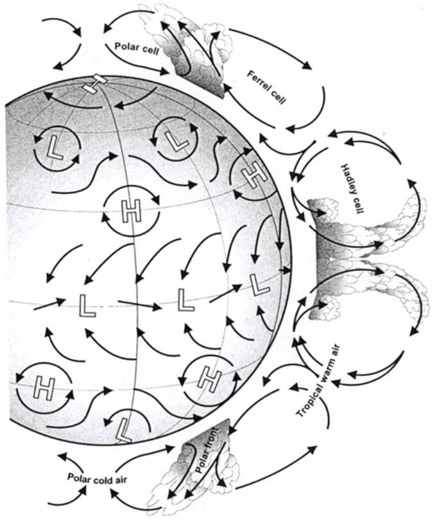
Outline

Earth System Models (ESM)

Regional Climate Modeling

1. assumption of some future development/ 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

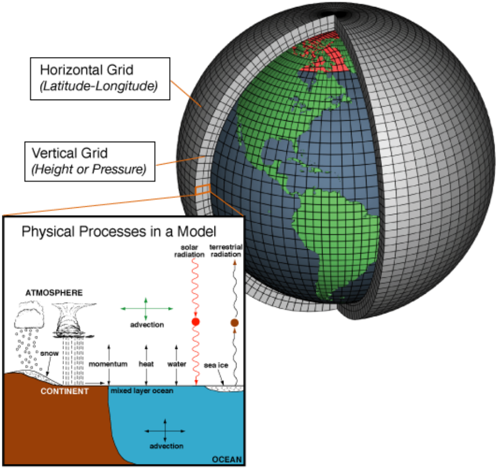
Global climate is not made up of regional climates.
Instead, regional climate should be understood as the result of an interplay of global climate and regional physiographic detail.

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

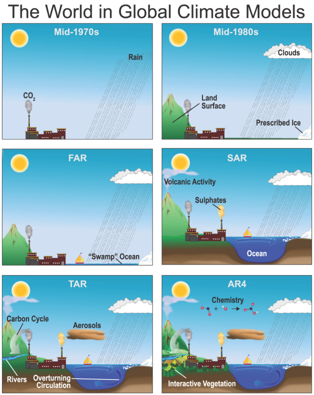
General Circulation Models



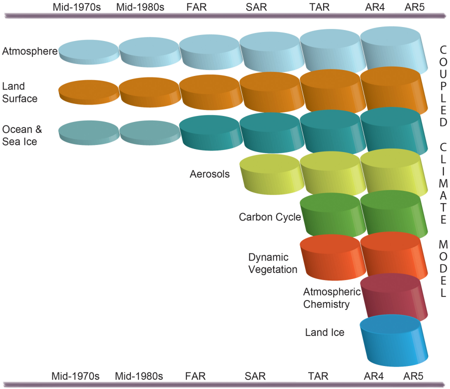
source: http://en.wikipedia.org/wiki/General_Circulation_Model

- *"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

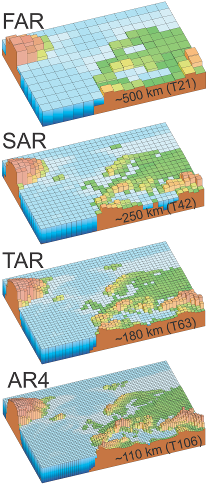


source: AR4 (2007)

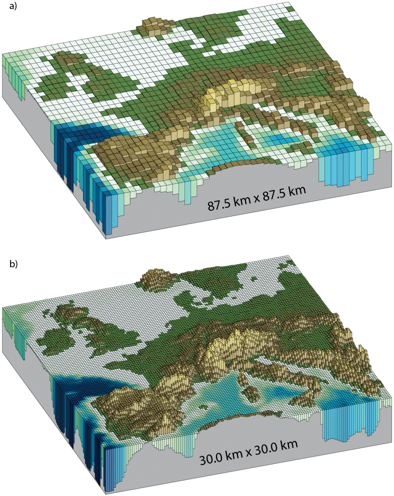


source: AR5 (2013)

ESM Resolution



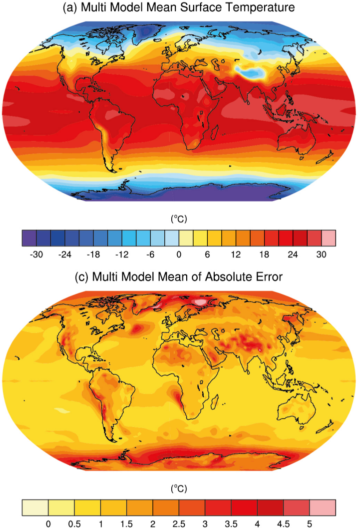
source: IPCC AR4 (2007)



source: IPCC AR5 (2013)

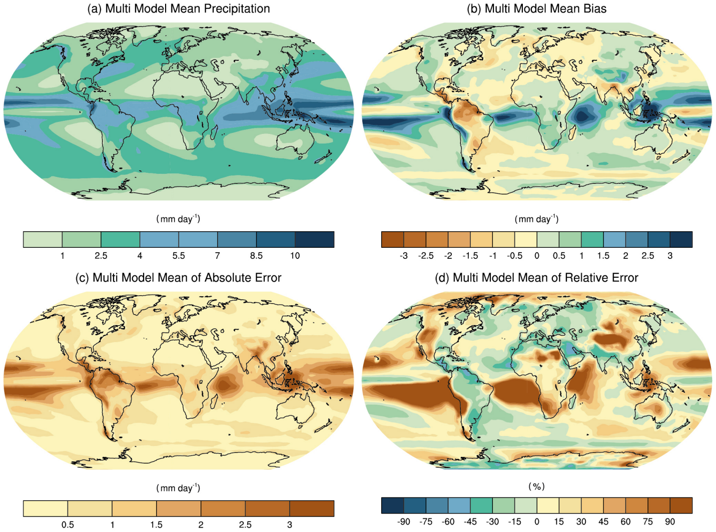
left: ESM resolutions FAR to AR4 *top right:* current ESM resolution
bottom right: current experimental ESM resolution

Performance of ESM: Annual Mean 2 m Temperature



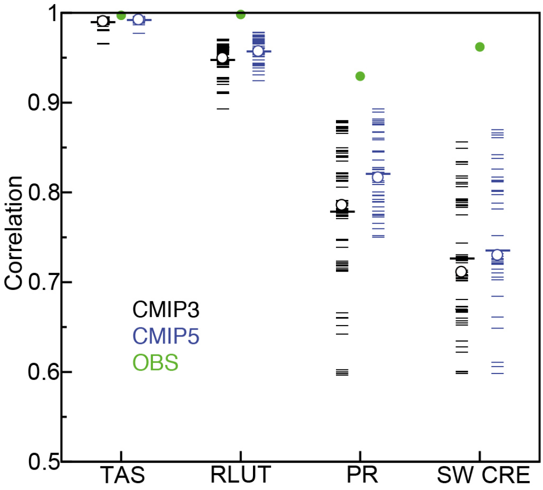
CMIP5 multi-model mean; time frame: 1980–2005; observation in (b) and (c): ERA-interim; (d) mean of absolute pairwise differences between ERA40 and JRA-25 reanalyses source: AR5 (2013)

Performance of ESM: Annual Mean Precipitation



CMIP5 multi-model mean; time frame: 1980–2005; observation in (b), (c) and (d): GPCP source: AR5 (2013)

Performance of ESM: centered pattern correlations

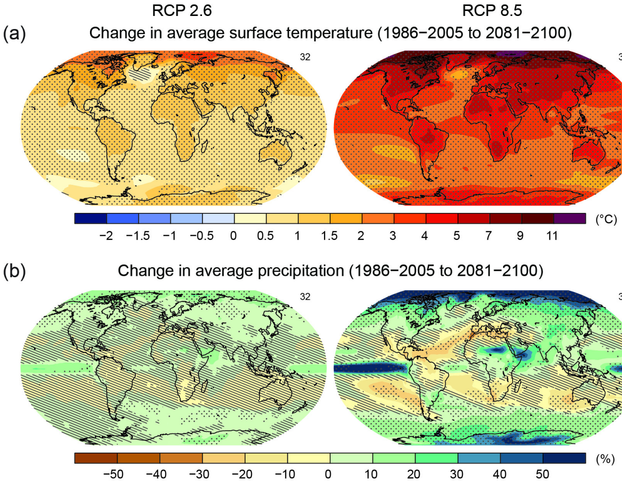


time frame: 1980–1999; TAS: surface air temperature, RLUT: TOA outgoing longwave radiation, PR: precipitation, SW CRE: TOA shortwave cloud radiative effect; OBS: correlations between default and alternate observations
source: IPCC AR5 (2013)

Performance of ESM in AR5/CMIP5

- large scale mean surface temperature patterns reproduced (pattern correlation 0.99), however systematic errors of several degrees in some regions
- models reproduce mean surface temperature increase in 2nd half of 20th century, including cooling after volcanic eruptions , fail to reproduce decreased warming of last 10 to 15 years (there was no decreased warming)
- reproduction of large scale precipitation patterns has improved, but still lacking compared to temperature
- simulation of clouds remains challenging
- general characteristics of storm tracks and extra-tropical cyclones are captured

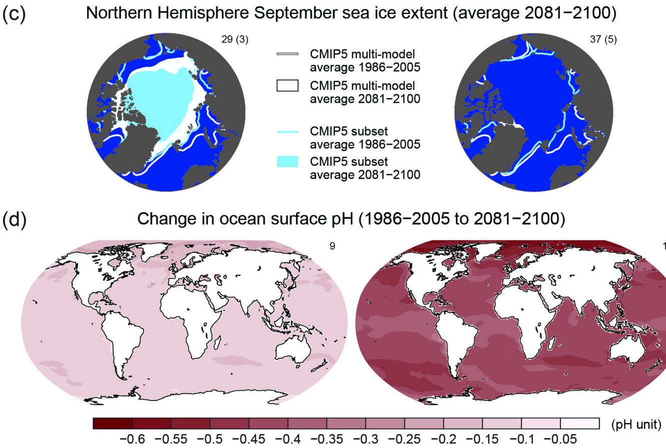
ESM Long Term Projection Mean Annual Surface Temperature and Precipitation



CMIP5 multi model mean; stippling: significant change ($\Delta x > 2\sigma$) and 90 % of models agree on sign; hatching: small Δx compared to internal variability ($\Delta x < \sigma$); upper right number: *n* models

source: IPCC AR5 (2013)

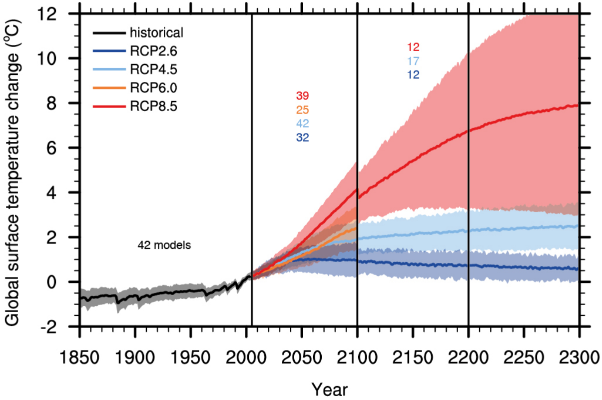
ESM Long Term Projection Arctic Sea Ice and Ocean Acidification



CMIP5 multi model mean; subset in (c) are models that most closely reproduce 1979–2012; upper right number: *n* models (*n*) models in subset

source: IPCC AR5 (2013)

ESM Long Term Projection Mean Surface Temperature



anomaly vs 1986–2005; 5th to 95th percentile; solid line: model mean; colored numbers: *n* models

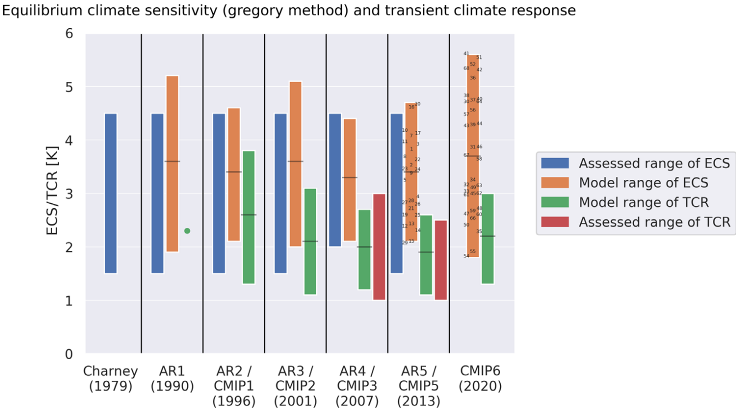
source: IPCC AR5 (2013)

CMIP6 Results: ECS, TCR

- in CMIP6 some models get rather hot when compared to previous CMIP rounds
- measured by climate sensitivities ECS and TCR

1. Equilibrium Climate Sensitivity (ECS), idea: double CO_2, let the model run to equilibrium, the resulting ΔT is called ECS
2. Transient Climate Response (TCR), idea: every year add 1 % CO_2 to the atmosphere until it's doubled (no equilibrium), ΔT is TCR

CMIP6 Results: ECS



source: Meehl *et al.,* 2020, DOI 10.1126/sciadv.aba1981

CMIP6: highest ECS ever with 6 models exceeding an ECS of 5 °C

CMIP6 Results: ECS

Reasons not entirely clear yet, publications mostly discuss

- cloud feedbacks
- aerosol cloud interaction
- so far no explanation applicable to all models running hot has emerged
- for further details see

Meehl *et al.,* 2020, DOI 10.1126/sciadv.aba1981
Zelinka *et al.,* 2020, DOI 10.1029/2019GL085782

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Regional Climate Modeling

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Scales and atmospheric processes (Orlanski 1975)

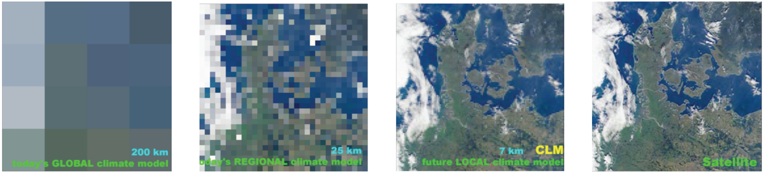
> 10 000 km	general circulations in the atmosphere (weeks to month)	macroscale α
10 000 – 2000 km	baroclinic waves (weeks to month)	macroscale β
2000 – 200 km	weather front and cyclones (days)	mesoscale α
200 – 20 km	orographic effects, land sea wind, urban effects (days)	mesoscale β
20 – 2 km	thunderstorms, 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 below 50 km and on time scales of one day or less
- 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

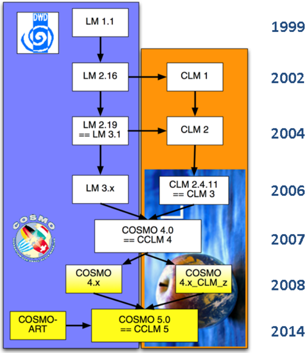
Dynamical Regional Modeling

- 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

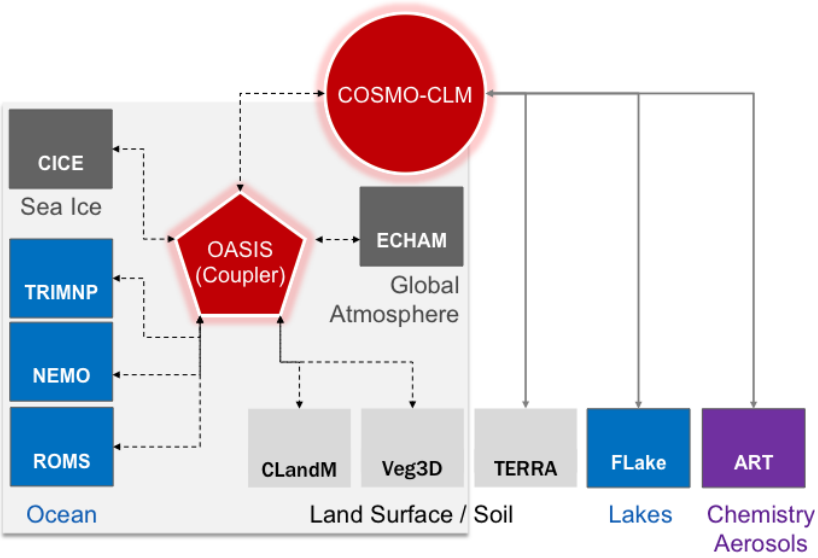
- first version of CCLM developed by PIK, HZG and BTU Cottbus on the basis of “Lokalmodell” (predecessor of COSMO), developed by DWD
- since 2005 community model of the German climate research
- 2007: unified model version for operational weather prediction and climate modeling
- current recommended 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:

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

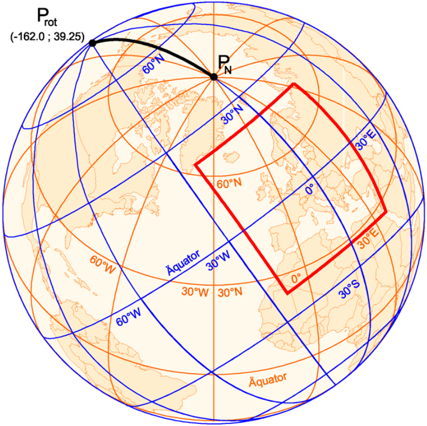
ρ air density, q mass fraction of x, t time, x constituent: d - dry air, v - water vapor, l - liquid water, f - ice, J diffusion flux of x, I source/sinks of x

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

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

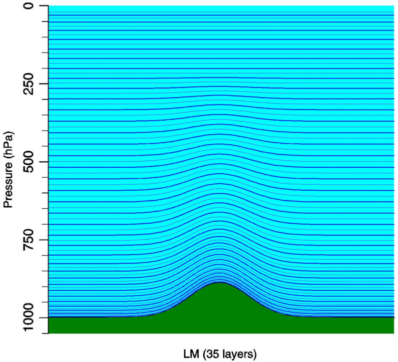
ρ air density, e specific internal energy, t time, p air pressure, v wind velocity, J_e heat flux, R flux density of solar/heat radiation, ε dissipation of kinetic energy due to viscosity

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:

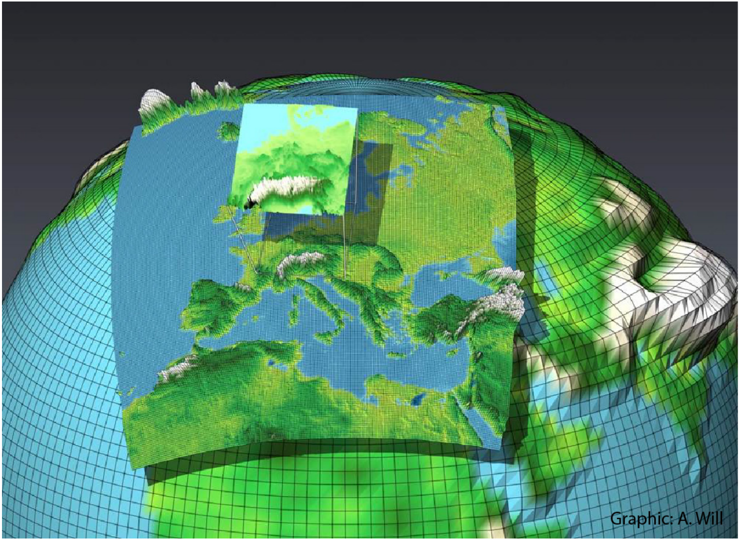
- specific cloud ice content
- turbulent kinetic energy
- specific rain, snow and graupel water content

CCLM – Diagnostic variables (examples)

calculated from prognostic variables e.g.

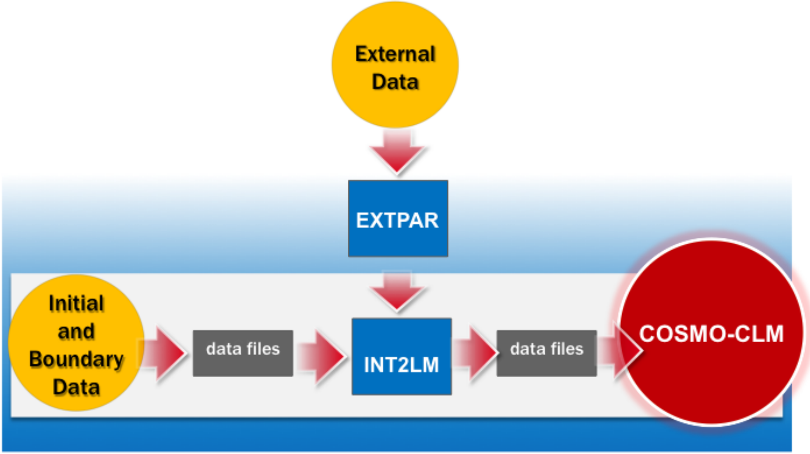
- air density
- cloud cover
- heat fluxes
- moist fluxes
- 2 m temperature
- 10 m wind

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

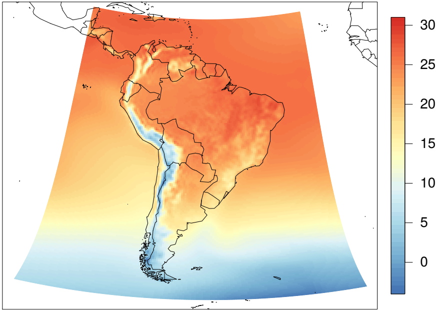
simulation period: 1 / 1 / 1979 – 12 / 31 / 2009

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

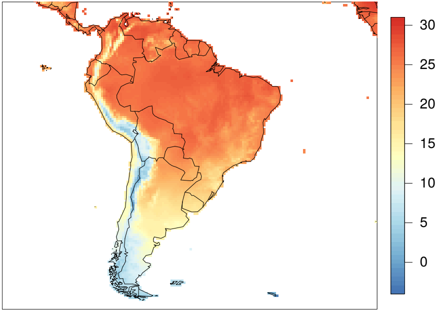
model version: CCLM 4.25_clm3 (setup by S. Lange)

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

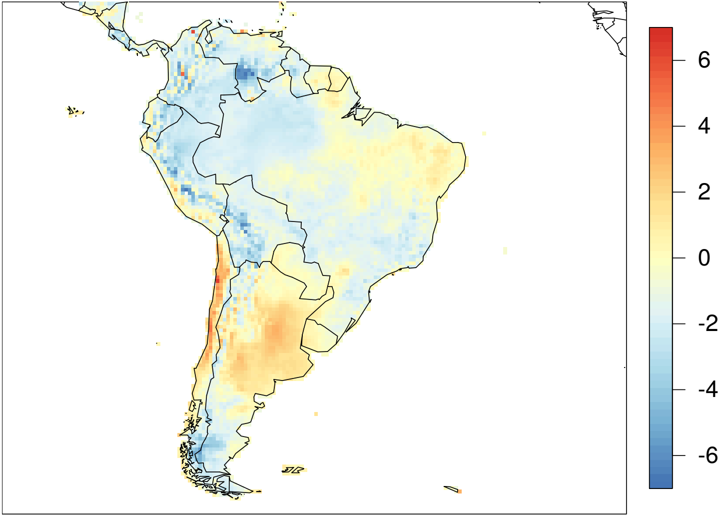


CCLM 4.25_clm3 (sim) [°C]



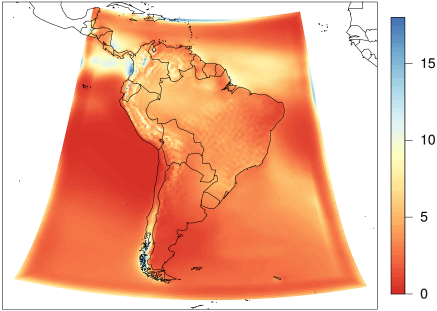
CRU TS 3.21 (obs) [°C]

Validation: Annual Average 2 m Temperature 1985–2009

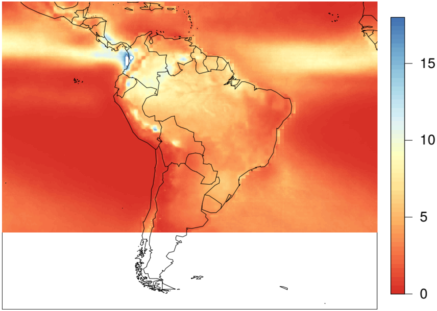


(sim – obs) [°C]

Validation: Annual Average Precipitation 1998–2009

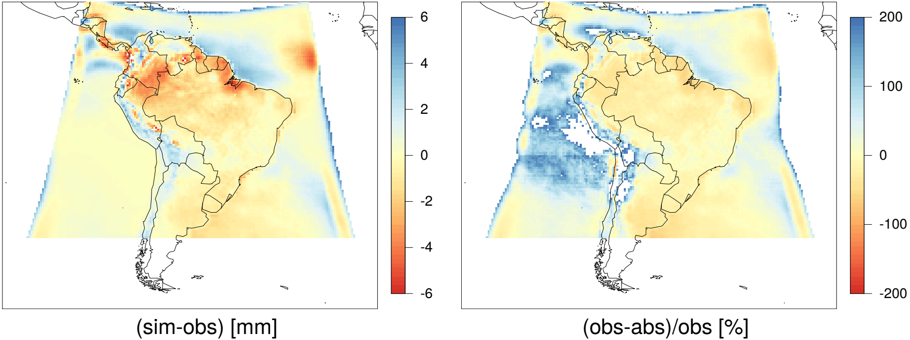


CCLM 4.25_clm3 (sim) [mm]



TRMM 3B42v7 (obs) [mm]

Validation: Annual Average Precipitation 1998–2009



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)

Climate Data

ISIMIP

Bias adjusted climate data from ISIMIP

`https://data.isimip.org/`

DKRZ

CMIP6 (requires registration)

`https://esgf-data.dkrz.de/search/cmip6-dkrz/`

at `https://esgf-data.dkrz.de/projects/esgf-dkrz/` you can find a lot more data, look at the right margin