Climate modelling and reanalyses

Lecture during

GNSS4SWEC First Summer School

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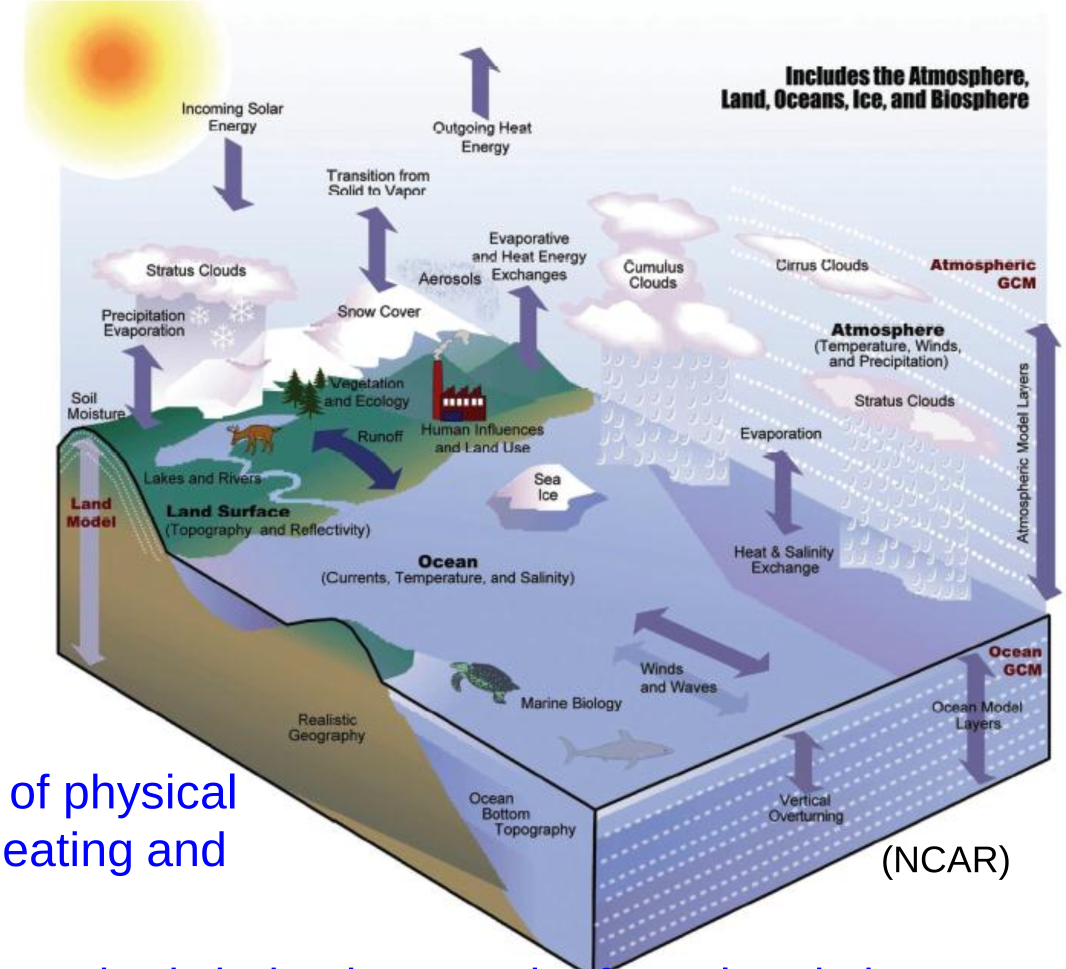
Outline

- Climate models
- Climate contra NWP models
- Reanalysis
- Observations for model evaluation
- Observed Climate change
- Climate scenarios

Climate model:

Three dimensional representation of the atmosphere coupled to the land surface and oceans (biosphere, carbon cycle, atmosphere chemistry)



(NCAR)

The atmosphere is governed by a set of physical laws expressing how the air moves, heating and cooling, moisture, and so on.

Although the equations describing atmospheric behaviour can be formulated, they cannot be solved analytically. Instead, numerical methods are needed to provide approximate solutions.

Given a description of the initial state of the atmosphere, the equations can be used to propagate this information forwards to produce a simulation of a future state.

Interactions between the atmosphere and the underlying land and ocean are important in determining the climate (weather).

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Equations describing the atmosphere:

$$\frac{\partial u}{\partial t} + \vec{V}\cdot\nabla u + \omega\frac{\partial u}{\partial p} - fv = -\frac{\partial \phi}{\partial x} + F_x$$

$$\frac{\partial v}{\partial t} + \vec{V}\cdot\nabla v + \omega\frac{\partial v}{\partial p} + fu = -\frac{\partial \phi}{\partial y} + F_y$$

$$\frac{\partial \phi}{\partial p} = -\alpha$$

Navier Stoke's equations (Newton's 2nd law)

$$\frac{\partial T}{\partial t} + \vec{V}\cdot\nabla T + \omega\frac{\partial T}{\partial p} \text{[illegible]}$$

Heat equation

$$\nabla\cdot\vec{V} + \frac{\partial \omega}{\partial p} = 0$$

Continuity equation

$$p\alpha = RT$$

Gas law

$$\frac{\partial q}{\partial t} + \vec{V}\cdot\nabla q + \omega\frac{\partial q}{\partial p} = S_q$$

Humidity equation

Equations describing the atmosphere:

7 unknowns: u, v, ω, T, α, ϕ, q
7 partial differential equations

Now we just have to discretise them in space and time and run them in a computer!

Navier Stoke's equations
(Newton's 2nd law)

Heat equation

$$\nabla\cdot\vec{V}+\frac{\partial\omega}{\partial p}=0$$

Continuity equation

$$p\alpha=RT$$

Gas law

$$\frac{\partial q}{\partial t}+\vec{V}\cdot\nabla q+\omega\frac{\partial q}{\partial p}=S$$

Humidity equation

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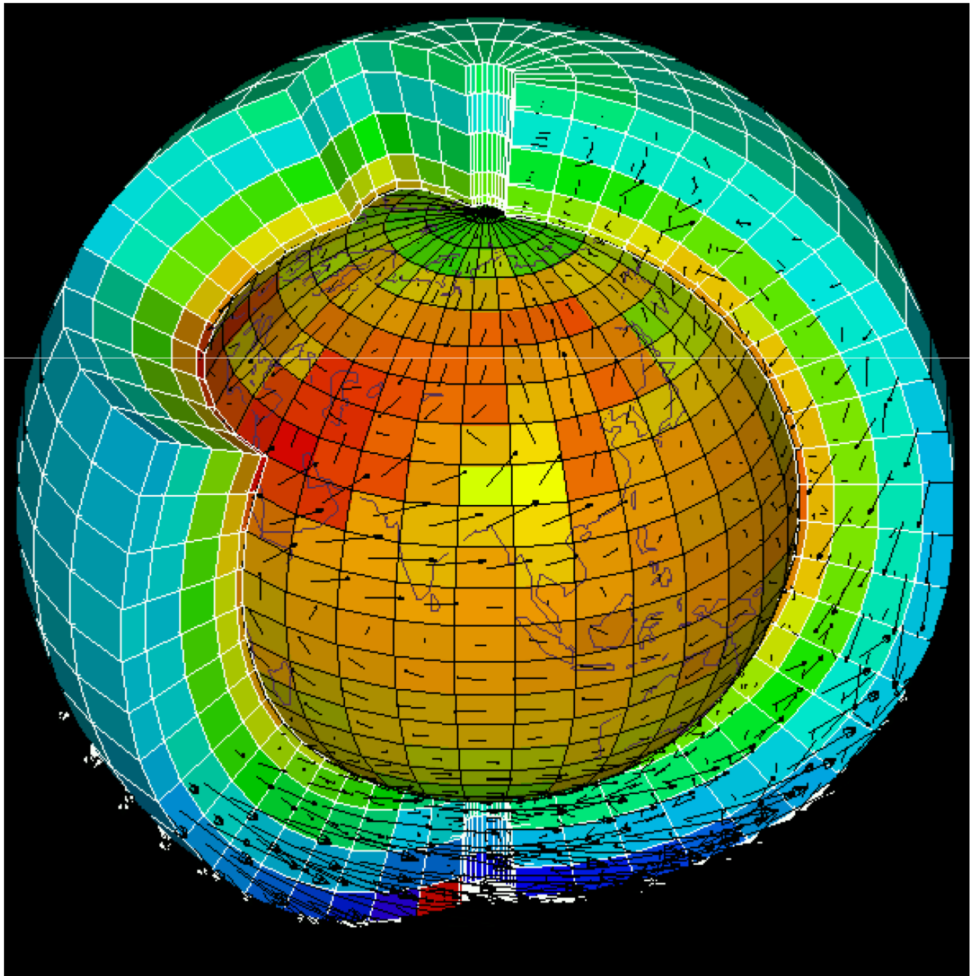
A General Circulation Model or Global Climate Model (GCM)

So, we end up with a huge box full with small boxes where the coupled equations are solved at each timestep



In a GCM these boxes cover the whole earth and are around

- **100-400 km wide**
- **20-90 vertical layers**

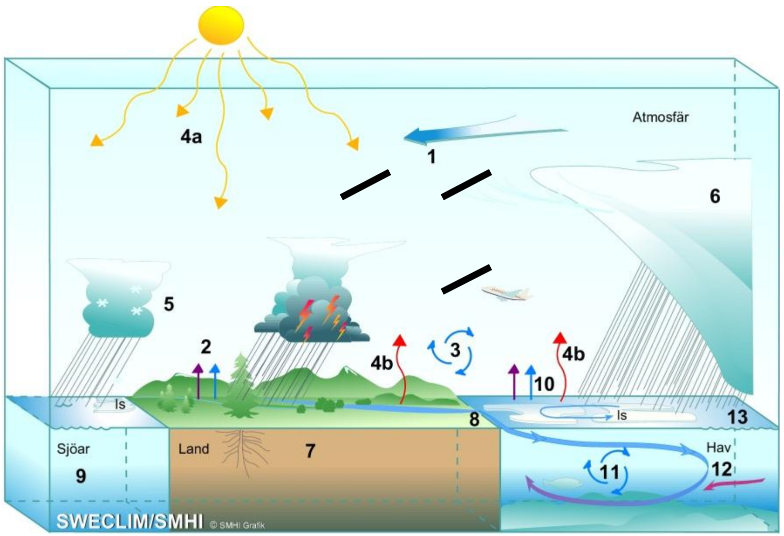
The time step is around 30 min

A General Circulation Model or Global Climate Model (GCM)

The information needed to run a GCM (atmosphere and ocean) is:

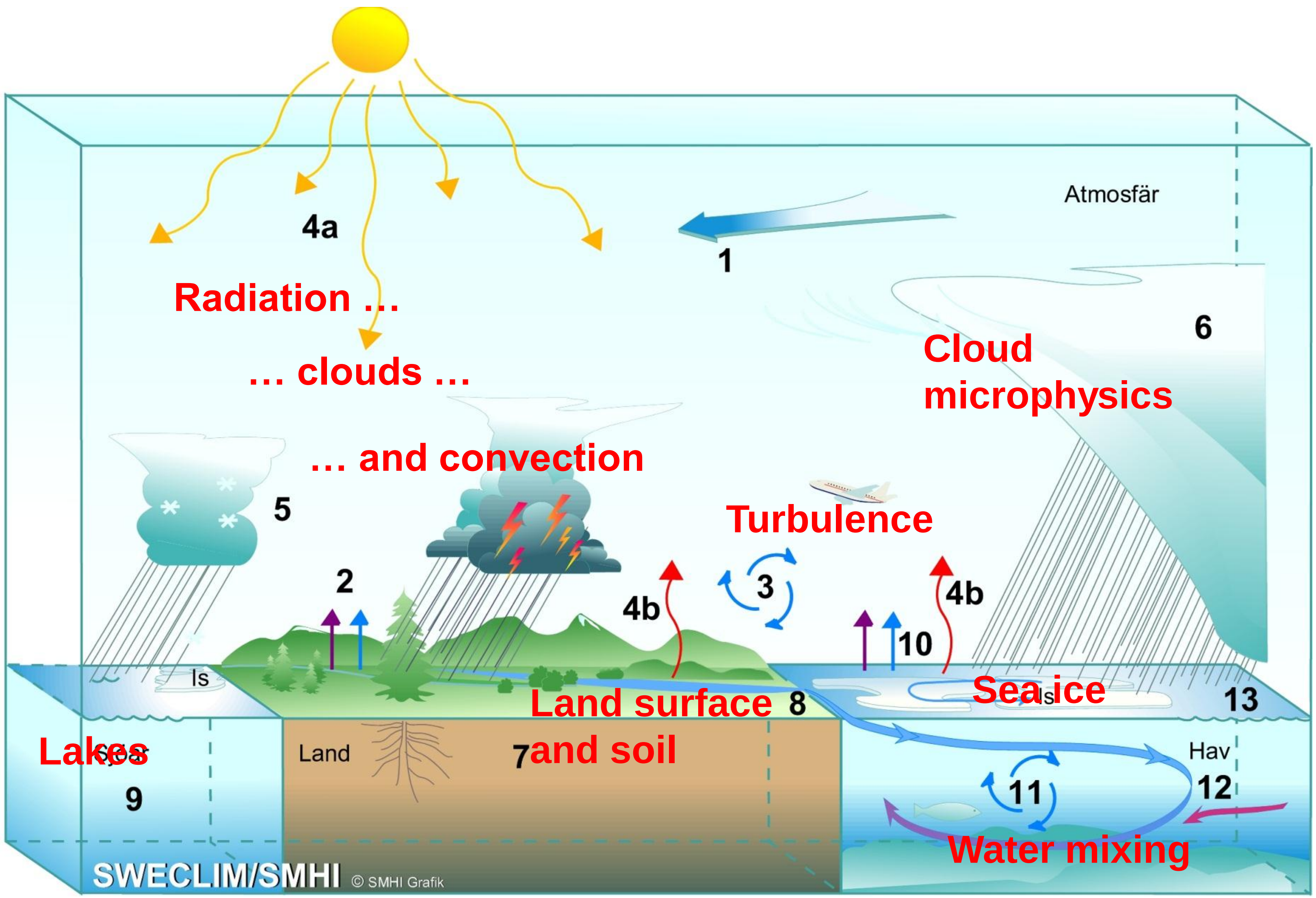
- ✓ **Initial state of all the variables in all boxes**
- ✓ **A description of the land surface (topography and land use)**
- ✓ **Solar radiation**
- ✓ **Gas and aerosol composition of the atmosphere**

Limitations of a GCM

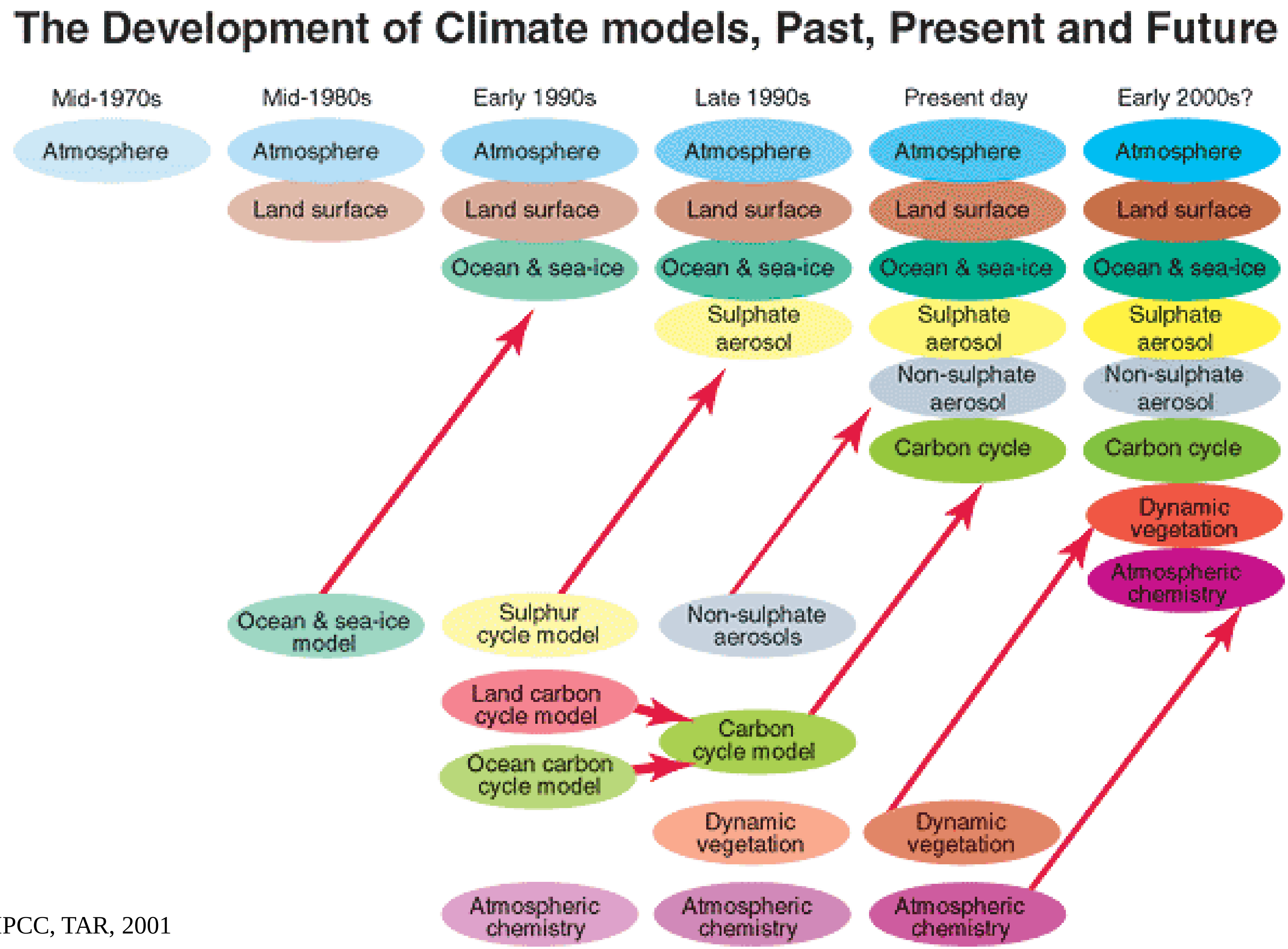


- Inside each box many processes take place that must be described in an approximate way (e.g. turbulence, cloud and rain formation, how aerosols interact with radiation and clouds, …)
- Very small boxes would give us less approximations BUT a very time consuming and slow model.
- Thus, a GCM is a compromise between details in physics and numerical speed of the model (how long simulations you need)!

Sub-grid parameterisations



Interacting systems



Source: IPCC, TAR, 2001

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Some important uncertainties in process descriptions in climate models

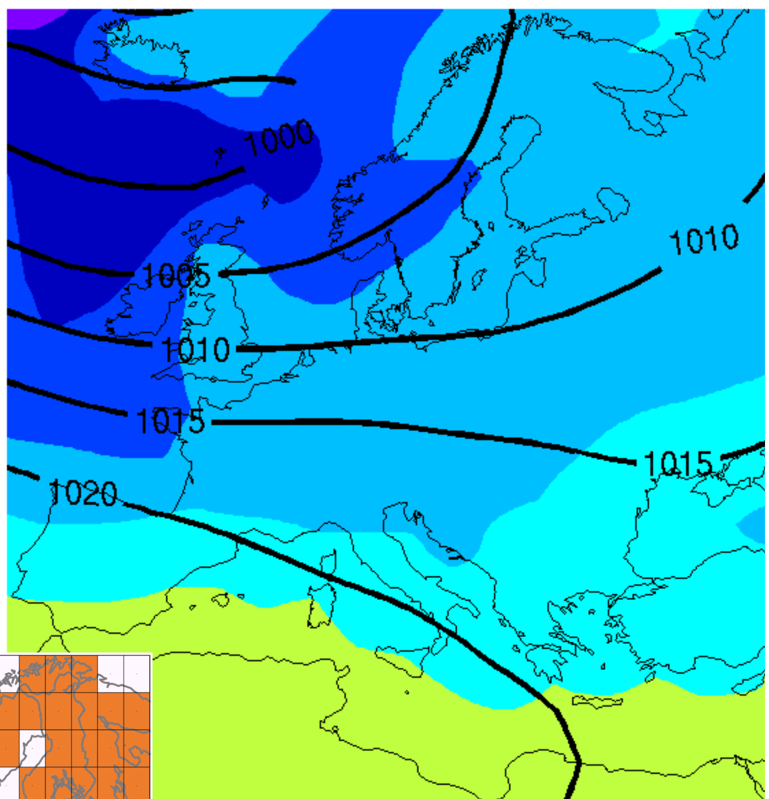
- Cloud feedback is still a major uncertainty.
- Aerosol effects on climate is still quite uncertain.
- The strength of the coupling between climate and the carbon cycle
- Sea ice development is uncertain
- Melting of ice sheets very uncertain → sea level rise uncertain

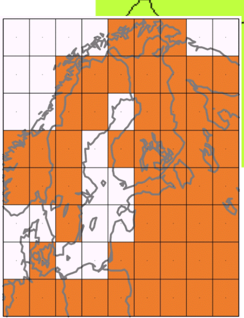
Regional climate models (RCM)

Why regional climate models?

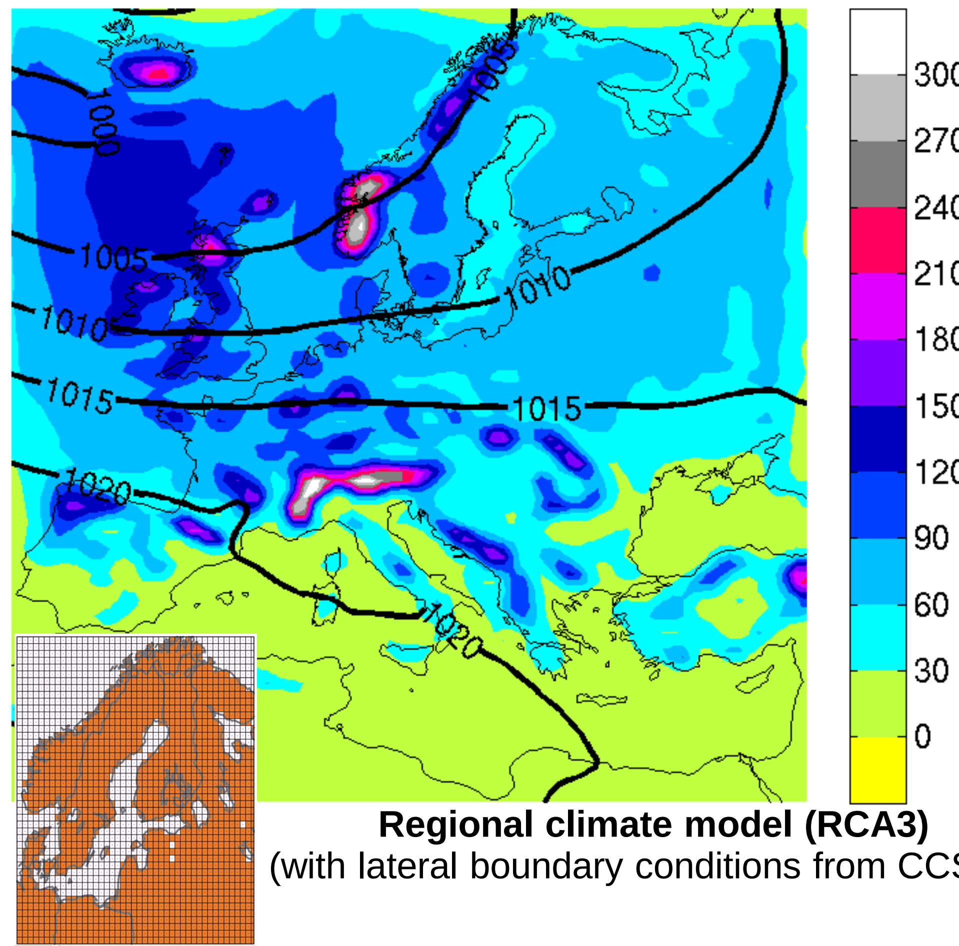
Can better represent horizontal heterogeneity e.g. in precipitation patterns as induced by complex topography and/or land/sea contrasts.

Simulated winter (DJF) SLP and precipitation (1961-1990)





Global climate model (CCSM3)



Regional climate model (RCA3)
(with lateral boundary conditions from CCSM3)

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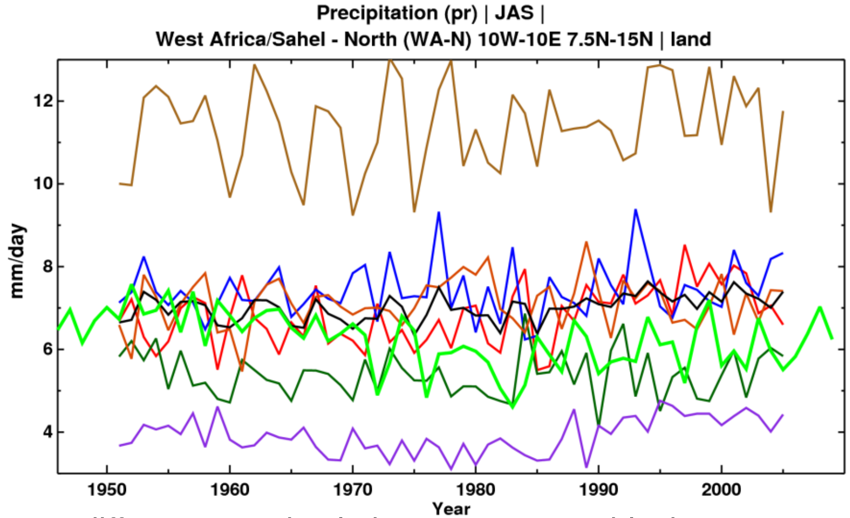
Downscaling by a single RCM can reduce spread among forcing GCMs

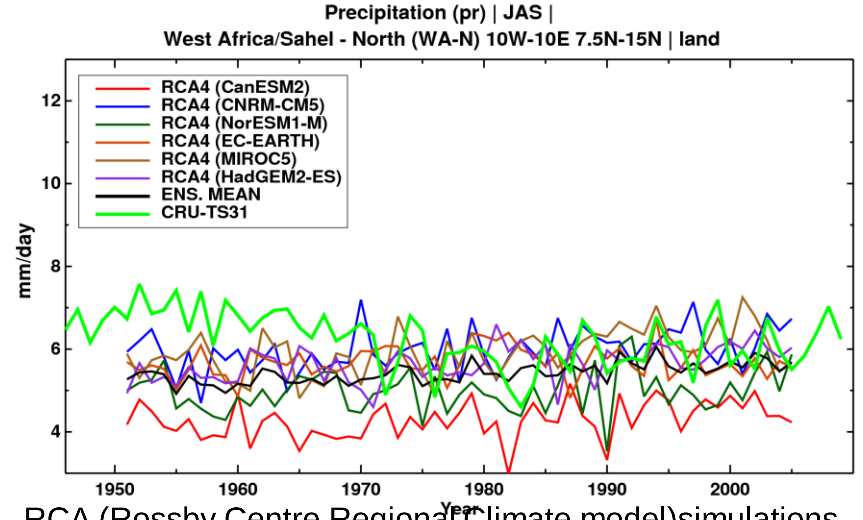
GCMs present day simulated precipitation over Sahel – large spread



6 differnt GCM simulations, ENS mean black curve

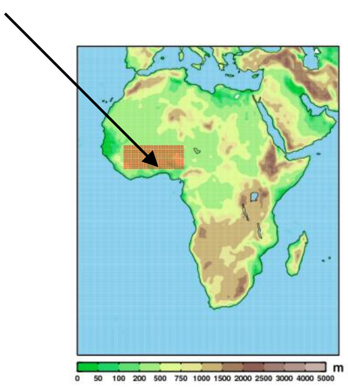
Observation green curve

RCA4 downscaled present day simulated precipitation over Sahel – smaller spread



RCA (Rossby Centre Regional Climate model)simulations.

Observation green curve



RCA4 corrects large precipitation biases in driving GCMs and substantially reduces spread of individual GCM simulations around observations

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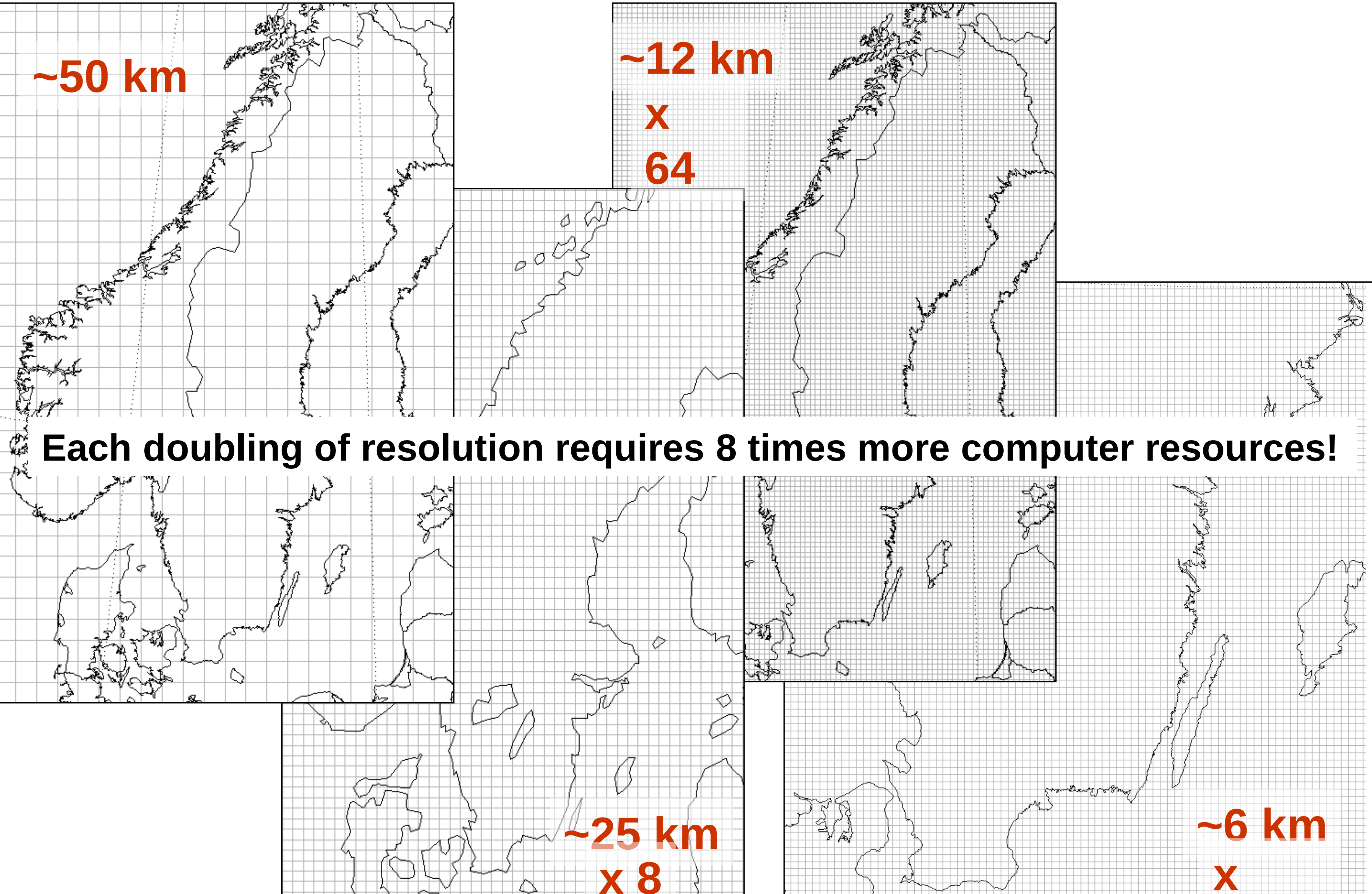
… but the cost is high!



Each doubling of resolution requires 8 times more computer resources!

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The difference between a Climate Model (GCM) and a Weather Prediction Model (NWP)

Climate is statistics of weather

From a weather forecast we expect to have

The correct value of a specific variable (temperature, wind precipitation) at a certain time and place.

From a climate simulation we expect to have

The correct statistics of variables and events like

- Temperature (mean, max, min, number of hot/cold days)
- Storms (how many, how intense)
- Precipitation (mean, number and intensity of heavy events)

The ocean is important for climate

A GCM used for climate simulations must include a model for the ocean

BUT

In a weather prediction model it is in principal enough to update the sea-surface temperature with observations from satellites.

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The initial condition for a weather/climate simulation

The physics in the models is very much the same

The part of e.g. SMHI’s weather prediction and climate simulation models that describes processes in the atmosphere and in the land surface are similar to 95%.

The methods to reach a good initial condition are very different

The initial condition is the values of temperature, humidity, wind and so on, that are given for each grid box at the start of a numerical simulation.

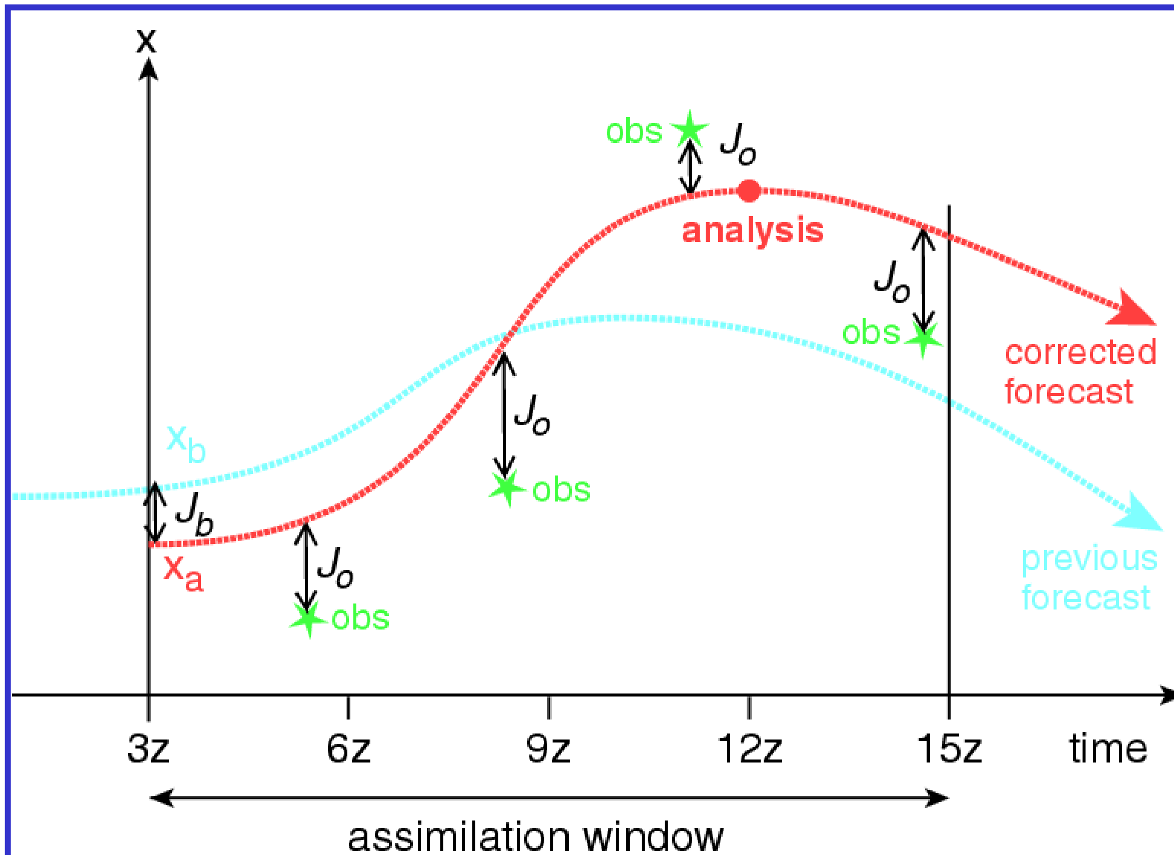
The methods to reach a good initial condition is fundamentally different in weather prediction and climate simulation modelling.

Initial condition in NWP

For weather predictions the initial condition is calculated as the "best mix" of a previous forecast (first guess) and new observations. This procedure is called data assimilation.

4-dimensional data assimilation:

A previous forecast (first guess) is mixed with observations to create a new initial condition (analysis) for a specific time (in this case 12Z).



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Initial condition in climate simulation

The initial condition for a climate simulation is given by a description of the state at the start time. This description we can get from:

- Analysed fields (old analysis from data assimilation)
- Another model
- Climatology

After the initial state is given the model is run for a certain period to reach a good balance between the model variables (spin up). The length of the spin up is decided by a combination of quality in the initial state and the time scale of the processes involved in the system.

The balance especially concerns slow changing variables with long “memory” like deep soil temperatures, snow pack, deep ocean layers, vegetation development, …

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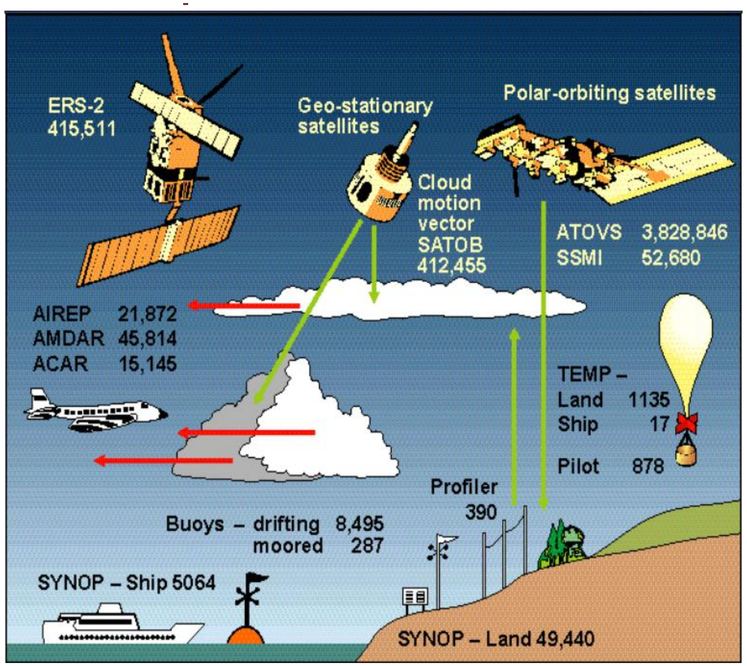
What is a climate reanalysis?

A numerical description of the recent climate combining models with observations. It contains estimates of atmospheric parameters such as air temperature pressure and wind at different altitudes and surface parameters such as rainfall, soil moisture content and water vapour. The estimates are obtained by running a forecast model and data assimilation system to “reanalyse” archived observations to create a global data sets describing the recent history of the atmosphere, land surface and ocean.

From http://www.ecmwf.int/en/research/climate-reanalysis.



Example of typical data sources for the data assimilation system

Different Reanalysis produced by ECMWF

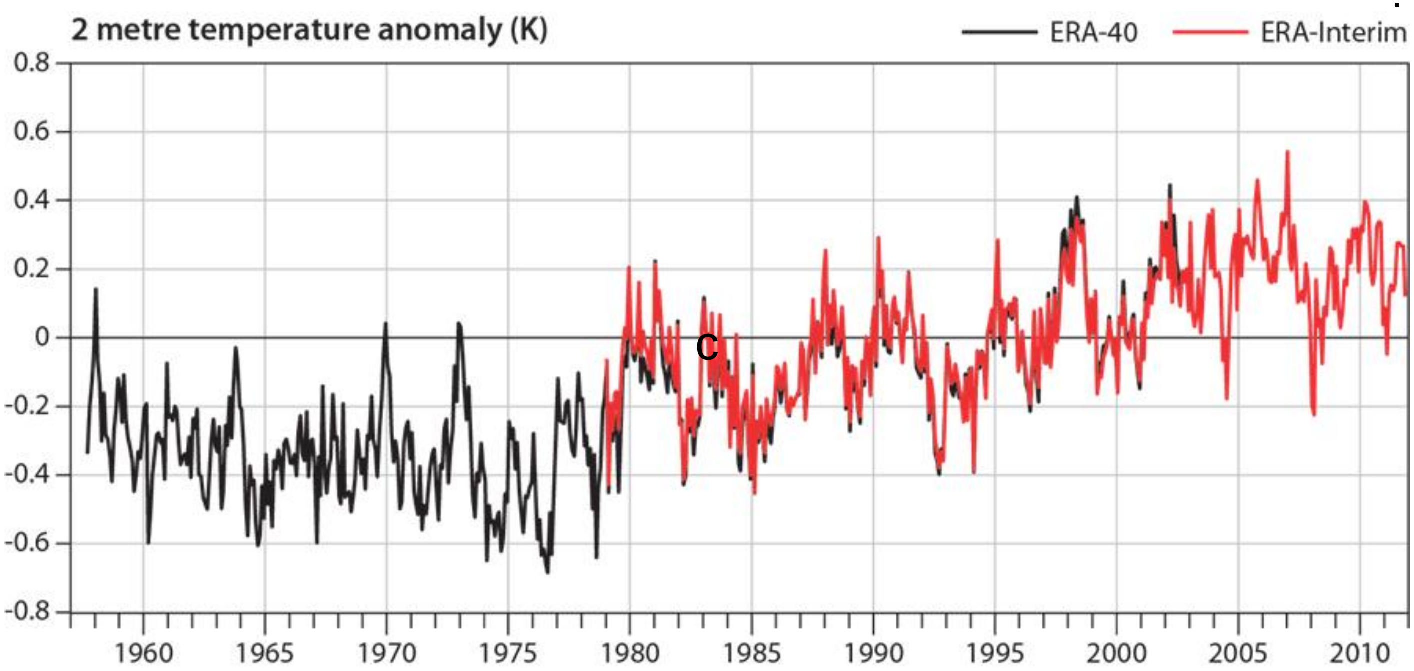
ERA-40 1957-2002, 125 km (T159) 60 vertical levels

ERA-Interim: 1979 – today(March 2014), 80km (T255) 60 vertical levels

ERA-20C: 1900-2012. Only assimilation of surface pressure and surface marine winds (production in progress)

Coupled Earth-system reanalysis: Coupled atmosphere-ocean data assimilation system (under development)

http://www.ecmwf.int/en/research/climate-reanalysis



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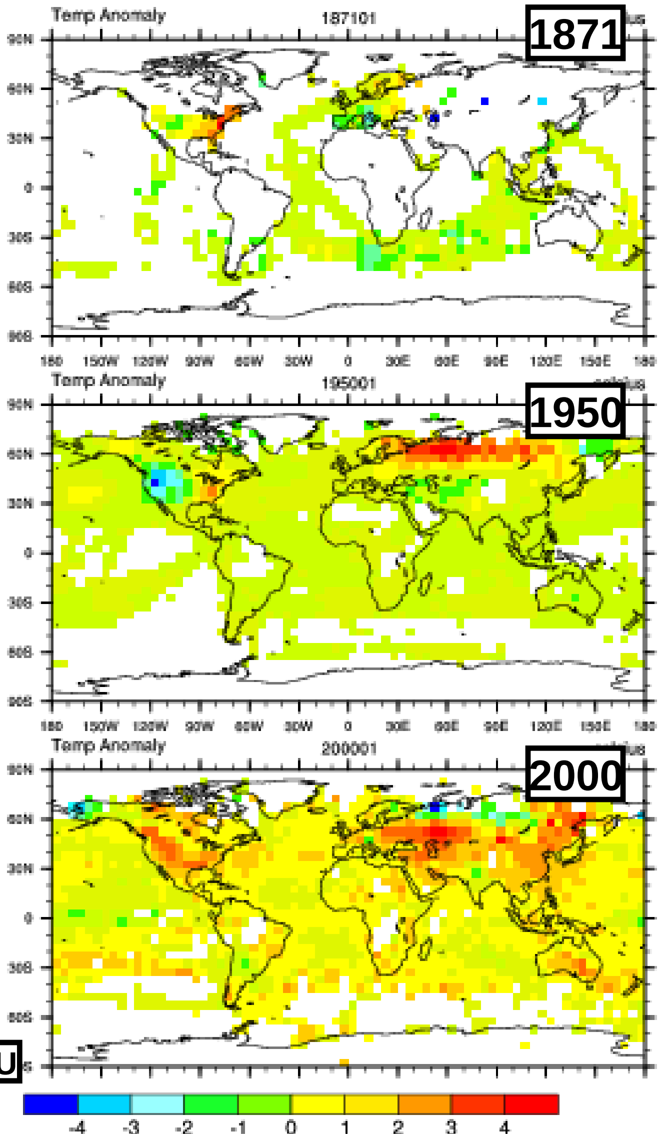
How to evaluate a GCM or a RCM?

- Perform long (~ 1000 years) control integrations with constant forcing conditions. By the end of the integration there should be no drift in the GCM climate.
- Simulate today's climate with prescribed climate forcing as similar to observations as possible.
- Simulate the climate during other historical periods.
- Compare results against climatologies, both for means and variability.

What observational data can we compare model results with?

- Surface based measurements
  Relatively long time series
  Issue of homogeneity and spatial coverage
- Radiosondes
  Limited spatial coverage
  Time series starts in the 1950's
- Satellite data
  Global coverage
  Limited time series (starts in the 1970's)
- Reanalysis products
  Global coverage
  Limited in time (1950's)



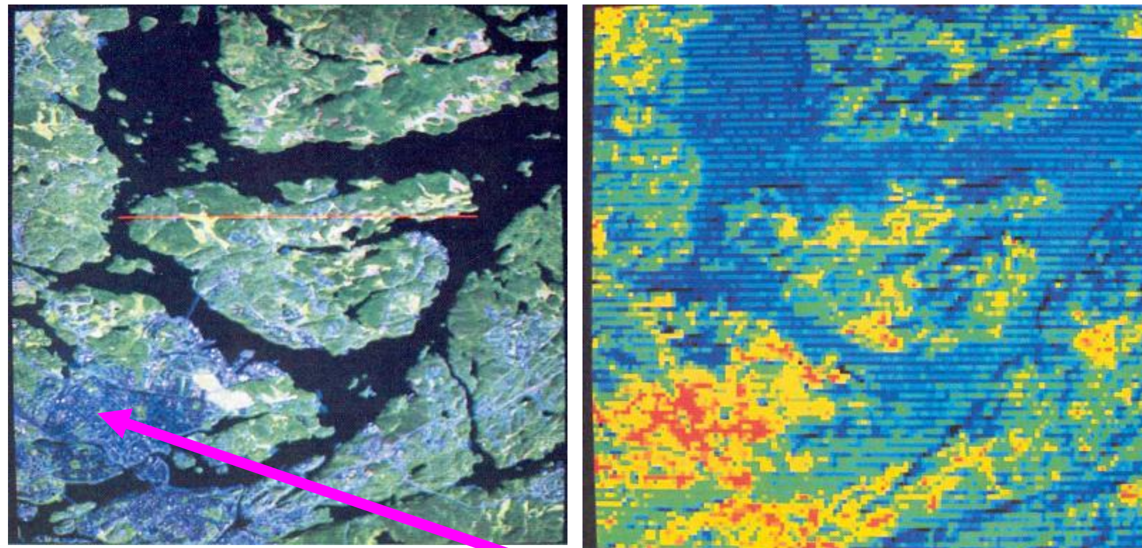
Gridded observed temperature anomalies from CRU

Homogeneity of observations: Spatial and temporal issues

Example from Stockholm

- Spatial inhomogeneities

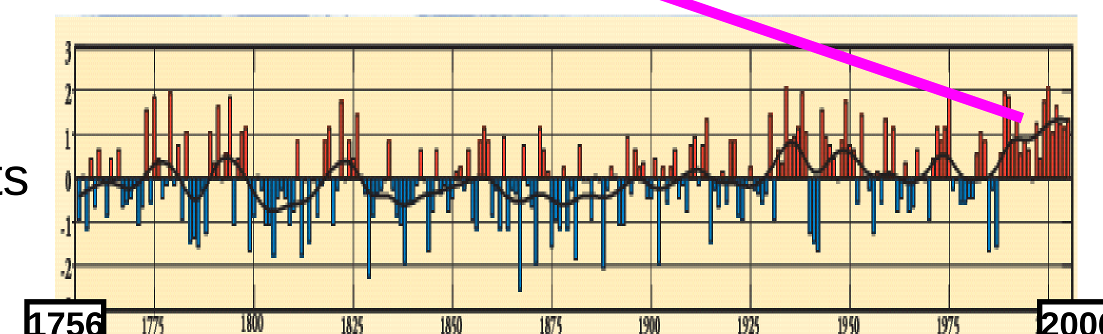
land / water
forests / open areas
rural / urban areas



Lunden, B., 1987. Satellite Thermography a Study of a Landsat-5 Sub-Scene over Stockholm. Geografiska Annaler. Series A, Physical Geography, Vol. 69, Nr. 3/4. 367-374.

- Temporal inhomogeneities

Changing local conditions
Relocation of instruments
Changing instruments
Urbanization



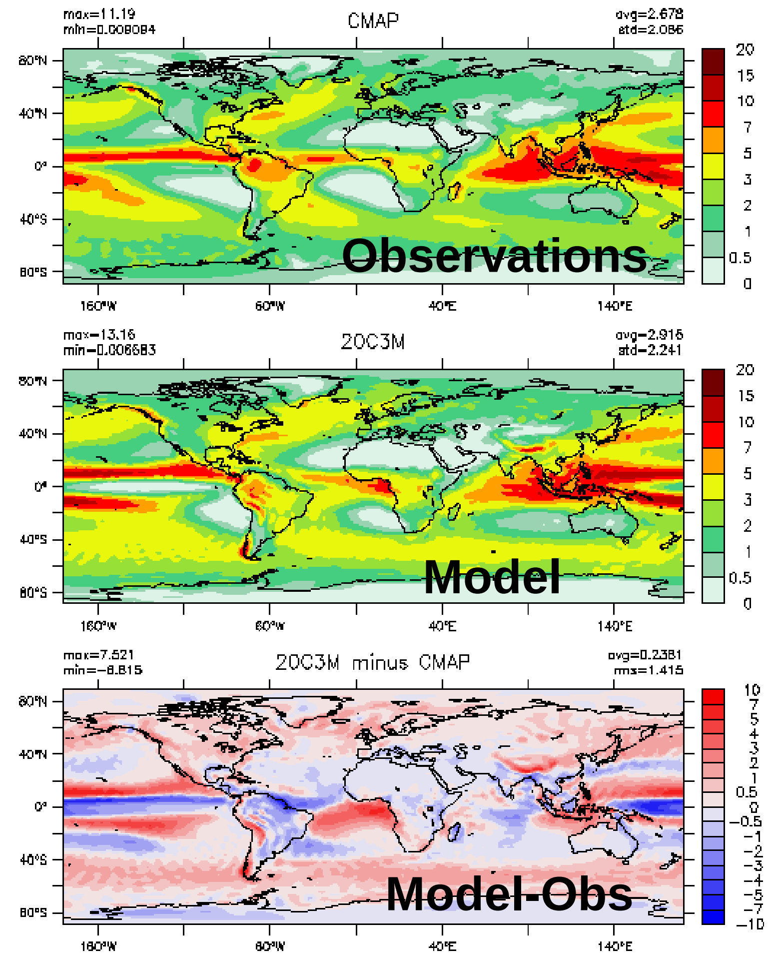
Moberg, A., H. Bergström, J.R. Krigsman, and O. Svanered. 2002. Daily air temperature and pressure series for Stockholm (1756-1998). *Climatic Change* 53, 171-212.

AOGCM evaluation

Present-day AOGCMs reproduce many features of today's climate, both in terms of means, variability and extremes

Some weaknesses with present-day AOGCMs are that they have a coarse resolution (>100km), they do not include all processes (e.g. the carbon cycle feedback), they have weaknesses in the understanding of parts of the climate system (in particular clouds are problematic)

Annual mean precipitation: OBS vs. AOGCM



AOGCM: Atmosphere-Ocean GCM

How can GNSS/GPS IWV be used for evaluation of climate models?

ES1206 activities - reprocessing and homogenization will make it easier to use GPS IWV by modellers E.g. for evaluating diurnal cycle (high temporal resolution) in moisture, especially for high resolution regional models (better comparison with station data). Need as long as possible GPS IWV time series and data from many stations.

Evaluation of IWV in the regional climate model RCA using GPS data

RCA and GPS IWV diurnal cycle similar, but RCA wetter during night and peaks later in the afternoon. Possibly due to coarse resolution (50km) or problems in the convective and surface schemes

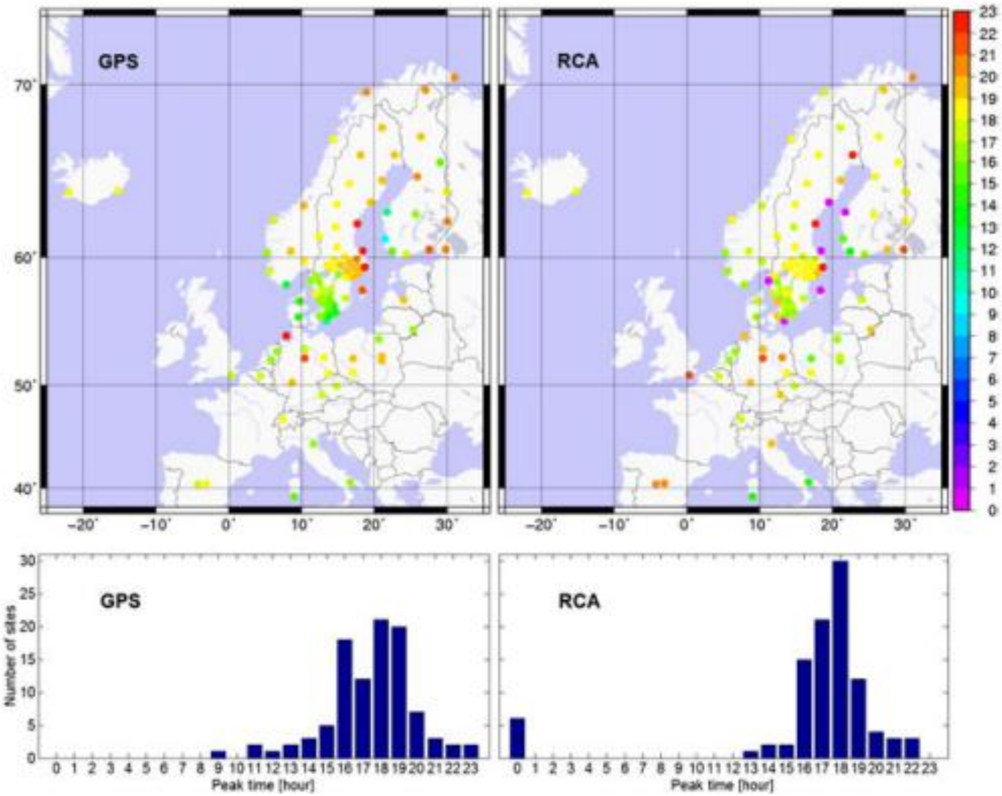


Figure 10. Peak time of the diurnal cycle of the IWV, for the summer months (JJA), obtained from the GPS data and the RCA simulation for each GPS site (upper panels) and histograms of the peak time (lower panels). The hour is in local solar time.

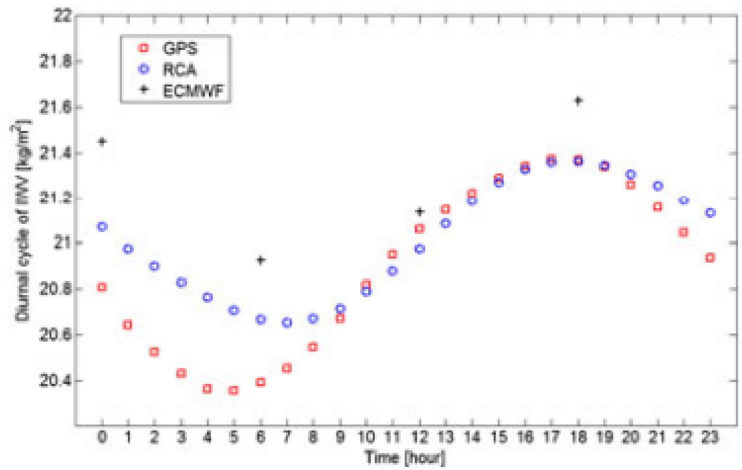


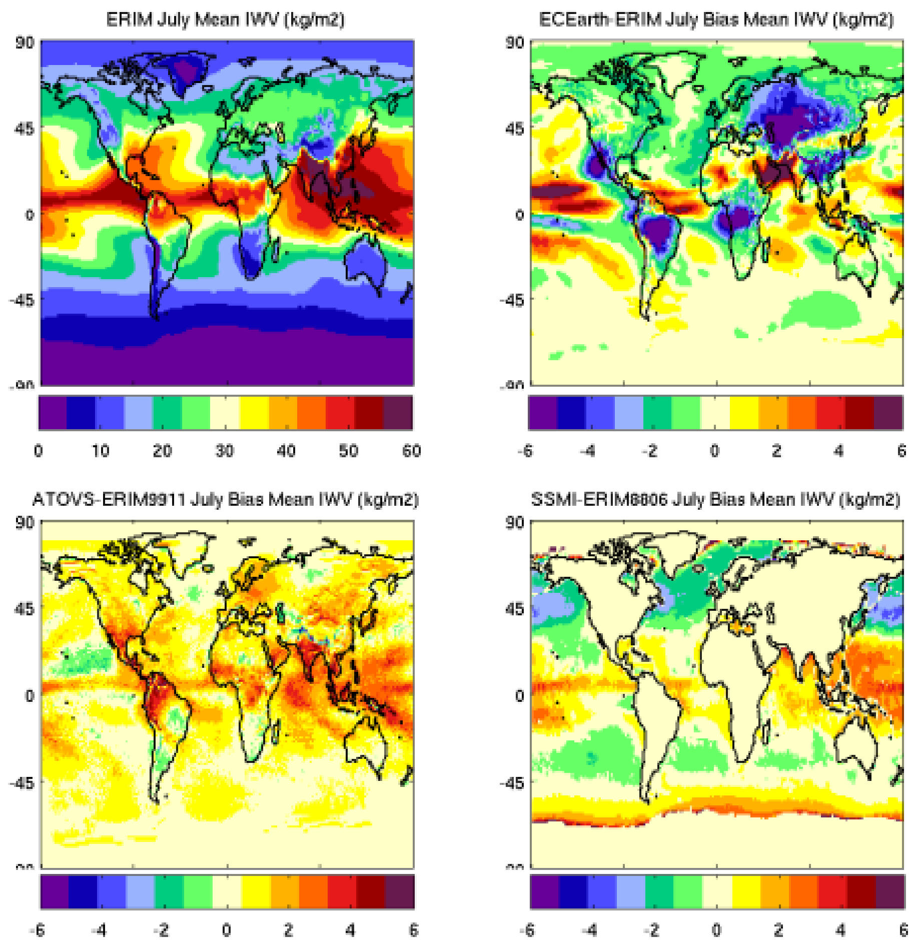
Figure 9. Diurnal cycles of IWV as a function of local solar time for the summer months (JJA) obtained from the data for all sites and all years.

Ning, Elgered, Willén and Johansson 2013 JGR

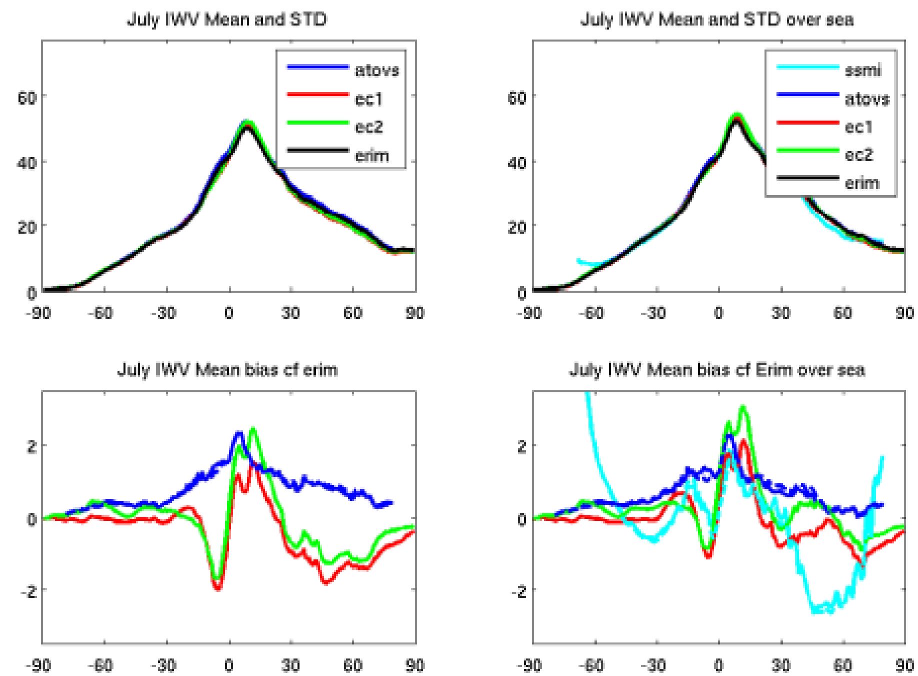
How can GNSS/GPS IWV be used for evaluation of climate models?

Different satellites give different estimates of IWV - Use GPS data for further independent evaluation, especially in “problem” regions (uncertain climate change signal and satellite retrieval issues). Few but good quality stations in West&East Africa, South America, India, high altitudes could have impact.

Comparison of IWV in EC-Earth(GCM), ERA-Interim and CM-SAF satellite data



Modelled and observed IWV regional and seasonal patterns similar, but ...
EC-Earth wetter over ocean and drier over land areas
ATOVS more IWV than ERA-Interim. SSM/I more IWV tropics and Antarctic, and less over NH high latitudes



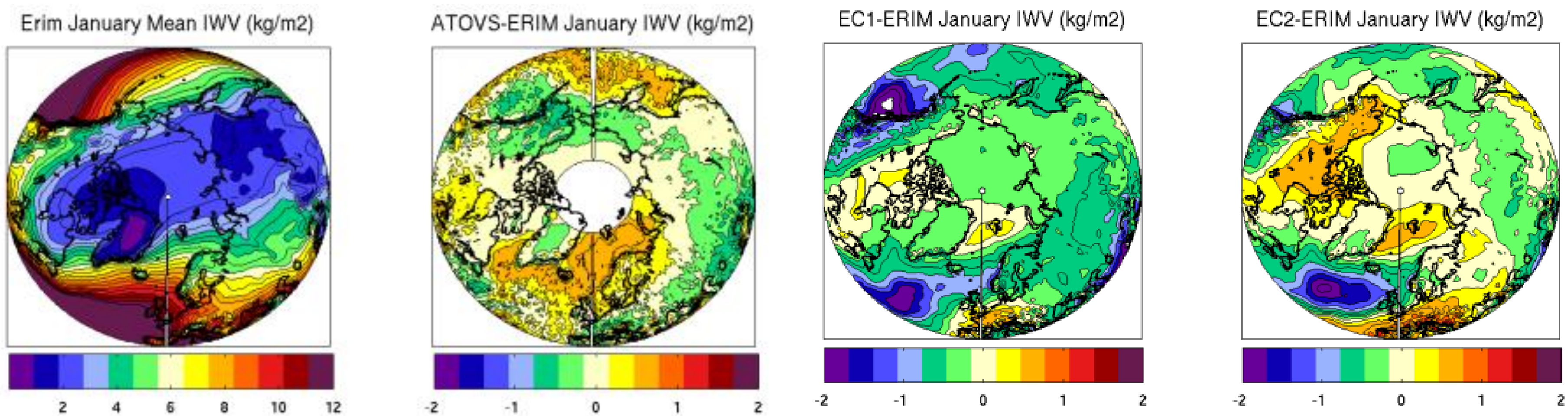
Willén 2013 CM-SAF, Climate Monitoring Satellite Application Facilities report

How can GNSS/GPS IWV be used for evaluation of climate models?

For high latitudes and polar regions where the satellite data is not as reliable even few stations can have a large impact. Since IWV vary between climate models and for small changes in the parameterisations. we also see large differences in IWV for the same model.

Comparison of IWV in EC-Earth, ERA-Interim and ATOVS data over the Arctic

ERA-Interim and ATOVS have similar IWV distribution but they are partly co-dependent (ERIM used in retrievals). EC-Earth GCM is too cold over the Arctic, sensitivity experiments with the model cloud parameterisation, increasing the amount of cloud water droplets and reducing the cloud ice crystals (as has been observed over the poles), gives a warmer and wetter model (EC2) and increased IWV, but no independent observational data to compare with.



Willén 2013 CM-SAF report

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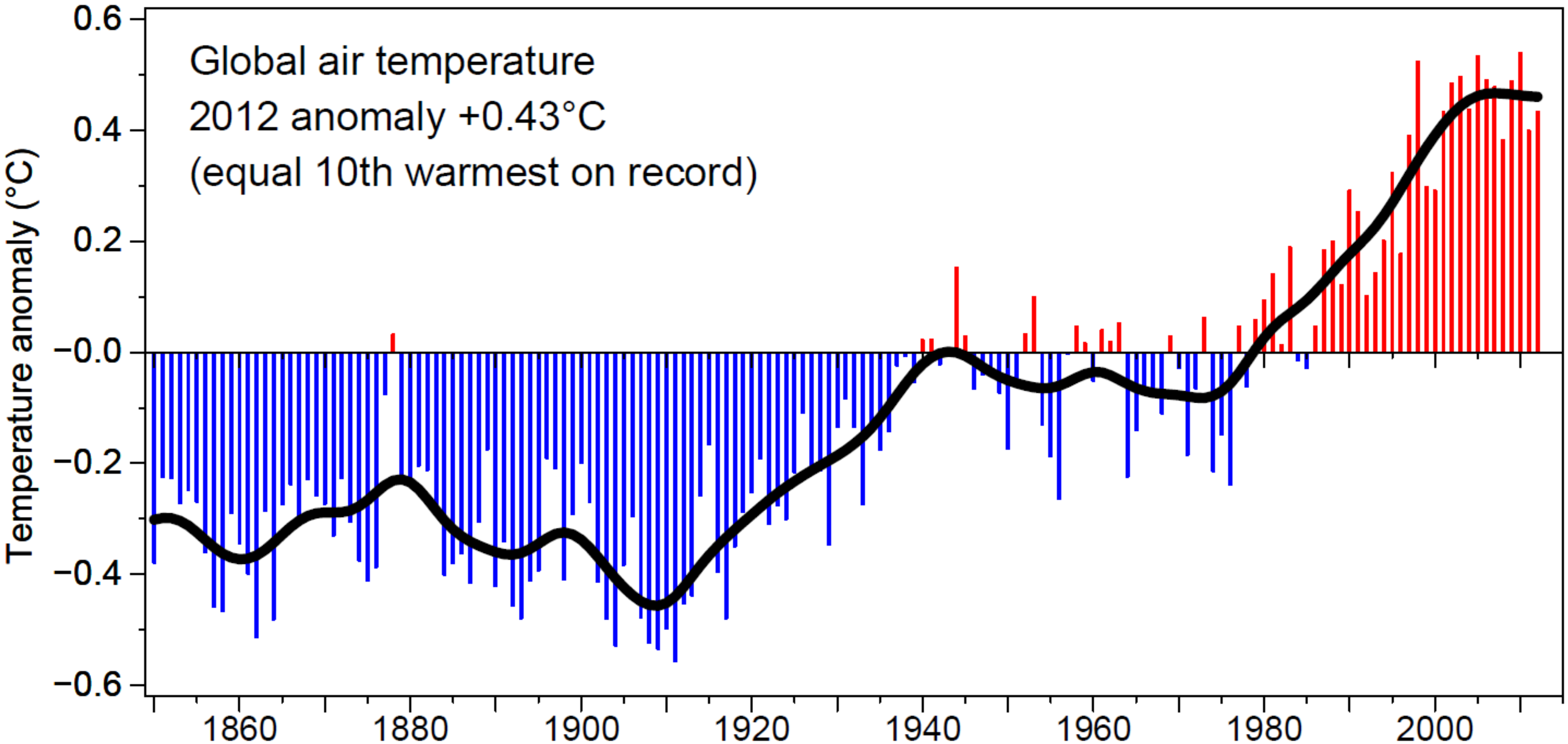
The climate is changing

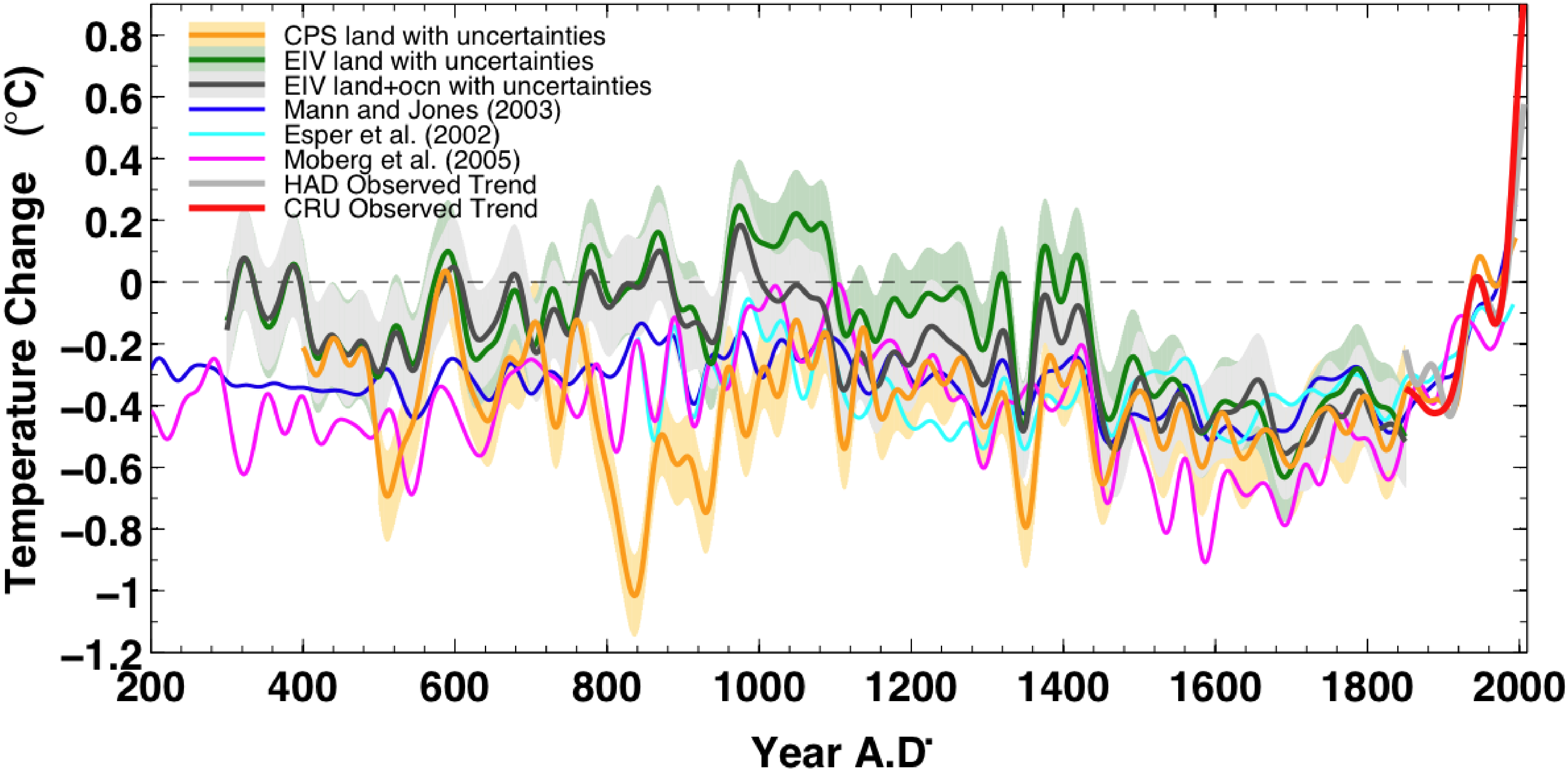
New records in global mean temperature often broken

Observed temperature (anomalies)



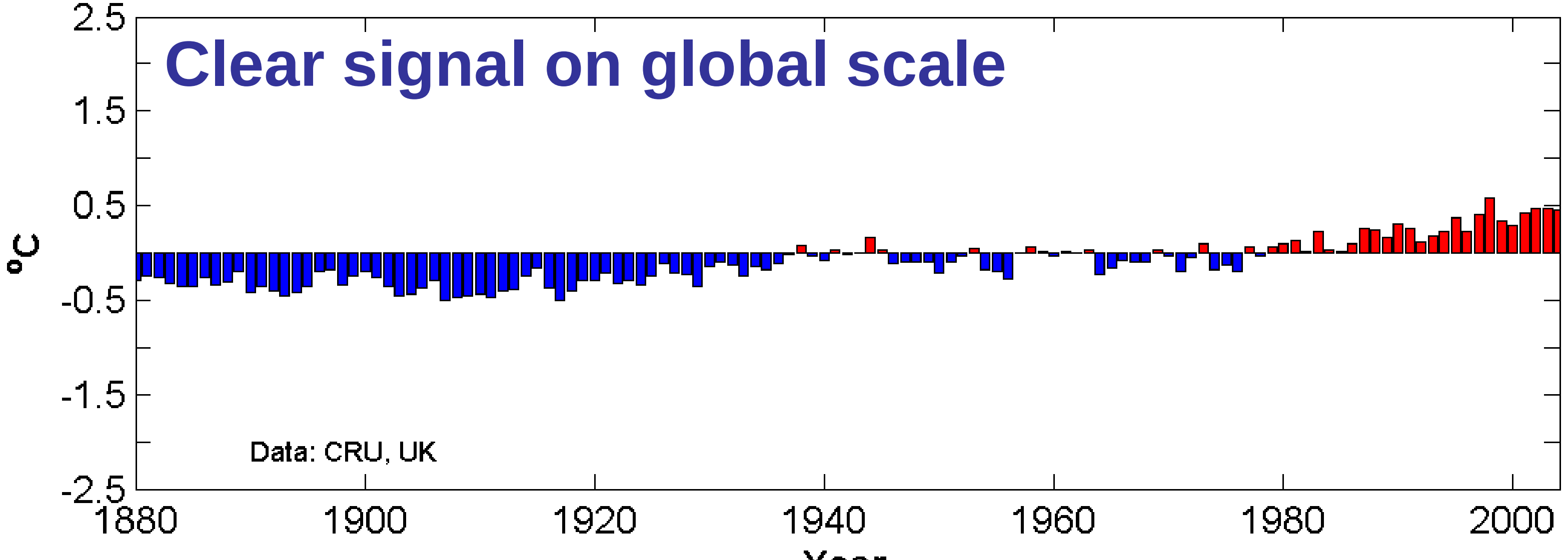
http://www.cru.uea.ac.uk/

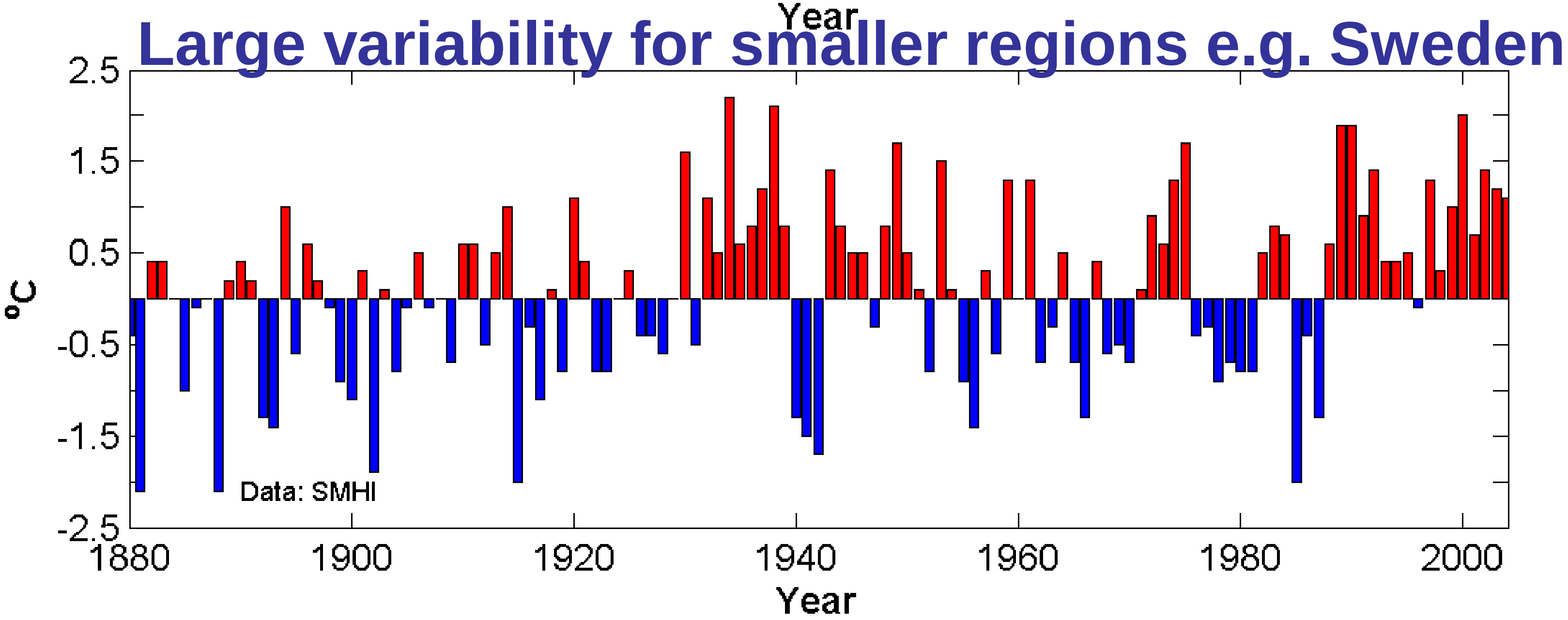
Temperature evolution year 200 - 2004



http://www.copenhagendiagnosis.org/

Change in mean temperatures: Globally and in Sweden





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The uncertainties in future climate consists of three main factors

- ✓ Limited process description (understanding and computers)
- ✓ Future greenhouse and aerosol concentrations
- ✓ Initial state of all the variables in all boxes

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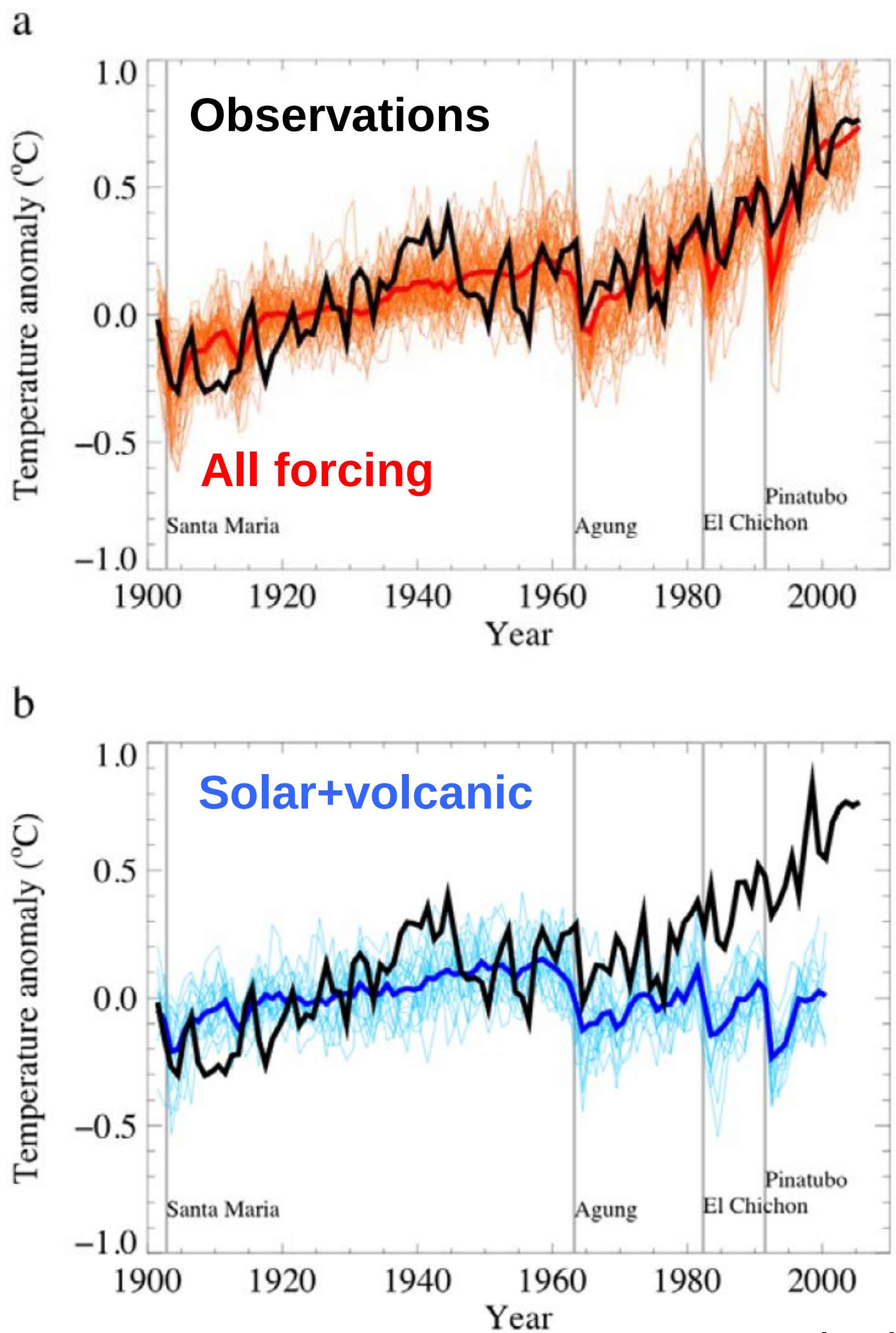
Are the models reliable?

Upper panel showing model simulations including all forcings: solar, volcanic and aerosols are closer to the observations, than the lower panel where the aerosols are not active in the models



Pachauri and Jallow, 2007

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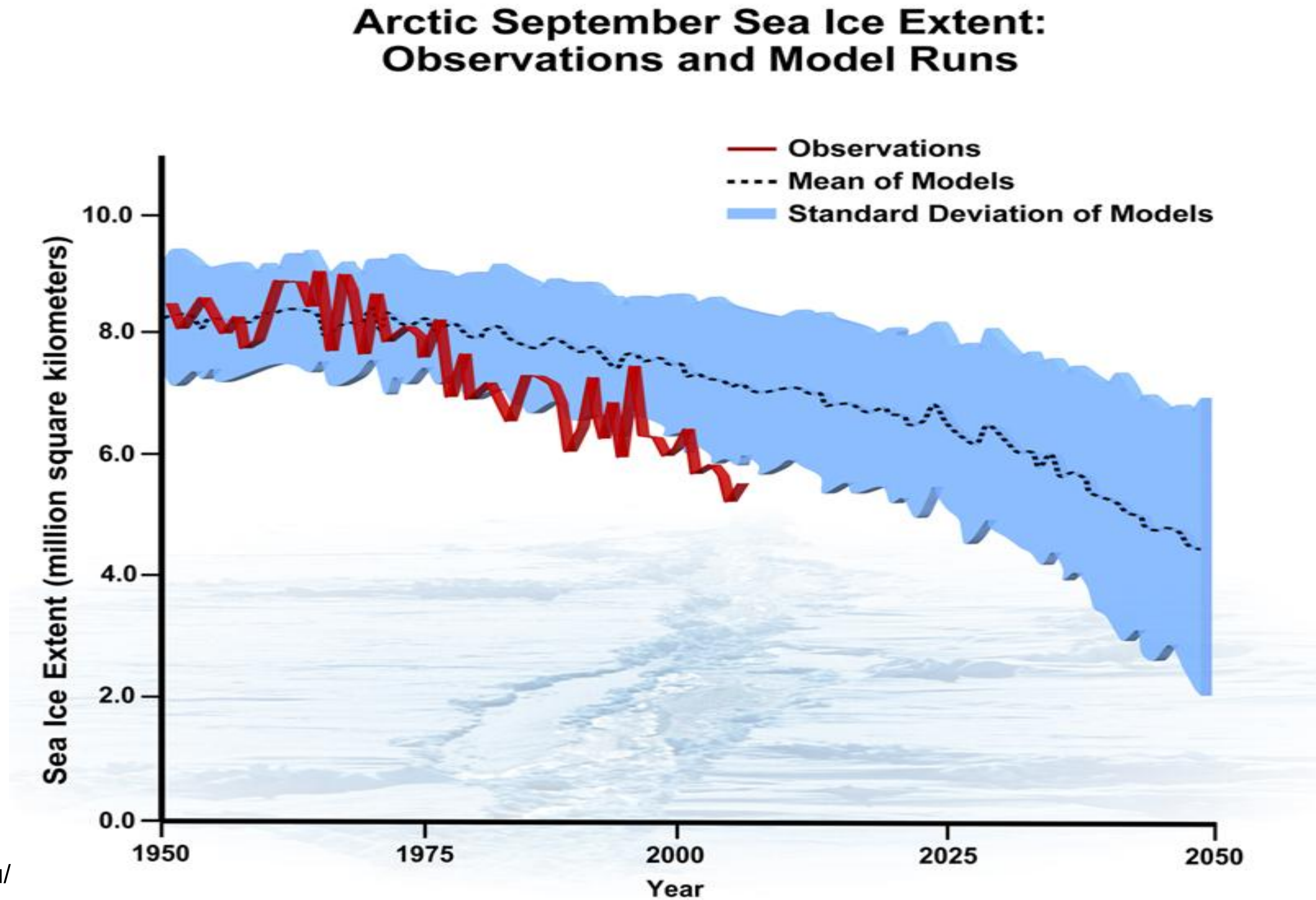
Are the models reliable?

They show main patterns in sea-ice reduction, but observed sea-ice decline faster than most models predict. Could be due to models issues, processes not captured or resolved, natural variability...



http://www2.ucar.edu/

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The uncertainties in future climate consists of three main factors

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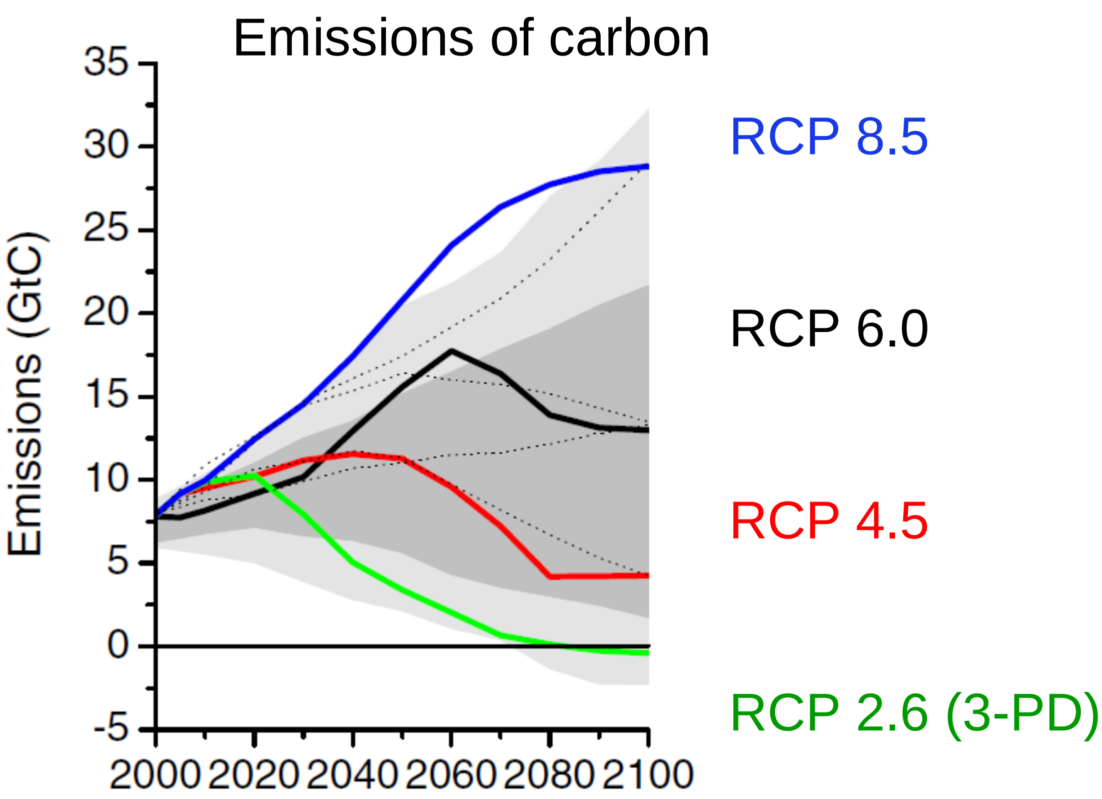
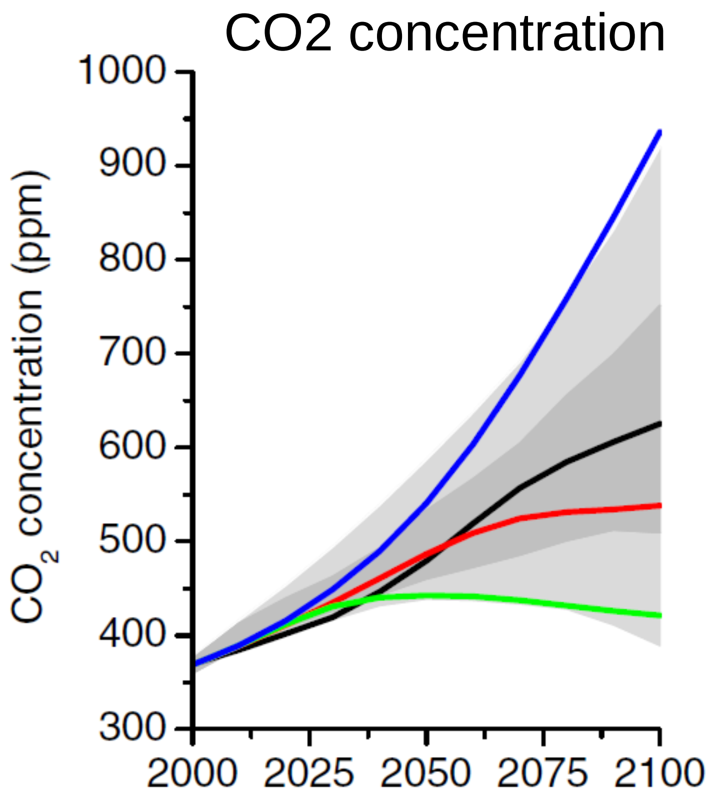
Emission Scenarios - RCP

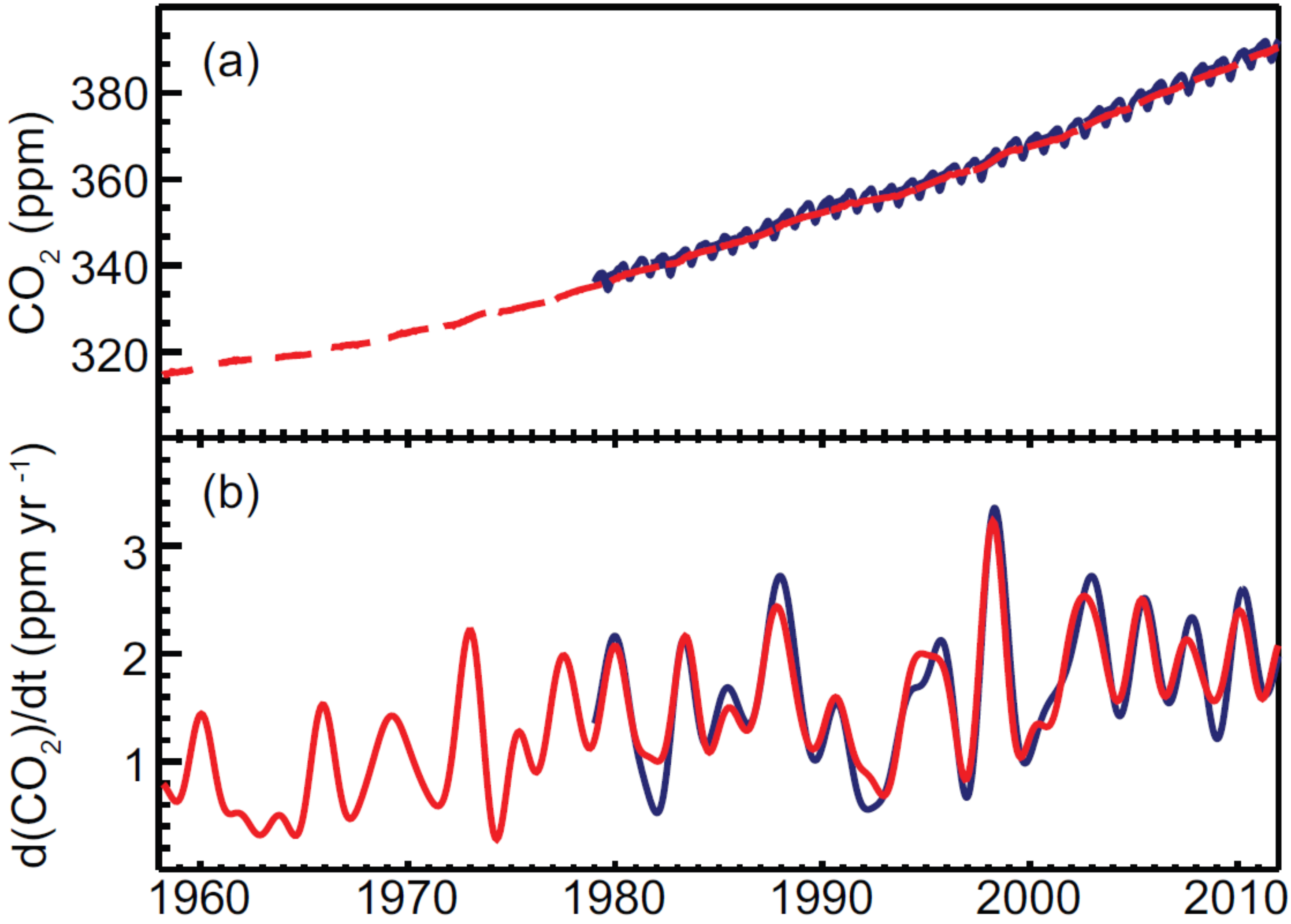
RCP – representative concentration pathway





Van Vuuren et al., Climatic Change, 2011

CO2 emissions



http://www.climatechange2013.org/images/report/WG1AR5_Chapter02_FINAL.pdf

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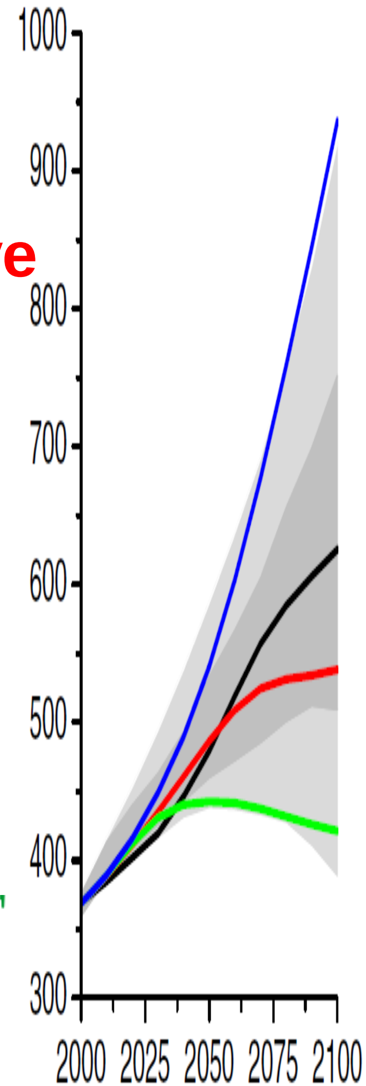
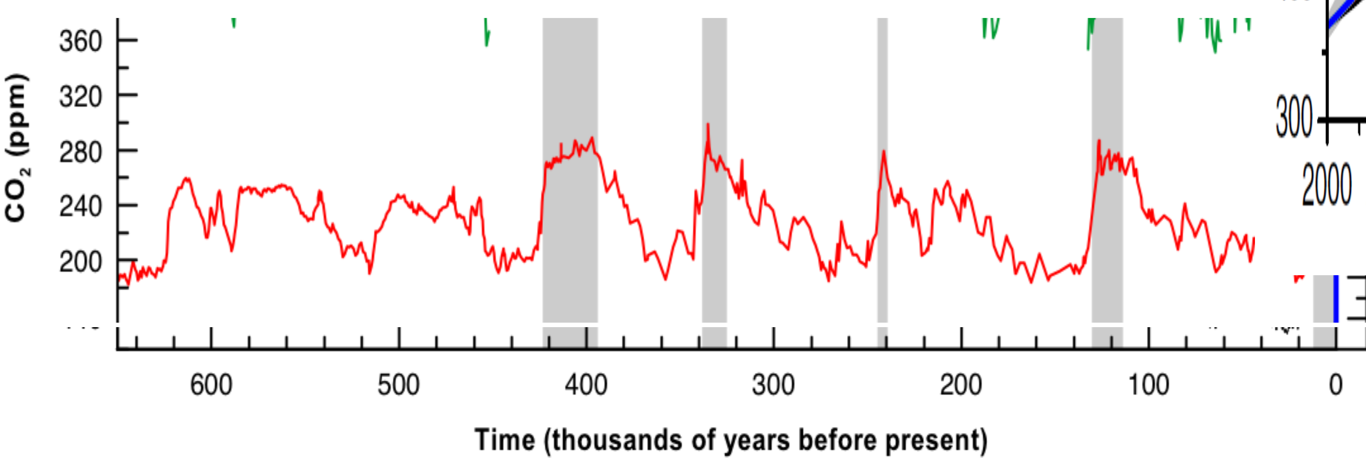
Atmospheric CO2 concentration in a longer perspective

The concentration of CO_2 in the atmosphere has reached a record high relative to more than the past half-million years, and has done so at an exceptionally fast rate. Current global temperatures are warmer than they have ever been during at least the past five centuries, probably even for more than a millennium. If warming continues unabated, the resulting climate change within this century would be extremely unusual in geological terms.

IPCC, 2007

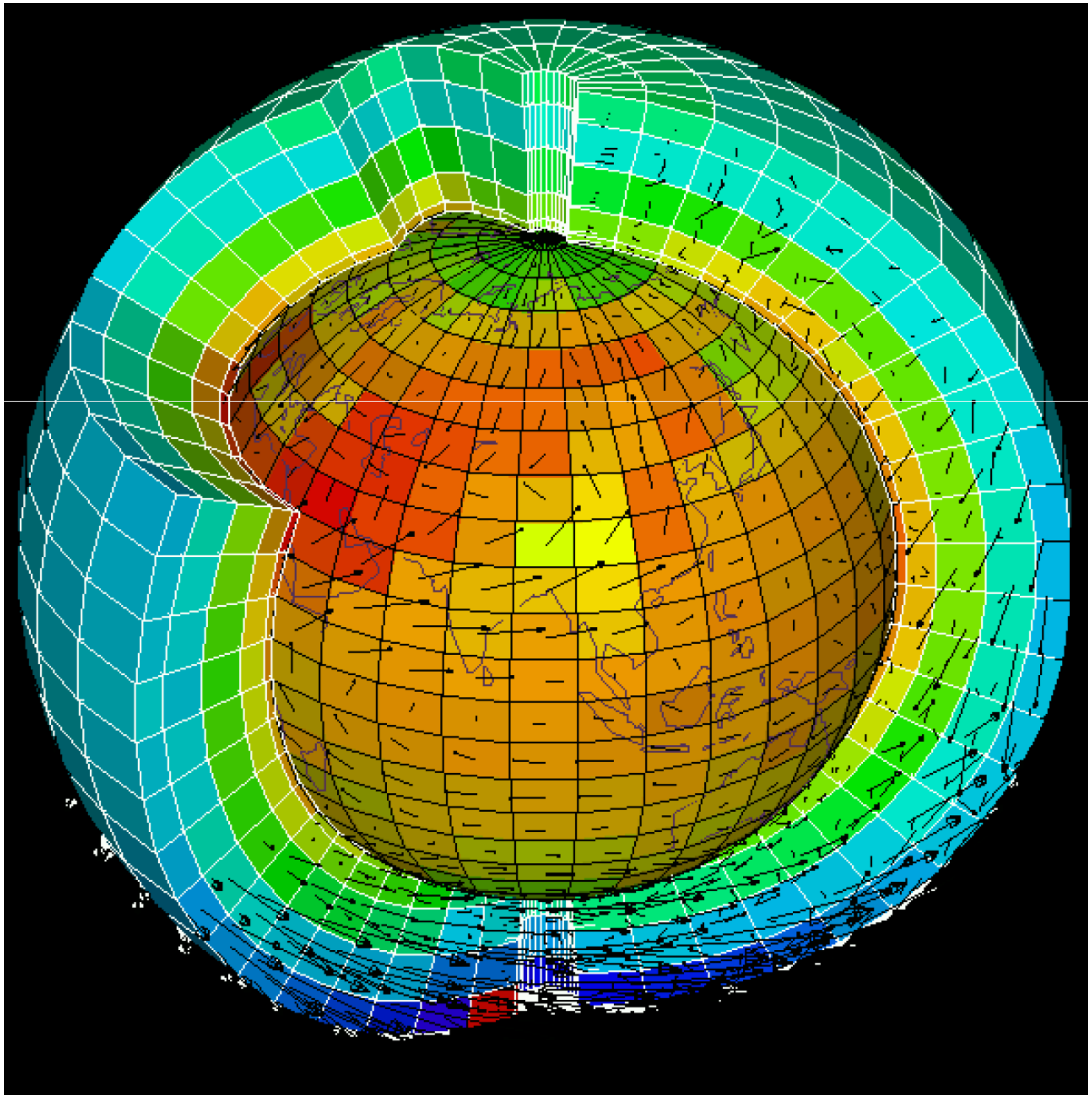




The uncertainties in future climate consists of three main factors

- ✓ **Limited process description (understanding and computers)**
- ✓ **Future greenhouse and aerosol concentrations**
- ✓ **Initial state of all the variables in all boxes**

The initial state has to be given all grid boxes



Atmosphere
Temperature
Humidity
Cloud water
Wind speed / direction

Short memory!

Land
Snow
Soil moisture
Vegetation

Long memory!

Sea
Temperature
Salinity
Flow speed / direction

Very long memory!

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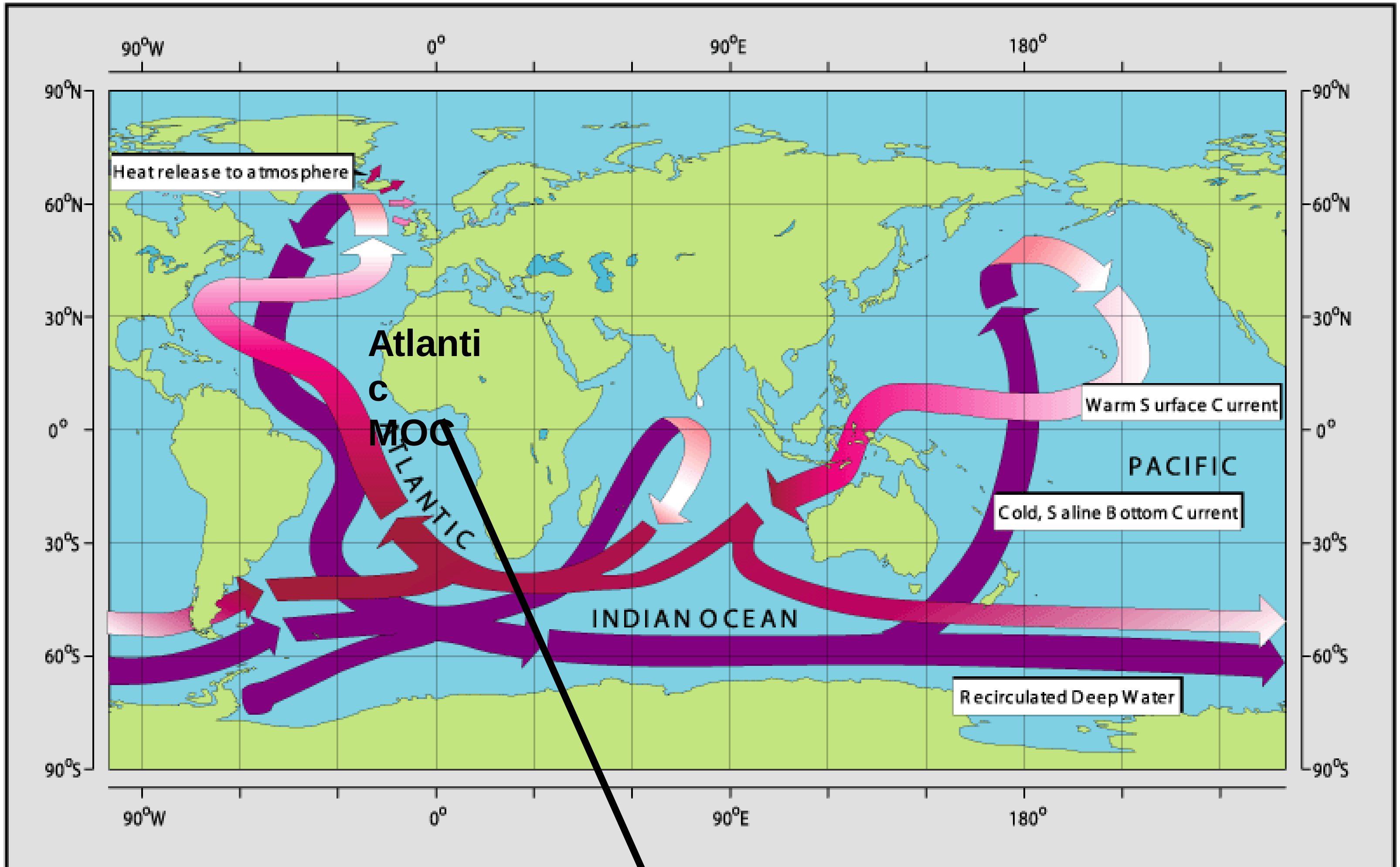
Ocean circulation - a memory of 100rds of years

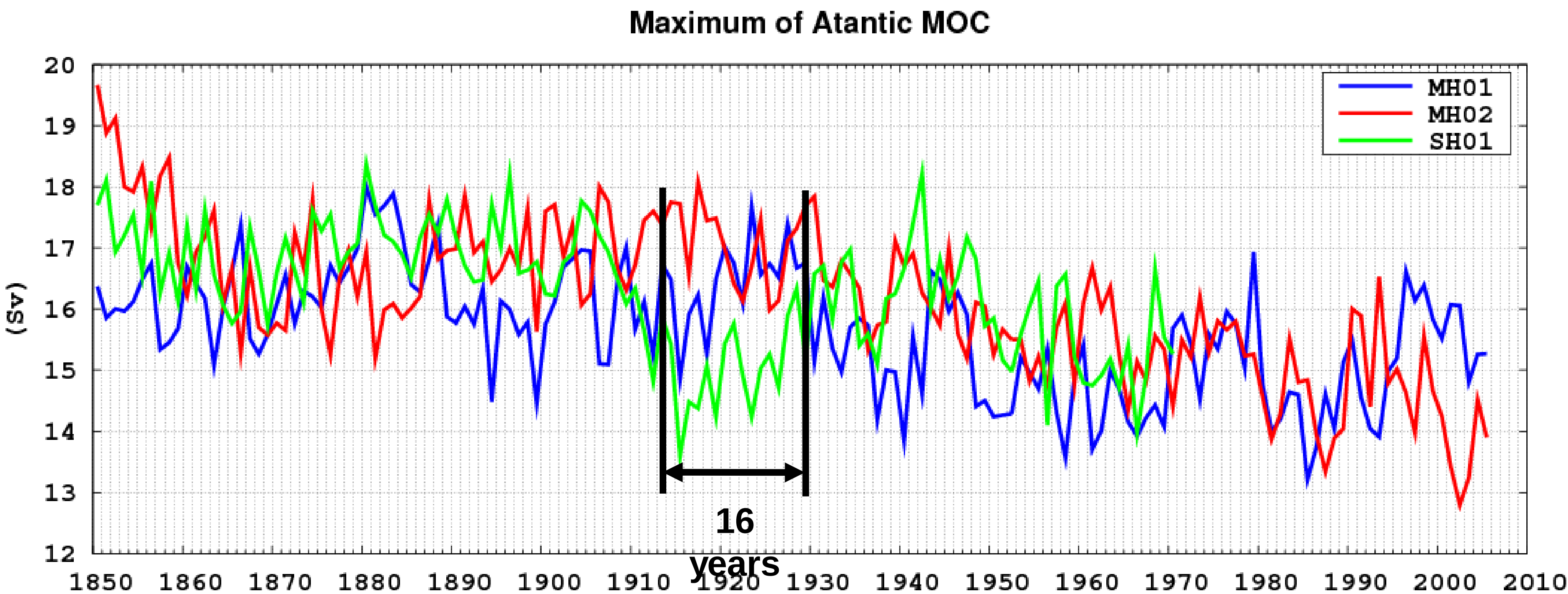


MOC – Meridional Ocean Circulation

http://www.clivar.org/publications/other_pubs/clivar_transp/d3_transp.htm

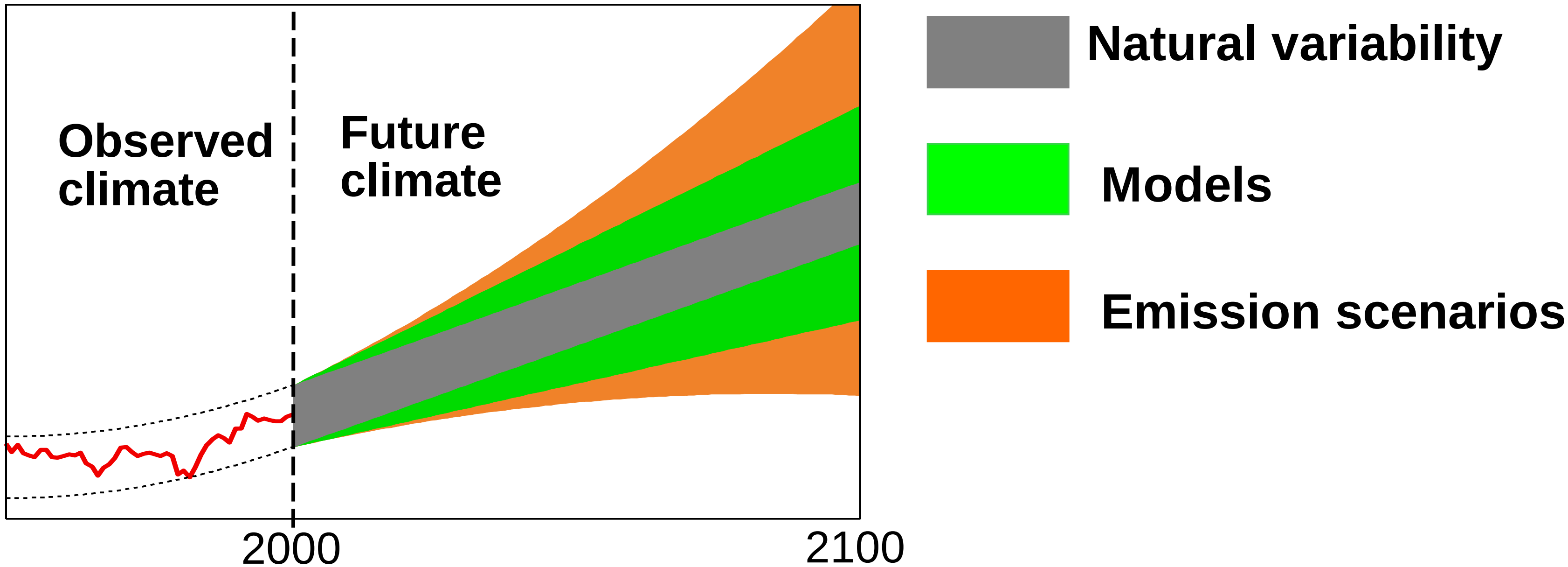
Simulated ocean circulation

Three AOGCM simulations with little differences in initial condition 1850. Exactly the same forcing (sun radiation, green house gases,…) Due to natural variability get different results when looking at shorter timescales



Source: EC-Earth simulation results via Klaus Wyser, Rossby Centre, SMHI

Schematic view of the uncertainties in climate change as a function of time



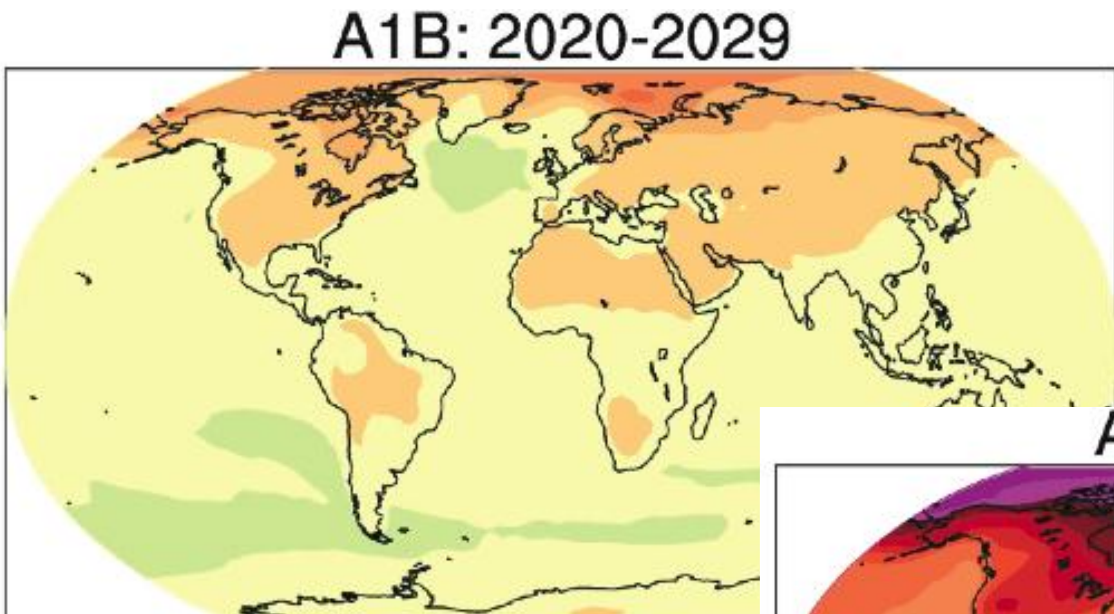
MAGNITUDE OF UNCERTAINTIES	Near future	End of the century
Natural variability	+	+
Models	(+)	++
Emission scenarios		++

From Jouni Räisänen

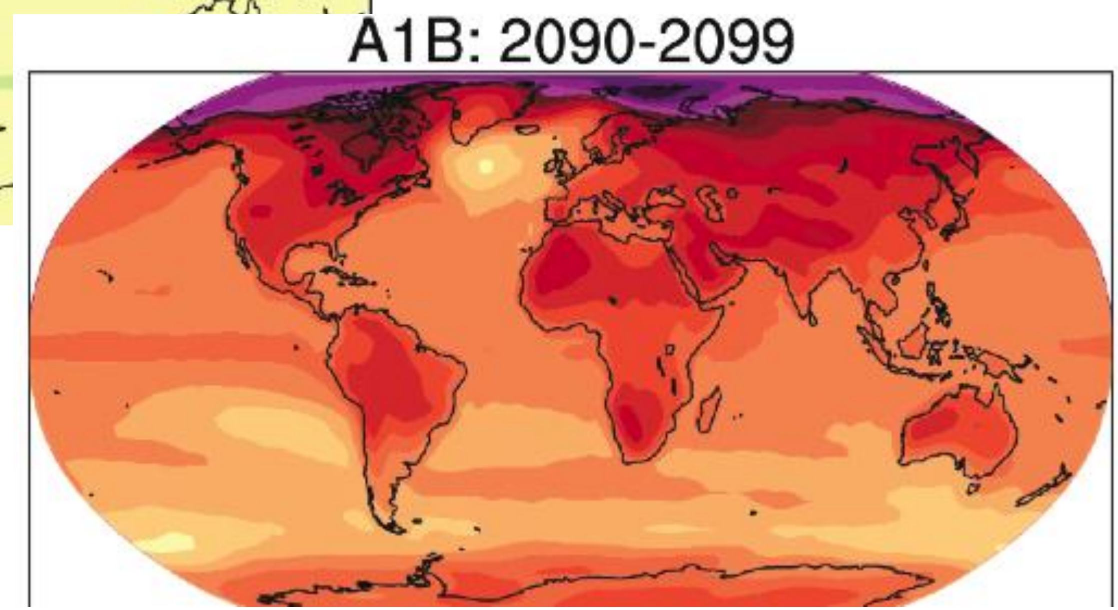
Some results from global and regional climate scenarios

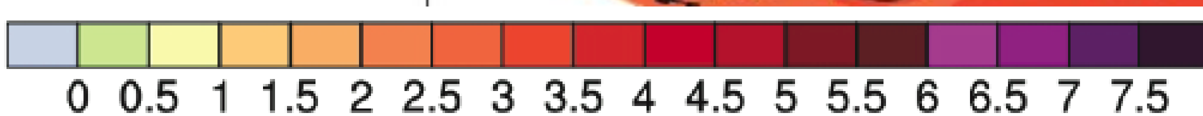
Future temperature changes

Source: IPCC (WGI) 2007

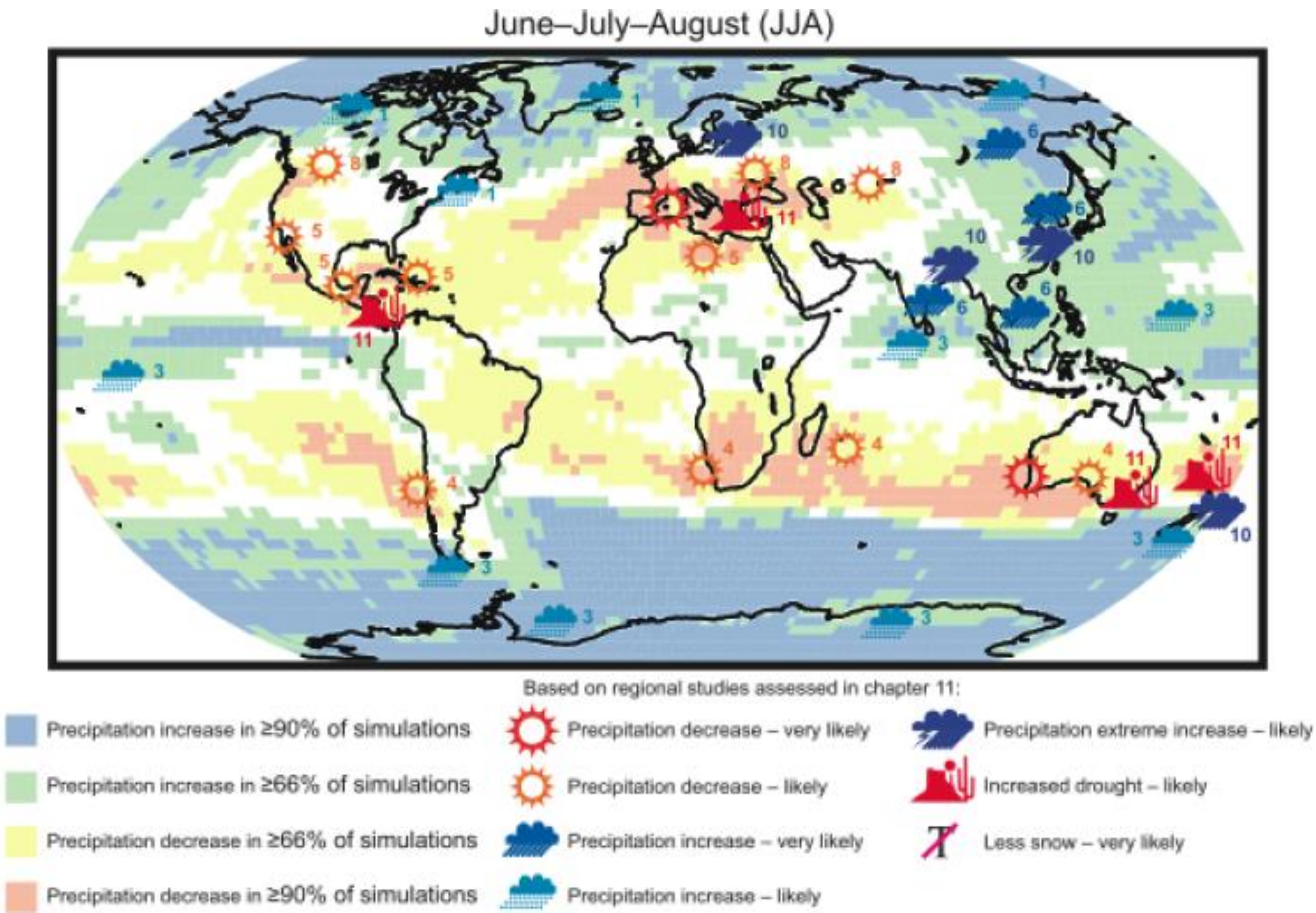


Temperature change (°C) compared to 1980-1999



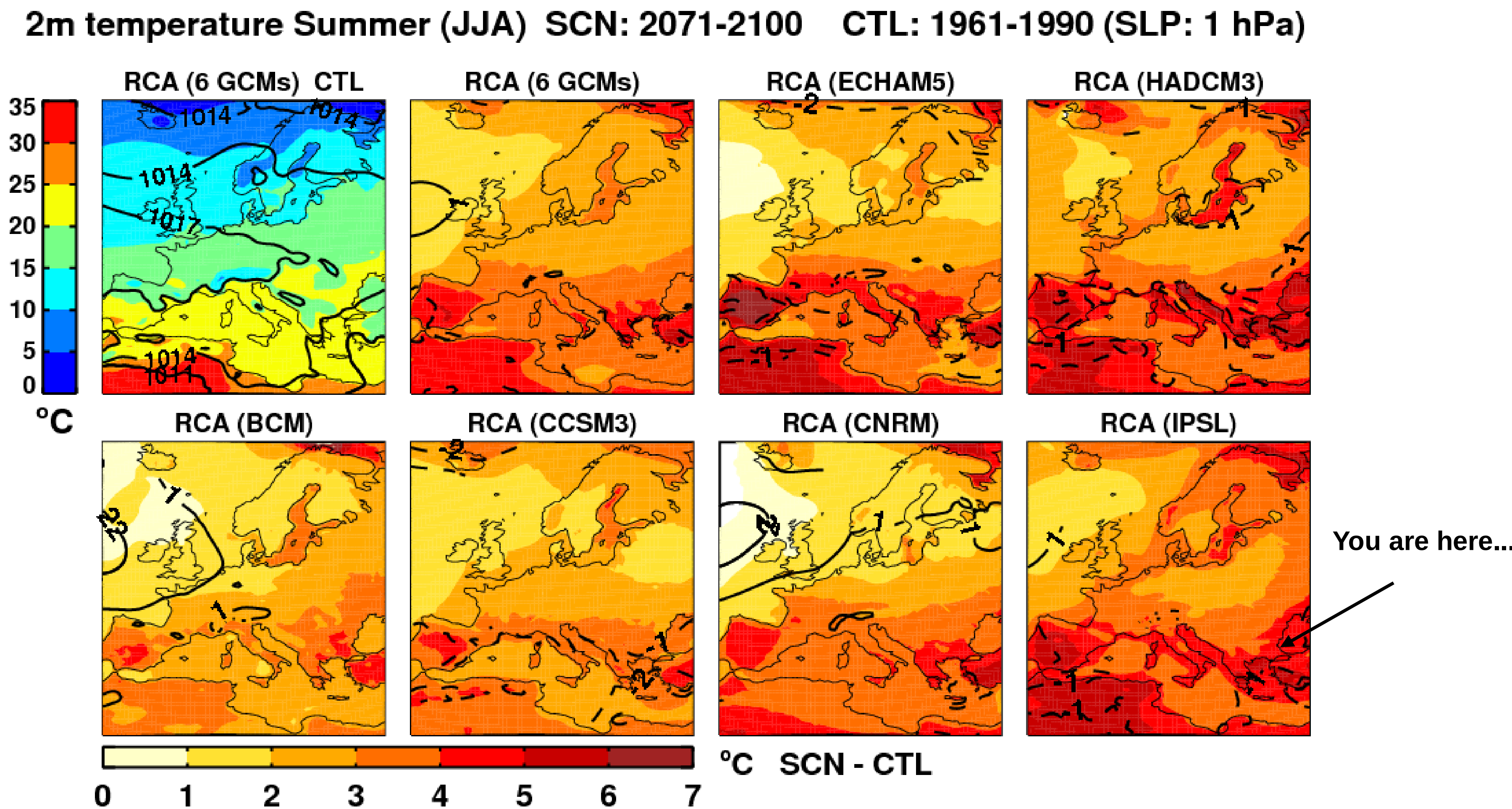


Future changes in precipitation, dry periods, extremes etc.



IPCC, 2007

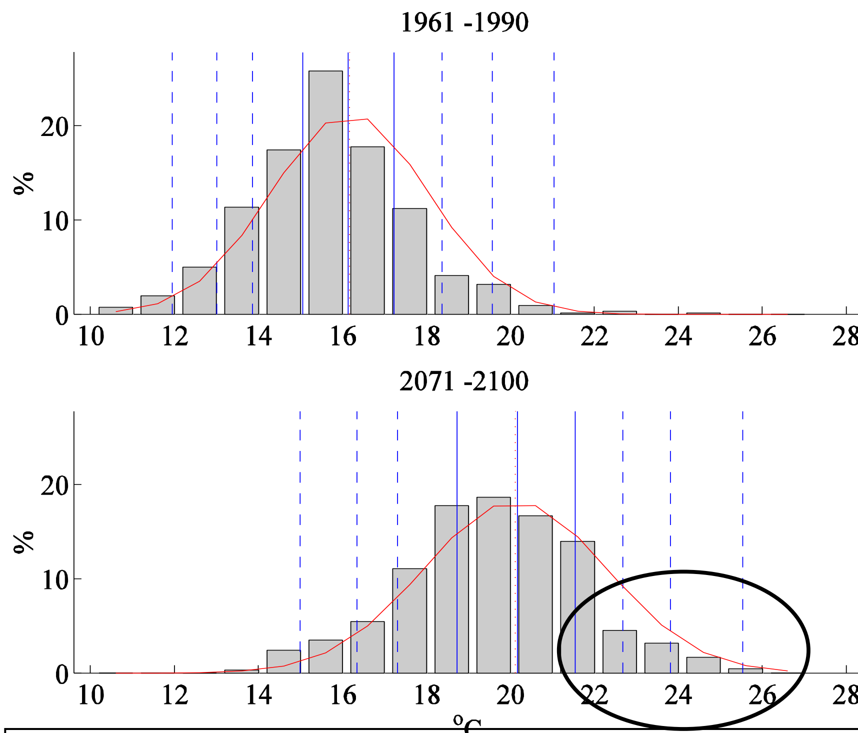
Changes in seasonal mean summertime temperature



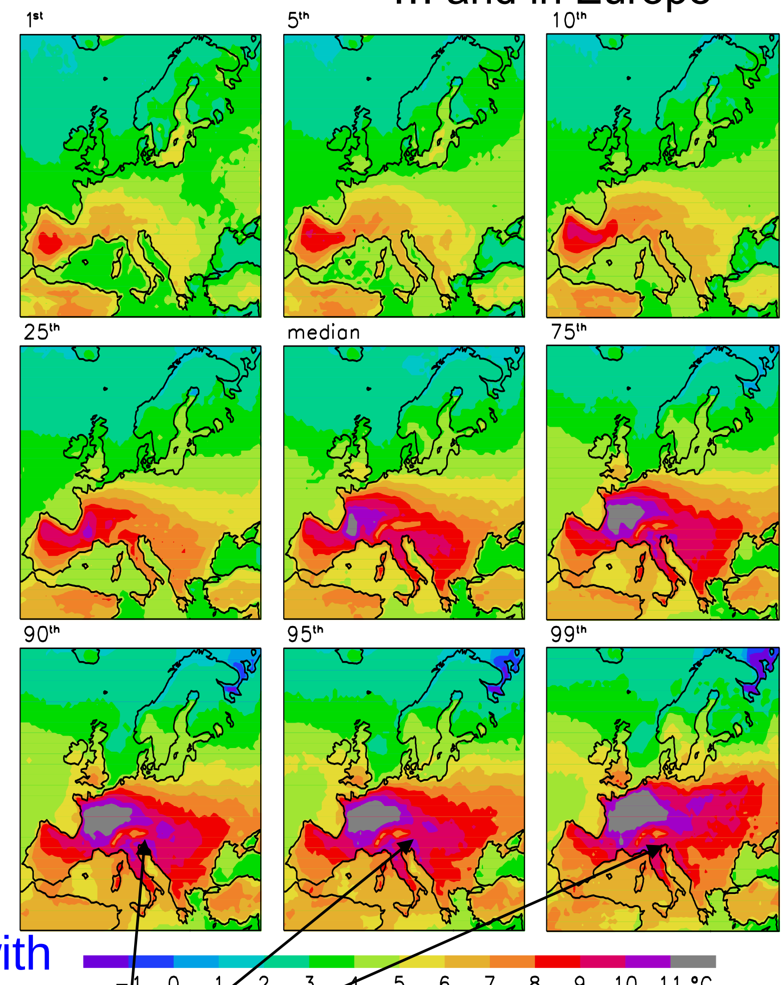
Rossby Centre Regional Climate model (RCA) driven by 6 different global climate models, warmer everywhere, largest changes in Southern Europe

Change in temperature climate distributions during summer (JJA)

In Stockholm … Difference between 2071-2100 and 1961-1990 … and in Europe



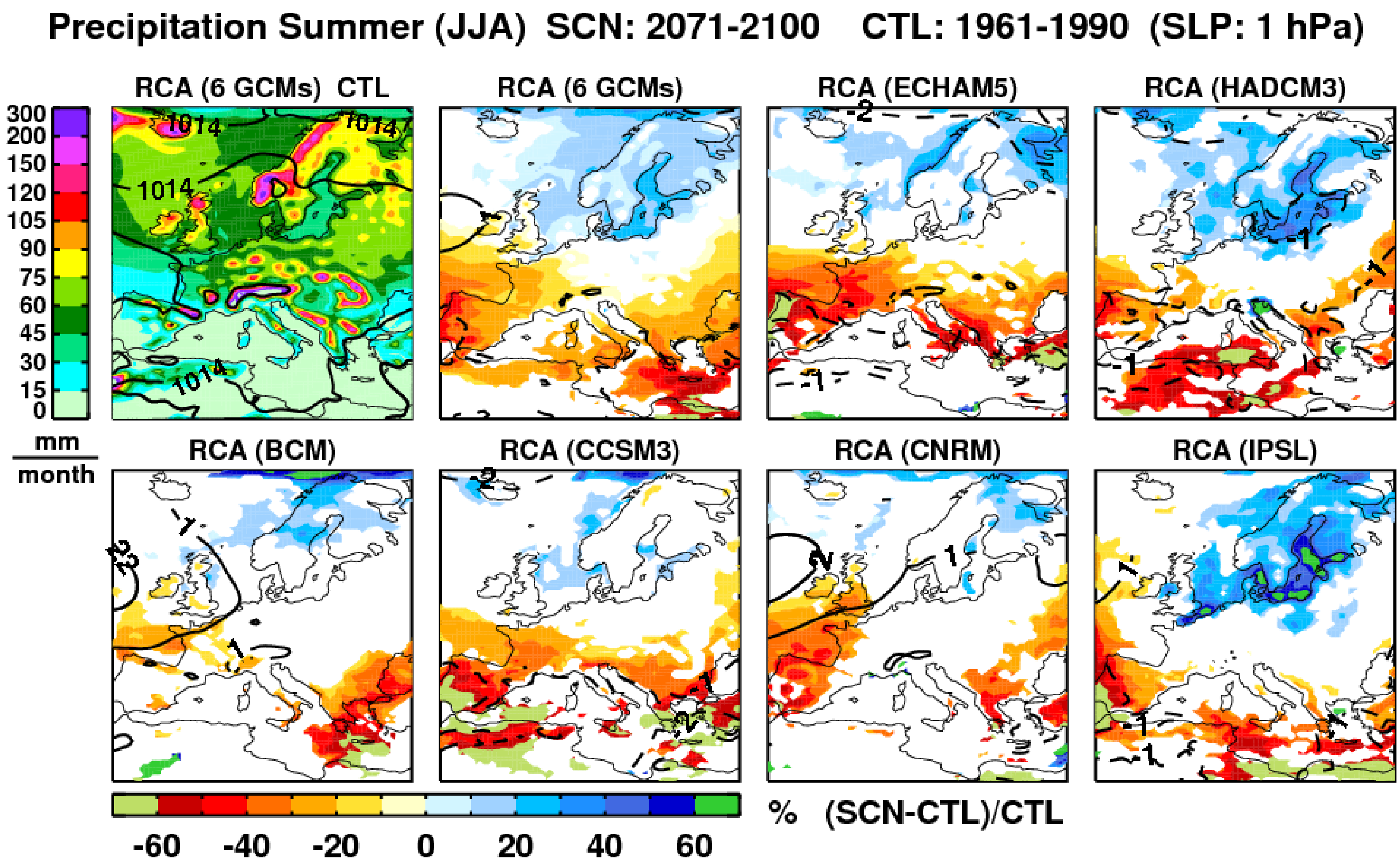
Percentiles for 1, 5,10, 25, 50 (median), 75, 90, 95 and 99% are shown in the figure



Regional climate models have broader spectra with more frequent hot days in the future for Stockholm.
Largest changes in south Europe in the higher percentiles

Kjellström, E., 2004. Recent and future signatures of climate change in Europe. *Ambio*, 33(4-5), 193-198.

Changes in seasonal mean summertime precipitation



RCA driven by 6 different global climate models - it gets wetter in north Europe and drier in south Europe, but regional differences depending on the driving global model

Some links for climate data

- http://www.ipcc-data.org/maps/
- http://iridl.ldeo.columbia.edu/maproom/Global/.Climatologies/.Select_a_Point/
- http://climexp.knmi.nl/