Global climate models and downscaling

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with contributions from
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Meteorological predictions and the use of numerical methods

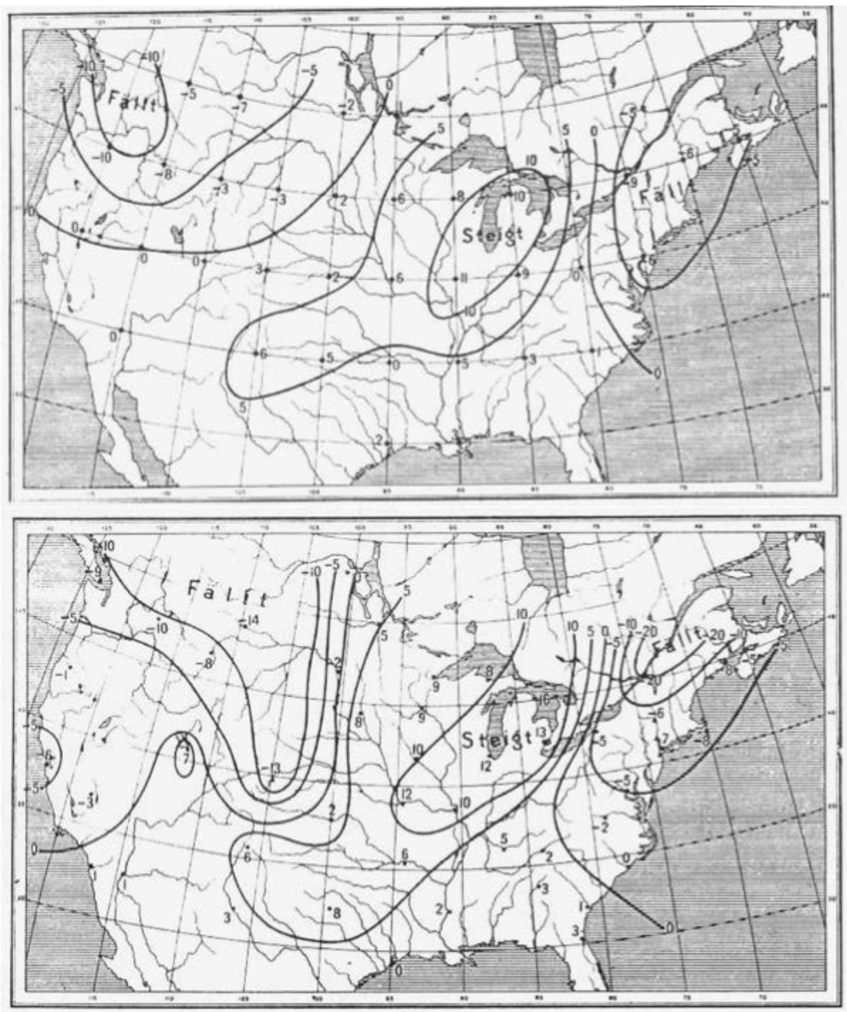
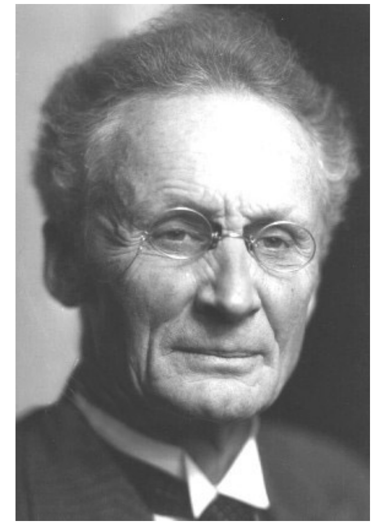


Figure 1.3 Top: Exner's calculated pressure change between 8 p.m. and midnight, 3 January 1895. Bottom: observed pressure change for the same period [Units: hundredths of an inch of mercury. *Steigt* = rises; *Fällt* = falls]. (Exner, 1908)

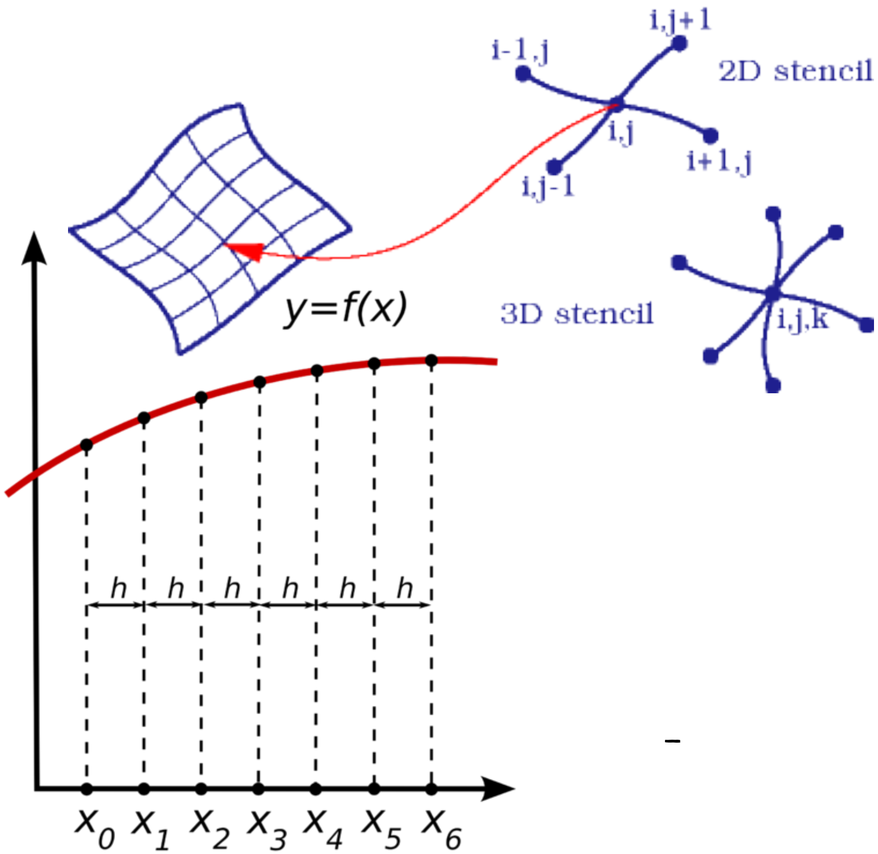


Wilhelm Bjerknes
(1862-1952)

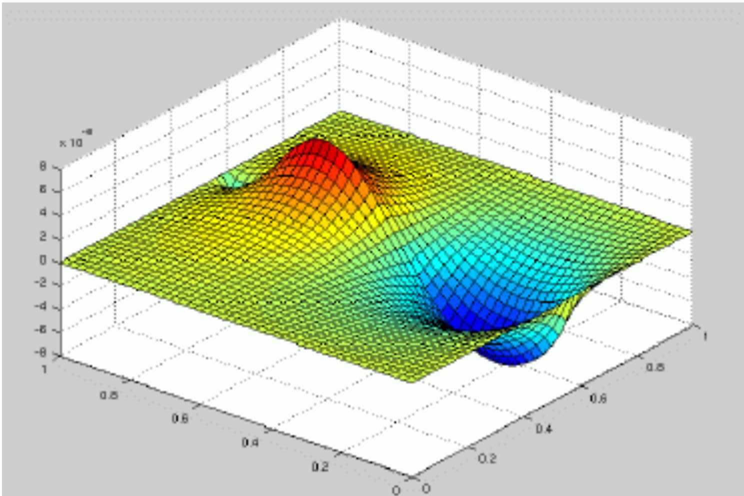
He suggested (1904) to consider weather forecast as an initial value problem, to be solved using the equations of Mathematical Physics.

Finite difference methods

- We use a discretized formulation on a grid in space and time:



$$f'(a) \approx \frac{f(a+h) - f(a)}{h}.$$



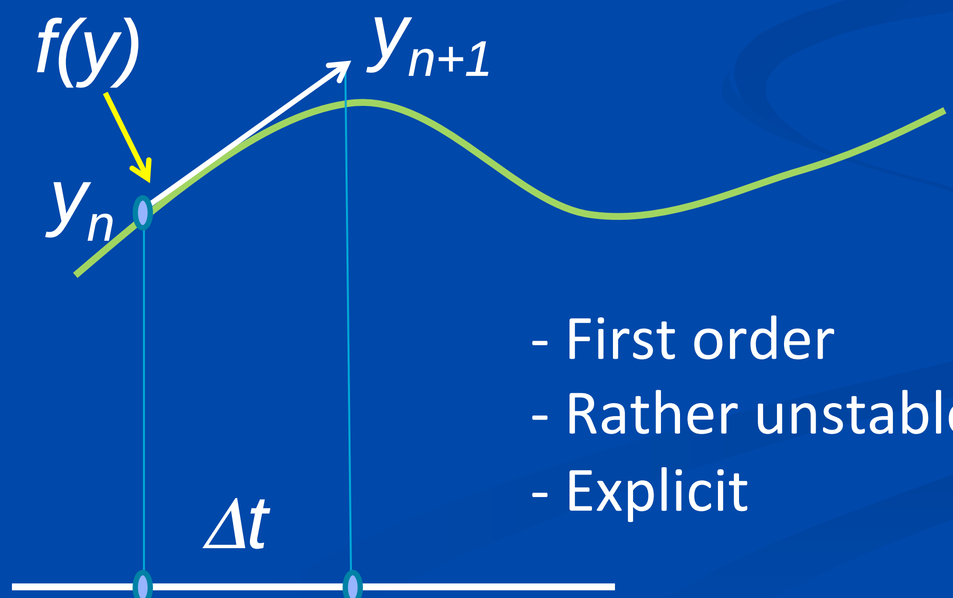
The Euler method

$$\frac{dy}{dt} = f(y)$$

$$y(t + \Delta t) = y(t) + \Delta t f(y(t))$$

$$y_{n+1} = y_n + \Delta t f(y_n)$$

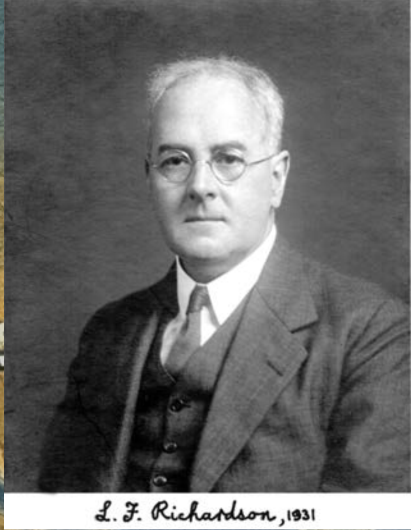
+ Truncation error



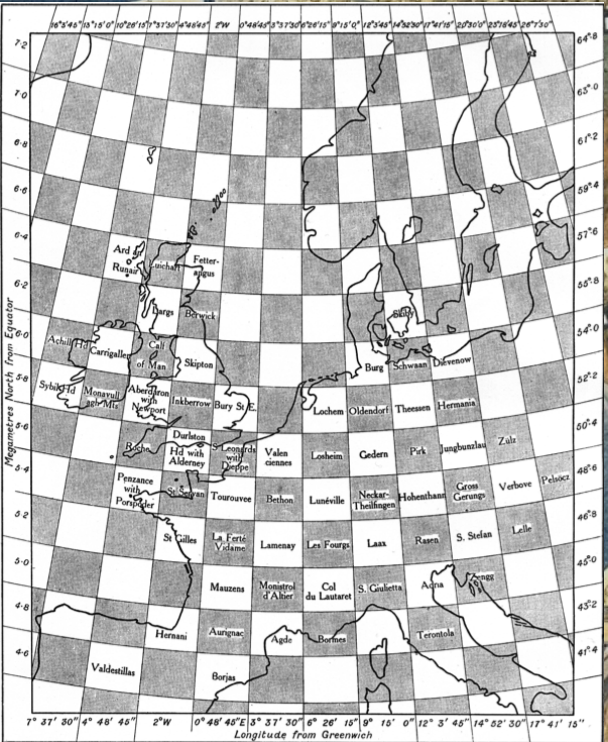
- First order
- Rather unstable
- Explicit


CHINA
SAHARA
SUDAN
ARABIA
INDIA
BRAZIL
CONGO
PACIFIC OCEAN
INDIAN OCEAN

L.F. Richardson, Weather Prediction by Numerical Process (1922):

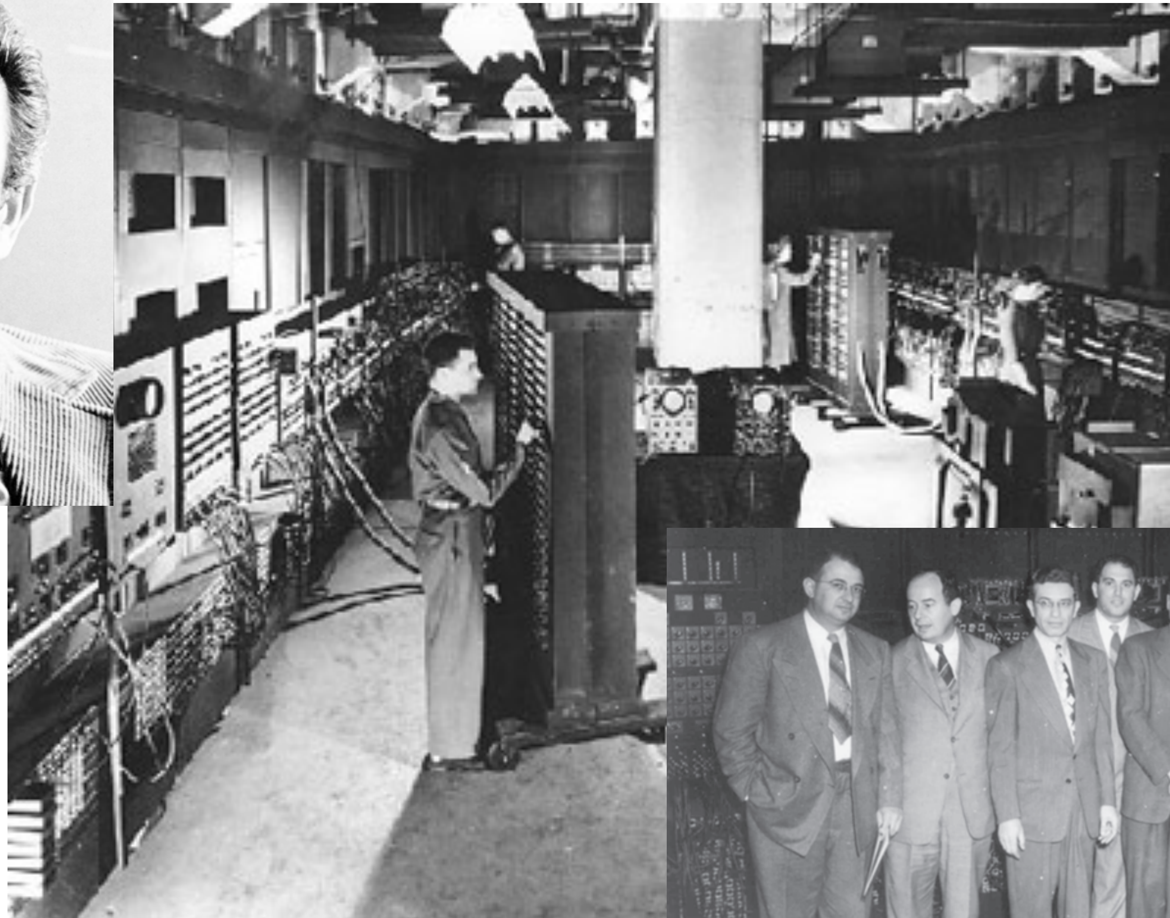


The forecast factory



"Imagine a large hall like a theater except that the circles and galleries go right round through the space usually occupied by the stage. The walls of this chamber are painted to form a map of the globe. . . . From the floor of the pit a tall pillar rises to half the height of the hall. It carries a large pulpit on its top. In this sits the man in charge of the whole theatre." (Weather Prediction by Numerical Process)

Jule Charney
(1917-81)



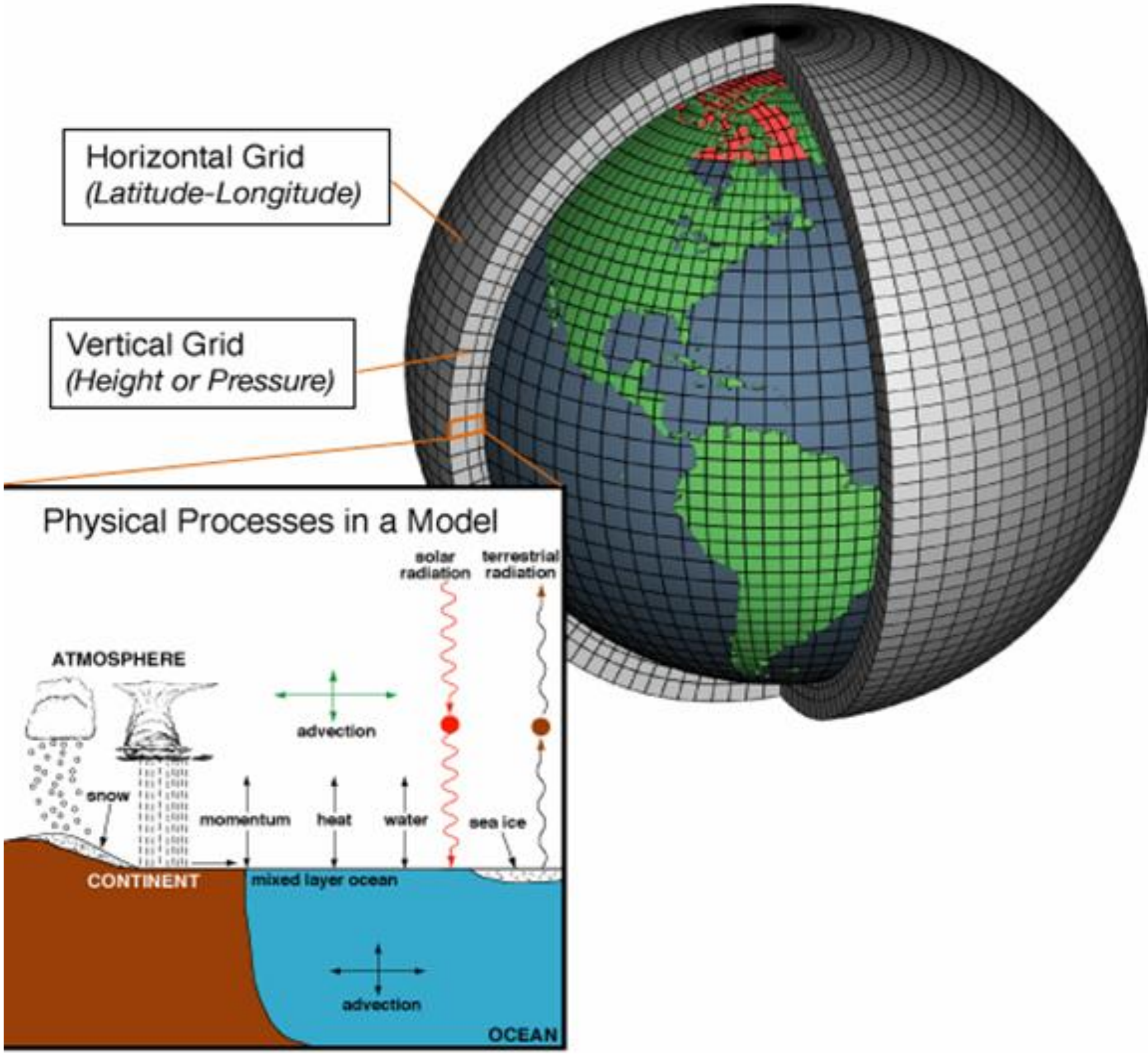
ENIAC

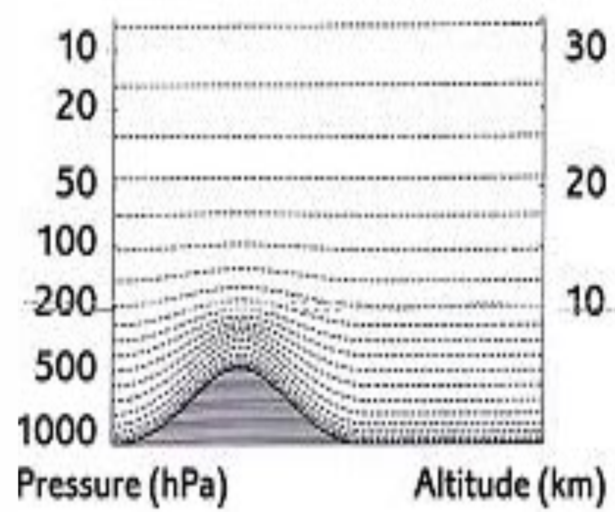
FIG. 1. Visitors and some participants in the 1950 ENIAC computations. (left to right) Harry Wexler, John von Neumann, M. H. Frankel, Jerome Namias, John Freeman, Ragnar Fjørtoft, Francis Reichelderfer, and Jule Charney. (Provided by MIT Museum.)

500 hPa geopotential height: solid=observed dashed=forecasted change

1950: First weather forecast for 24h using the first electronic computer (ENIAC) and **simplified equations for the atmosphere (QG)**

General circulation models





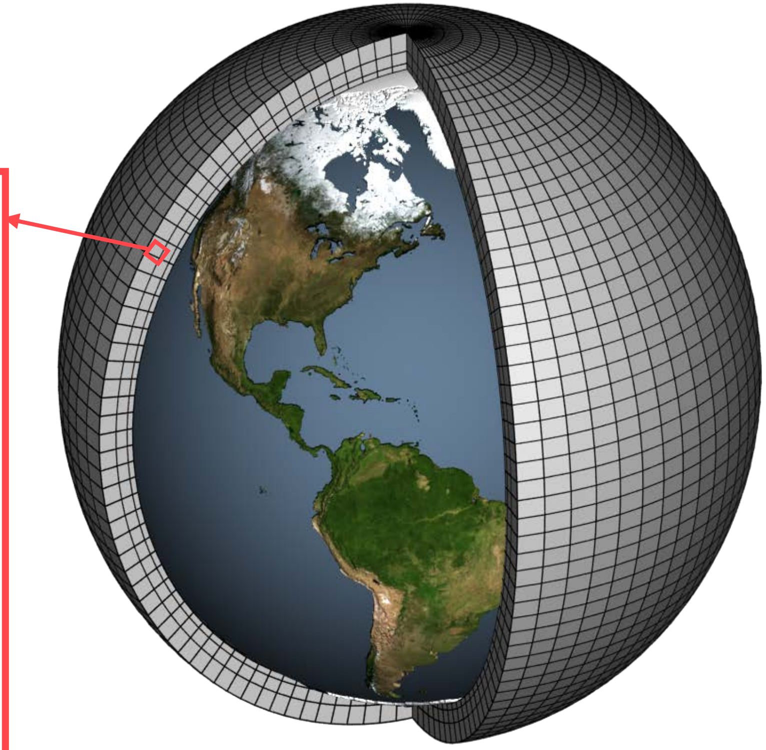
Mathematical equations that represent the physical characteristics and processes are entered for each box

Primitive equations (3D):

Hydrostatic approximation
Boussinesq approximation

Vertical coordinate:
pressure, or entropy

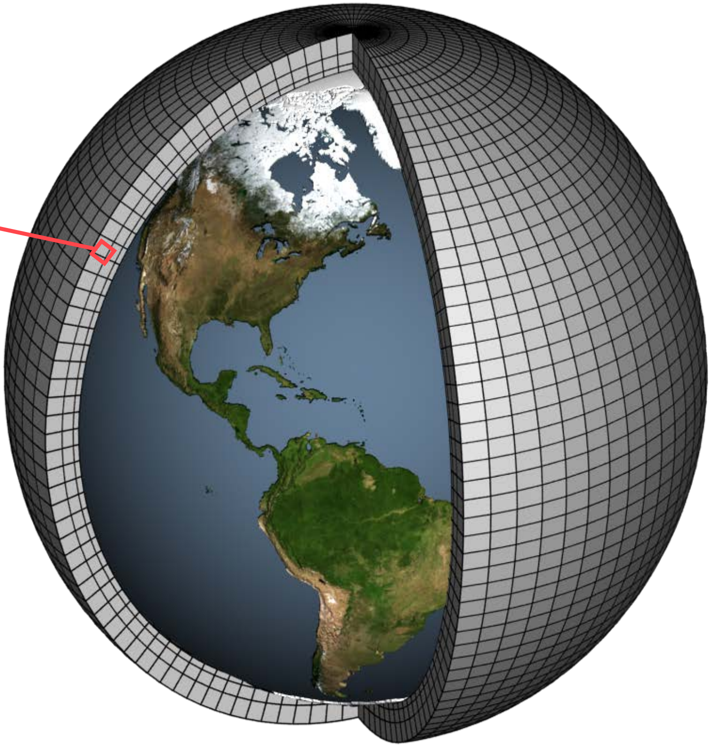
Perfect gas (atmosphere)
Thermodynamics



(from a lecture by S. Gualdi – CMCC)

Equations are converted to computer code and climate variables are set

```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxcel(k))
      do 1480 i=2,imtm1
        boxfx             = fx*dxt(i)*fm(i,k,jc)
        sddt              = (ta(i,k,m)-t(i,k,jc,nm,m))*boxfx
        svar              = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                            *boxfx
        n                 = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)     = tvar(k,m,n)     + svar
        n      = nhreg*(mskvr(k)-1) + mskhr(i,j)
        if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
          termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
          tvar(k,m,n)     = tvar(k,m,n)     + svar
```



(from a lecture by S. Gualdi – CMCC)

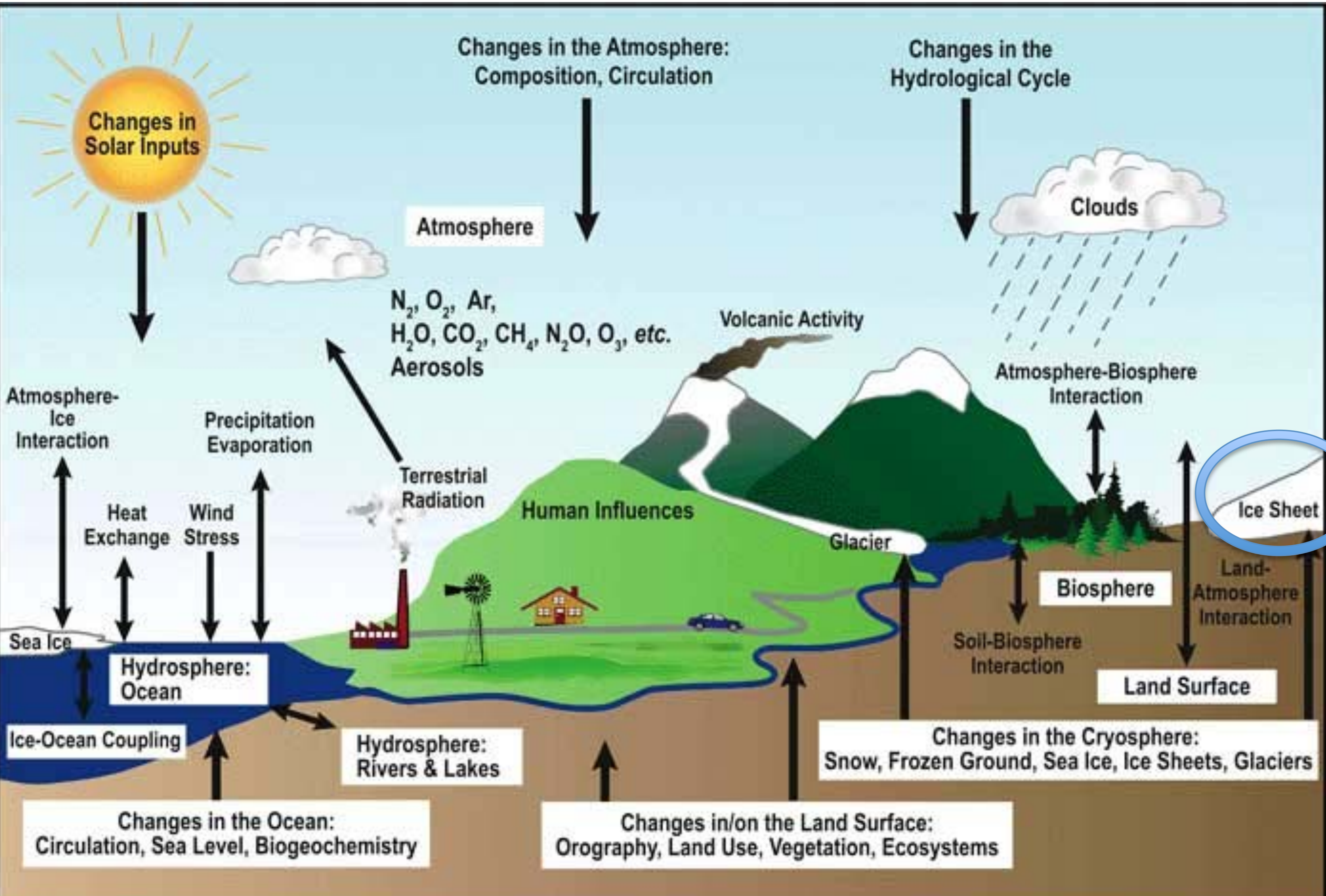
From meteorology to climate:

There is much more than the atmosphere:
Earth System processes

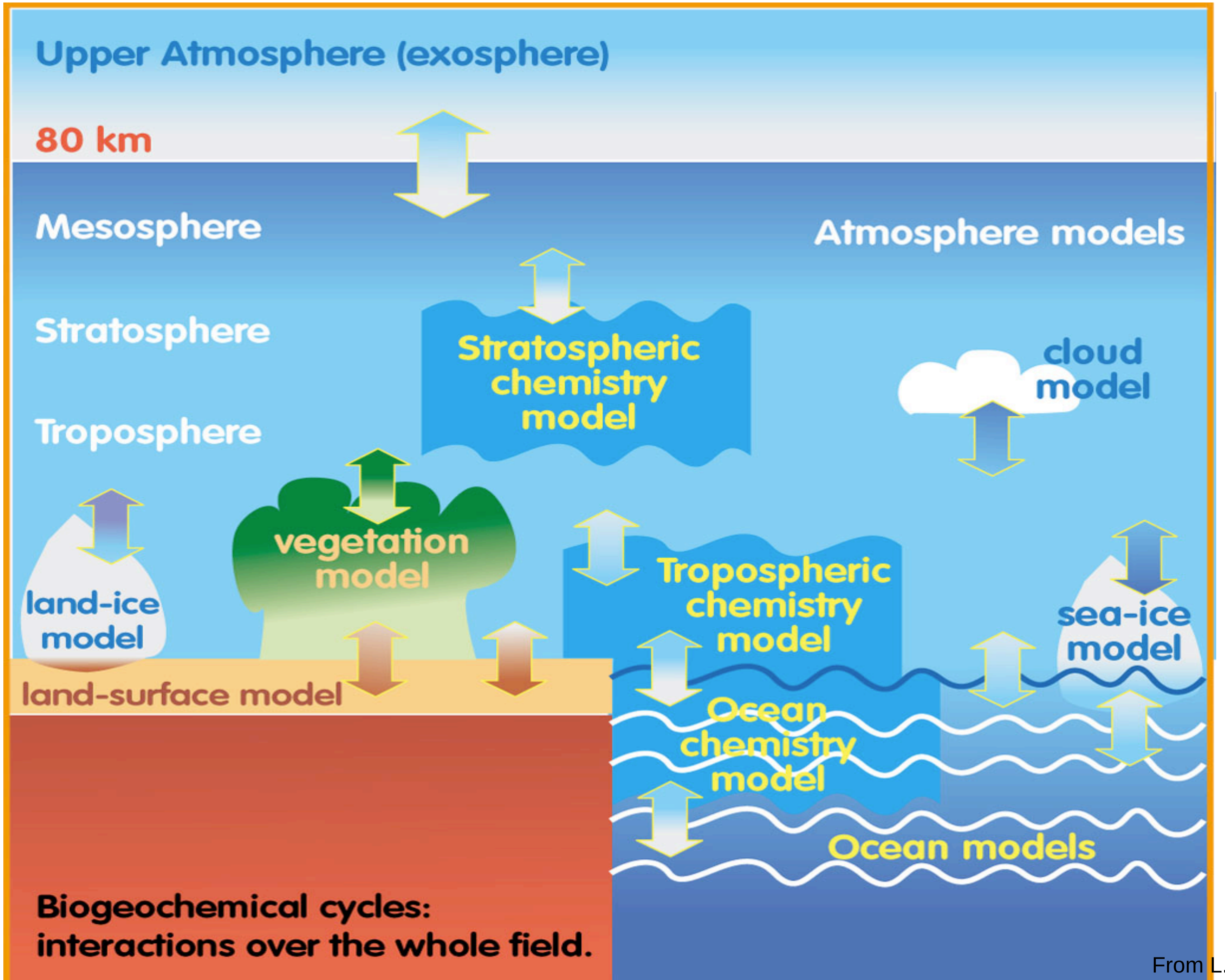
What are the climatic processes
that we need to take into account?

It depends, of course, on the time scale

Earth System processes (100 yr)

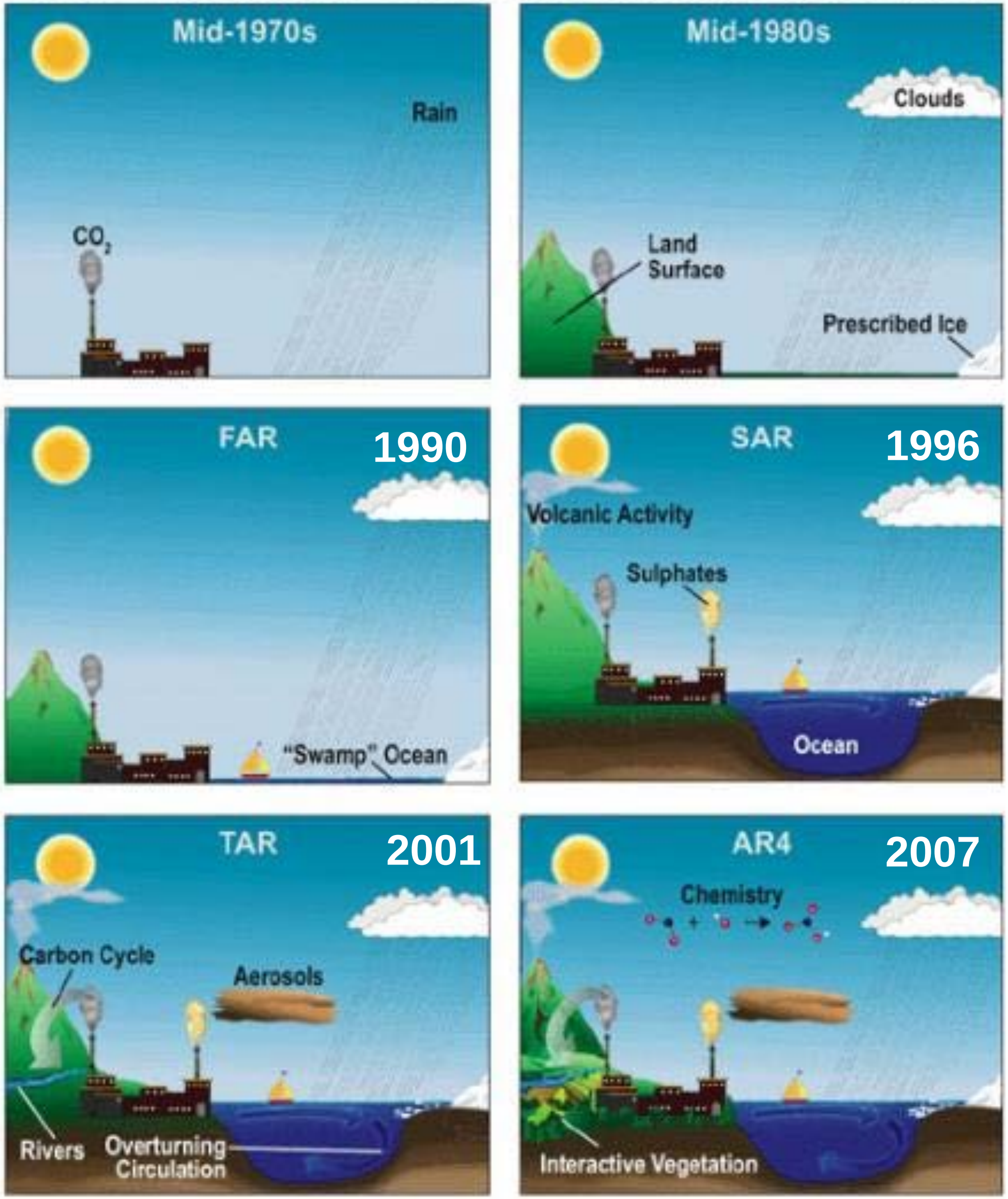


Main components of a global Earth System model



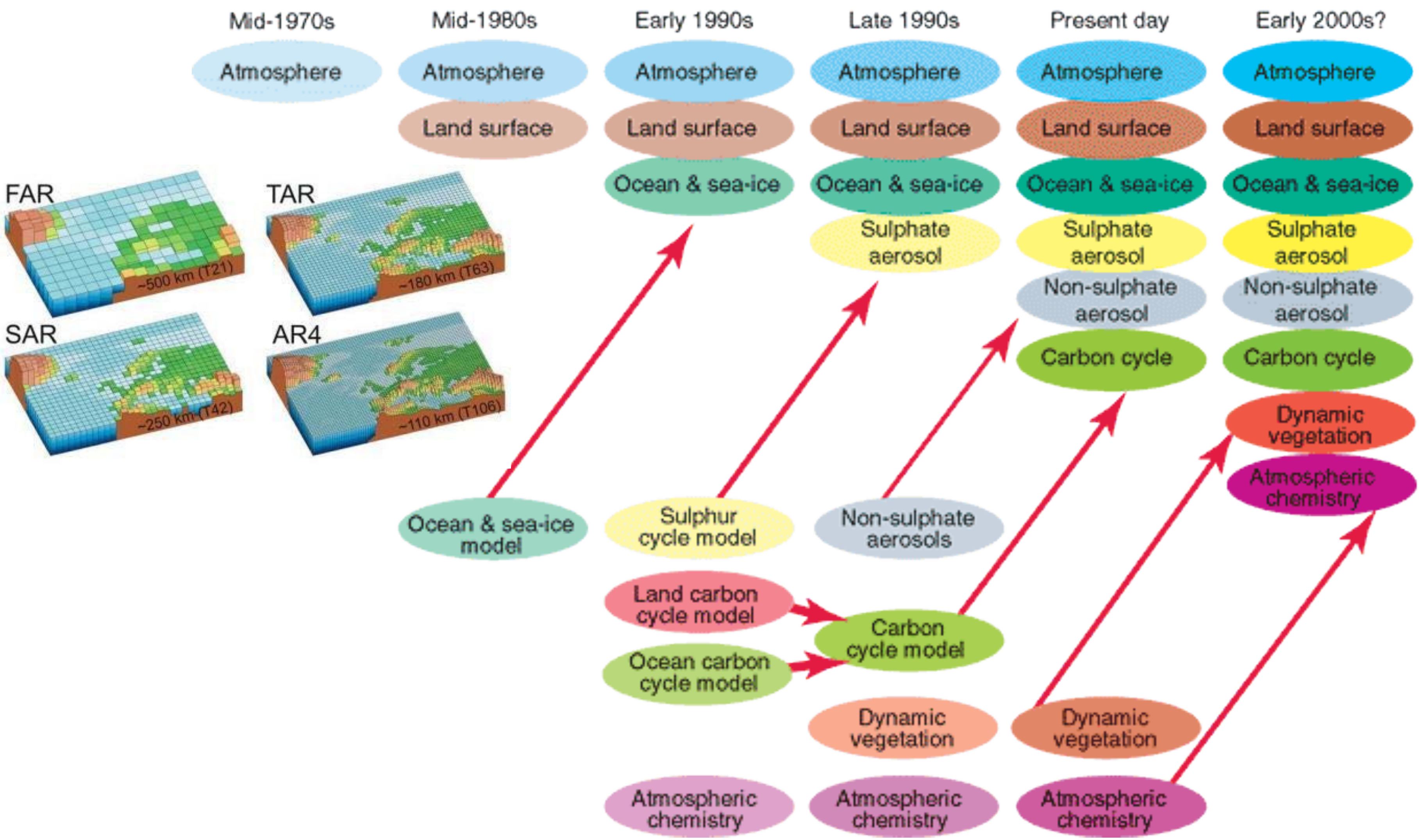
From L. Bengtsson, 2005

The World in Global Climate Models



Le Treut et al. 2007

The Development of Climate models, Past, Present and Future



But remember that sometimes "Less is more"

IPCC TAR, 2001

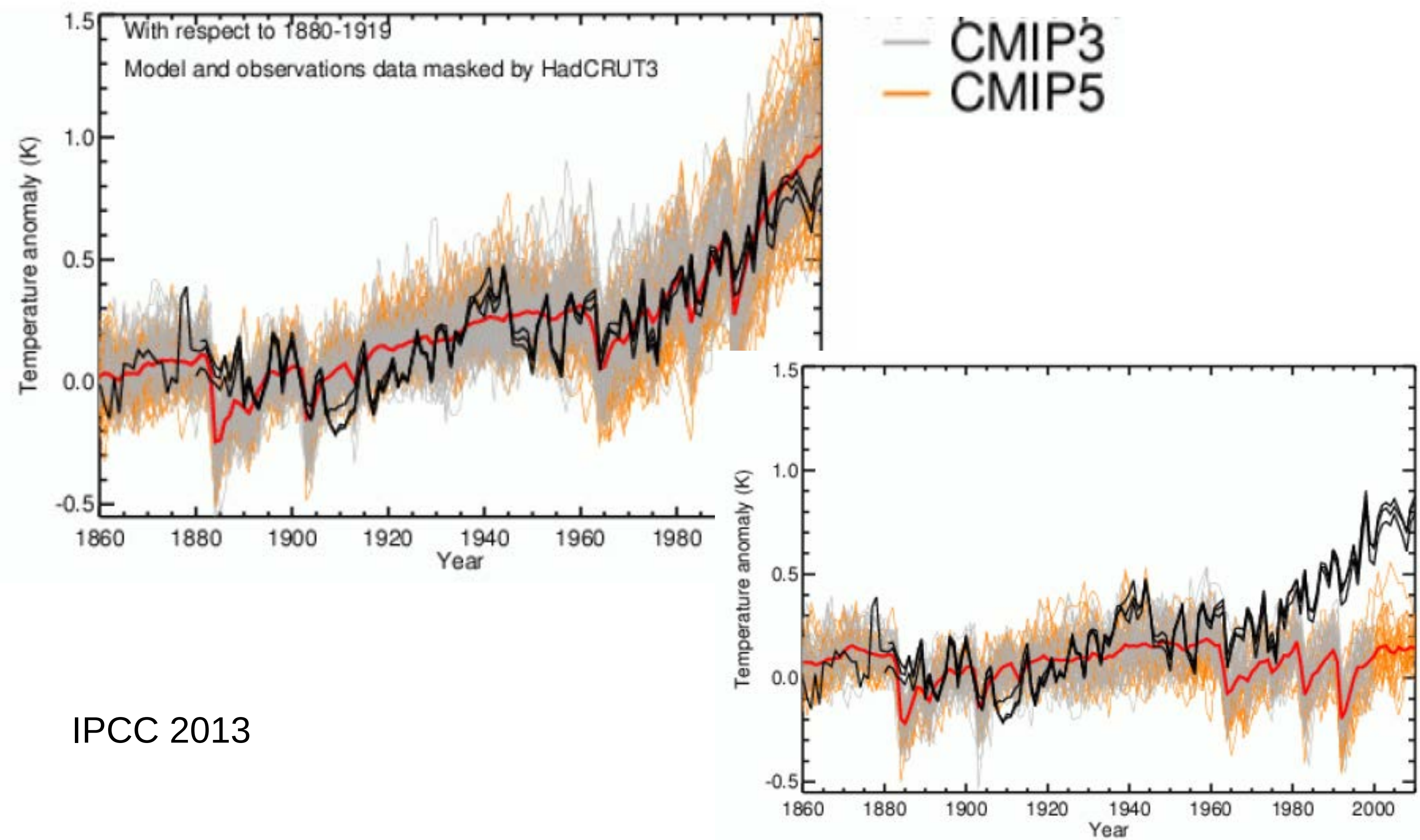
Other crucial elements of climate modelling:

External forcings
Solar variability
Orbital variability
Volcanoes
GHG concentrations
Aerosols
(often, use equivalent radiative forcing at TOA)

Initial conditions

Parameterization choices

Model validation: reproduction of current climate



IPCC 2013

Model validation: Global precipitation

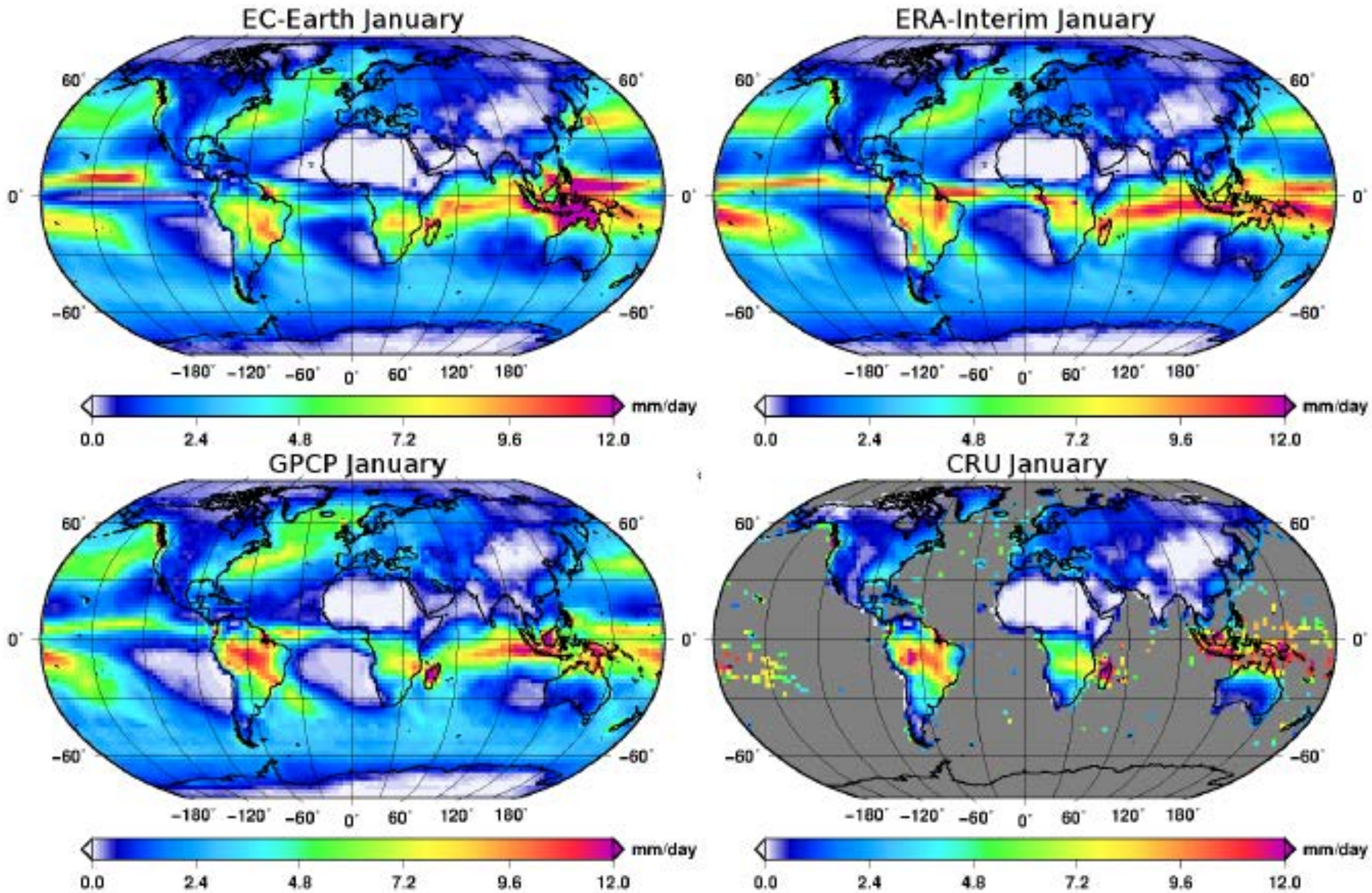
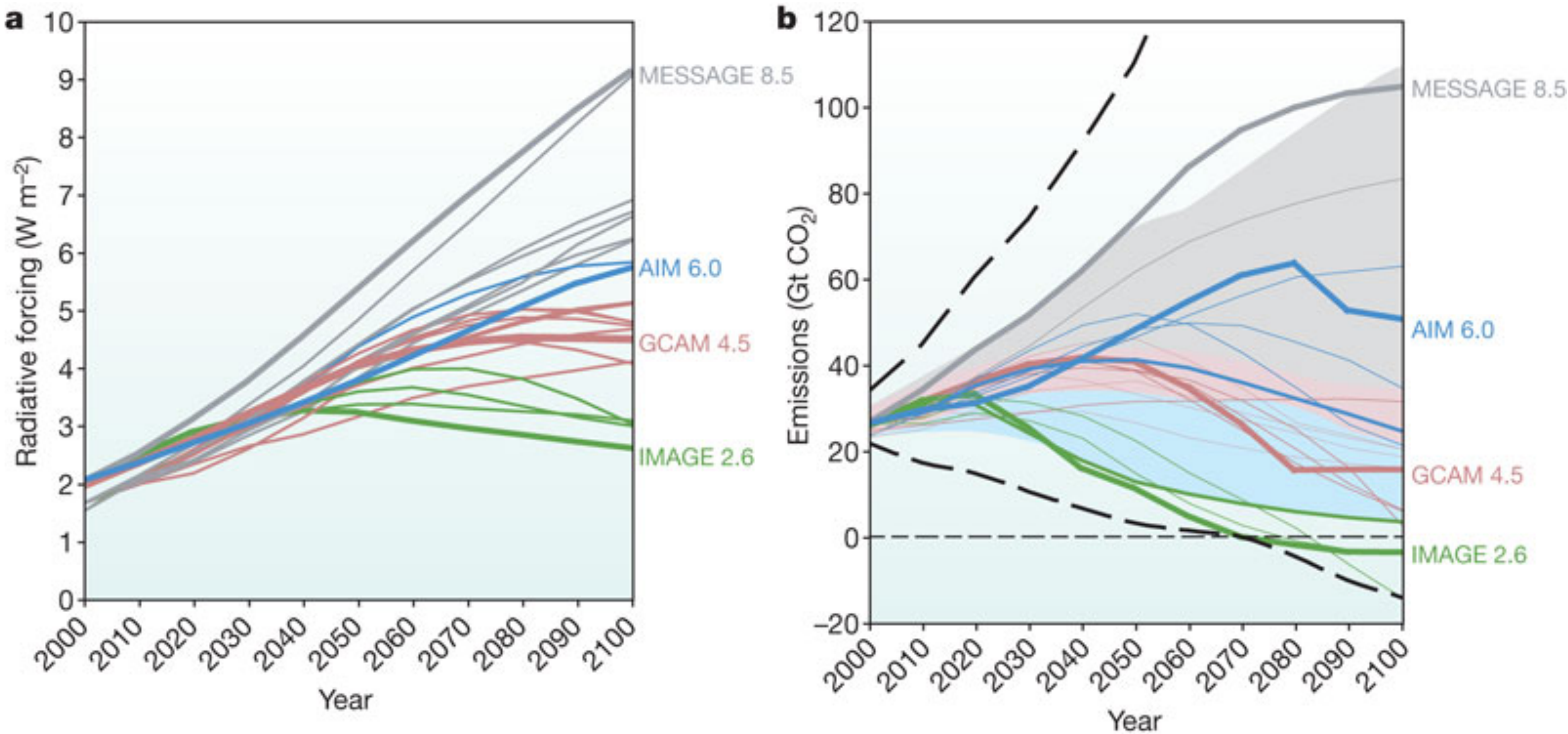


Figure 1: Multiannual mean (1980-2005) January precipitation from EC-Earth, ERA-Interim, GPCP and CRU.

L. Filippi, Master Thesis

Representative concentration pathways



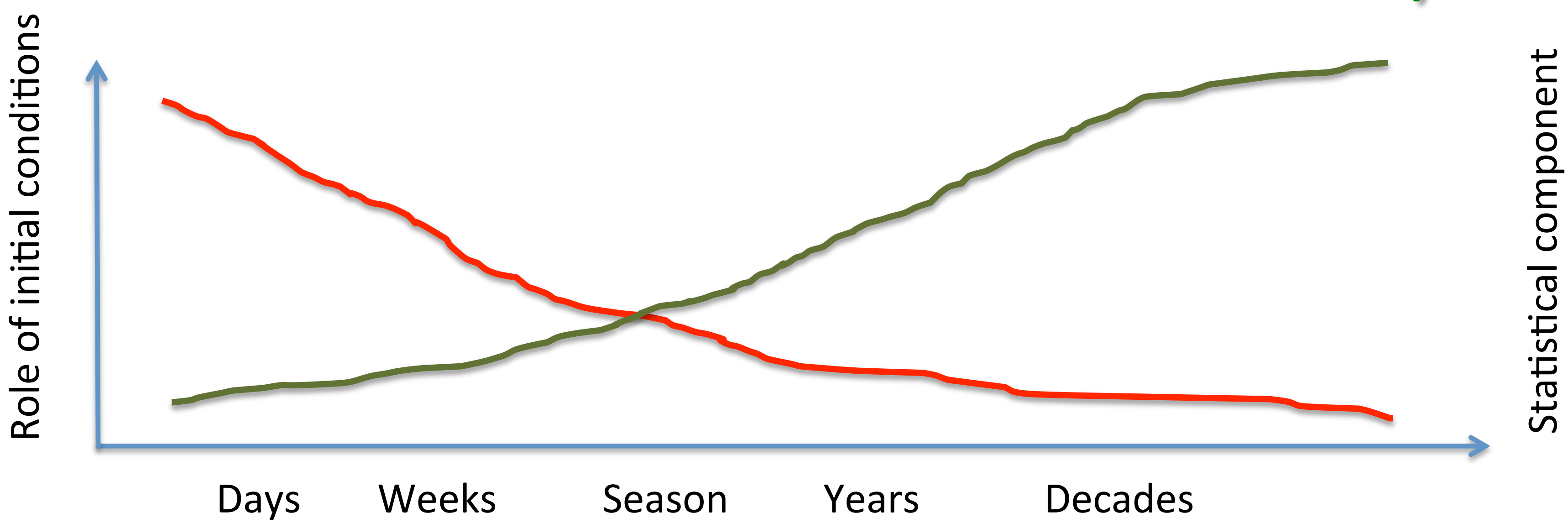
RH Moss *et al.* *Nature* **463**, 747-756 (2010) doi:10.1038/nature08823

nature

The difference between weather and climate

Predictions of the first and second kind (Edward Lorenz)

What is climate predictability? (position on the attractor vs invariant measure on the attractor…)



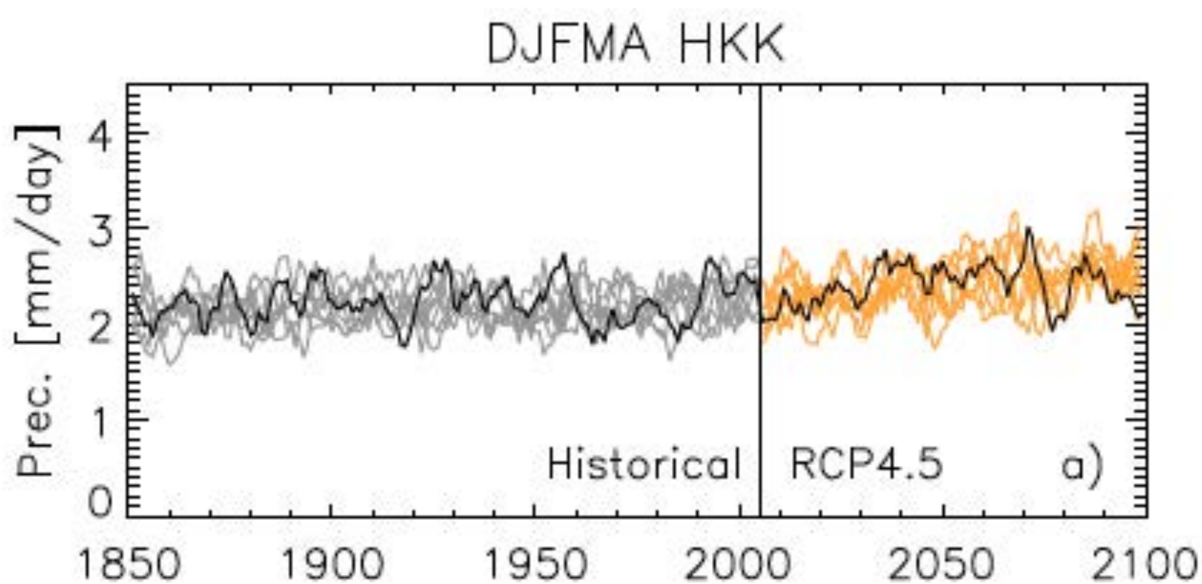
Climate simulations are statistical

A given year in a climate simulation does not mean anything

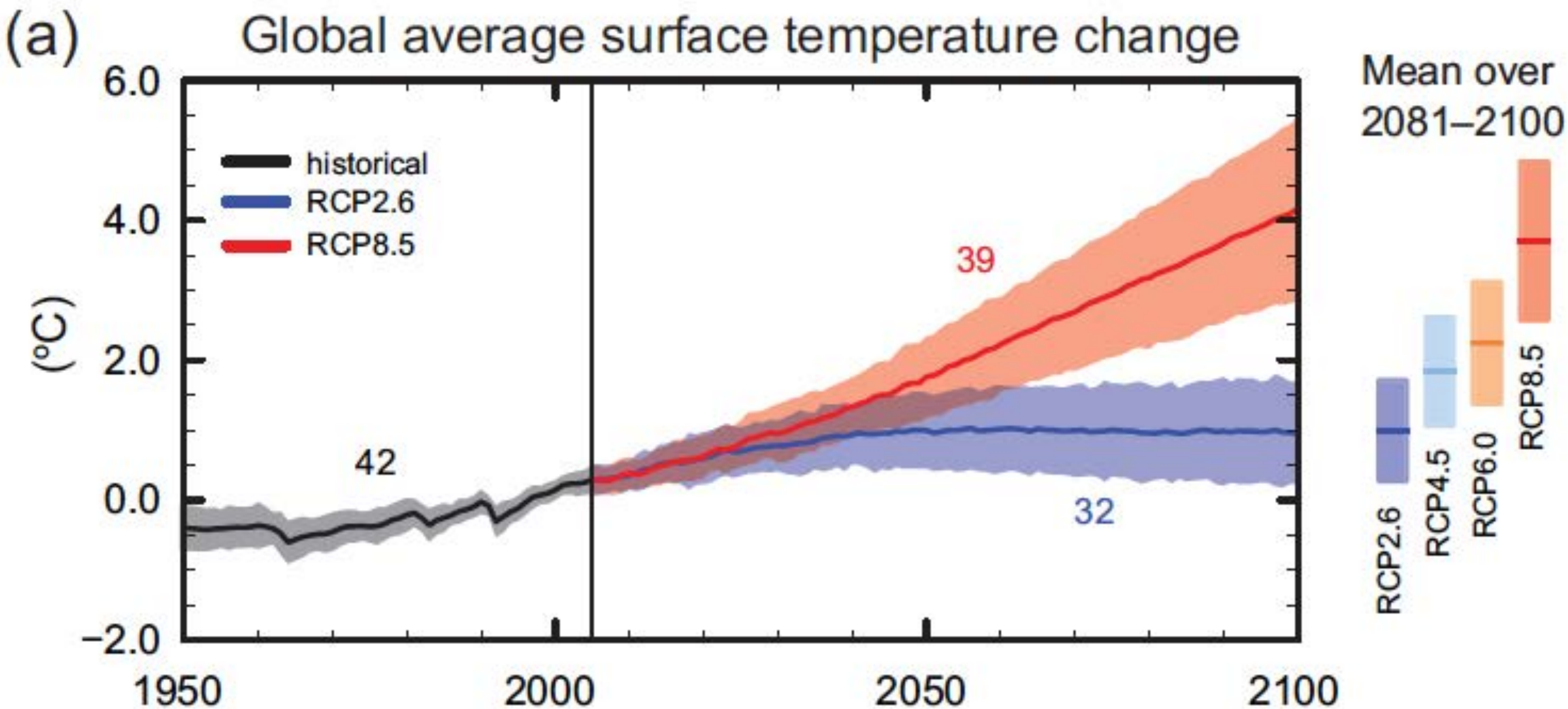
Only trends and statistical quantities (PDFs) are meaningful

Climate ensemble predictions

Start from different initial conditions
and generate an ensemble of simulations
with the same model and same parameters/forcing
or with different models ("multimodel superensemble")
and/or with different parameter choices

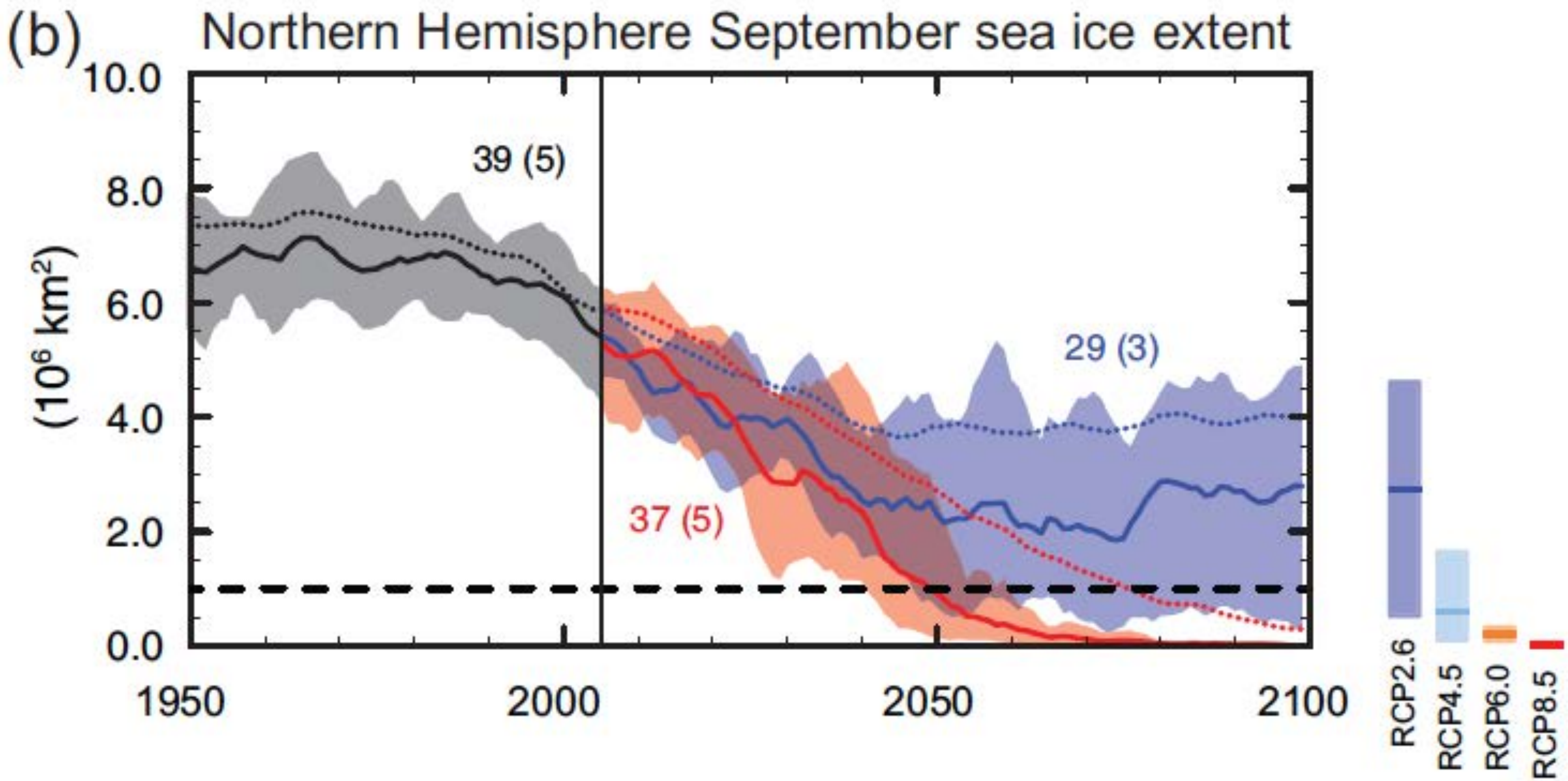


Simulations of future climate



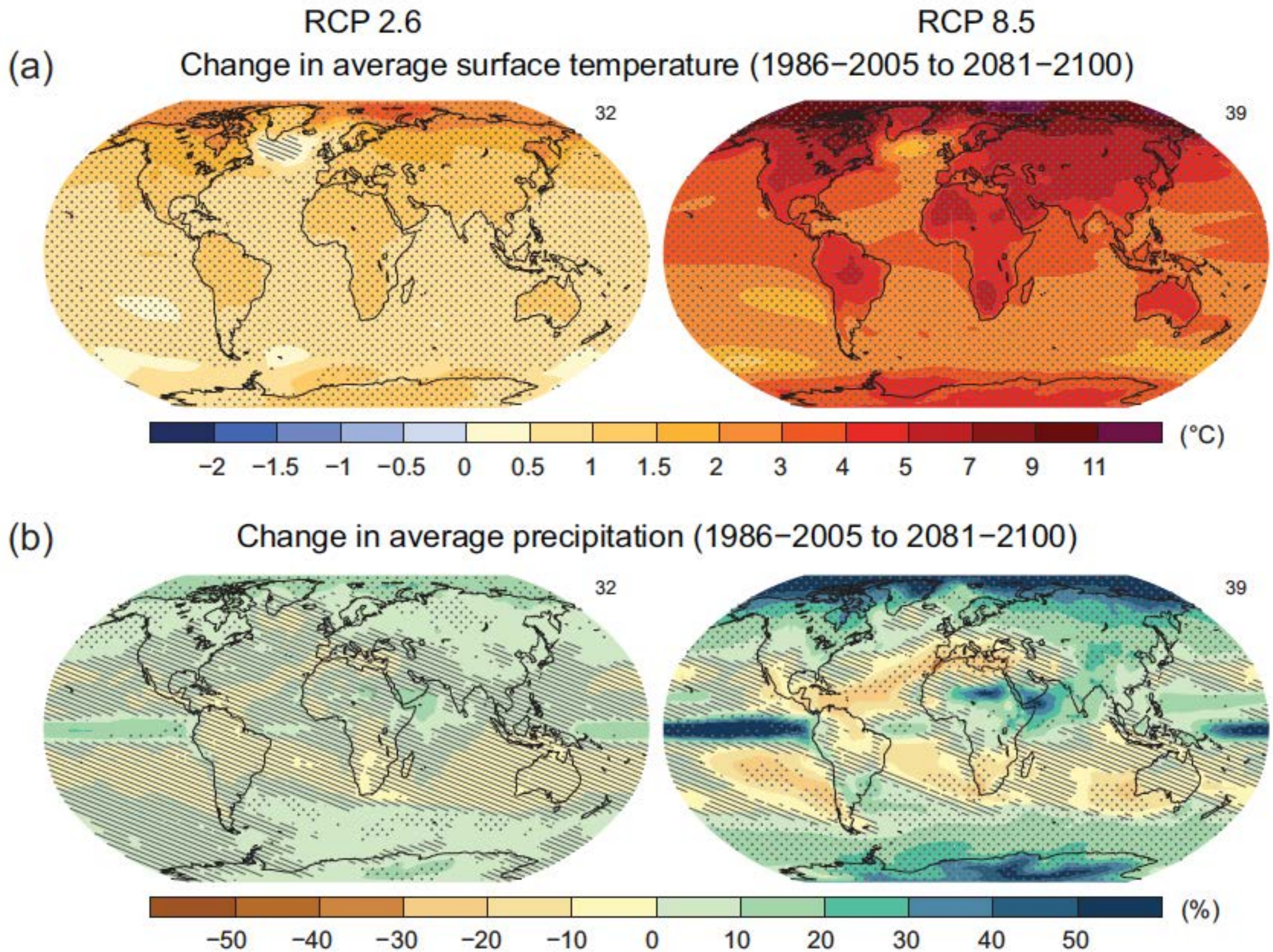
IPCC 2013

Simulations of future climate



IPCC 2013

Simulations of future climate



IPCC 2013

The concept of seamless predictions

- Weather and Climate: Same physical processes (but acting on different space and time scales)
- Initial conditions vs boundary conditions (predictability of the first or second kind)
- From weather → to seasonal → to decadal predictions
- Advantages: climate models profit from advances in NWP and vice-versa

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor. Soc.*, in press.

A European Earth-System-Model for climate studies

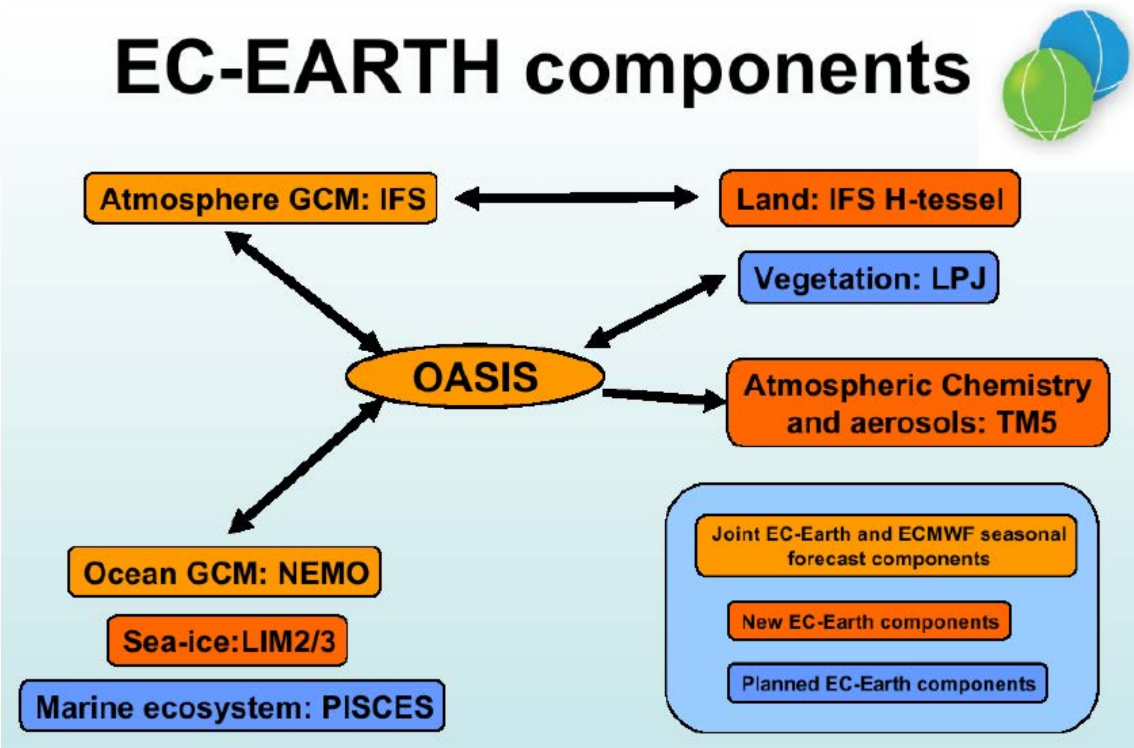
The EC-Earth Model

Based on the idea of "seamless predictions"

ECMWF IFS atmosphere (31r1 - T159L62/N80)+ Land/veg module

+ NEMO2 ocean (OPA/ORCA1) (1° L32)

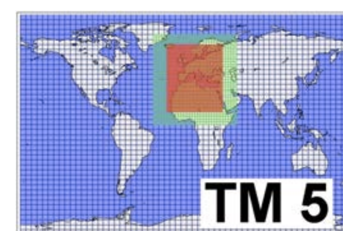
+ TM5 chemistry/aerosols (6°x4° / 3°x2°)



Integrated Forecast System ECMWF

NEMO

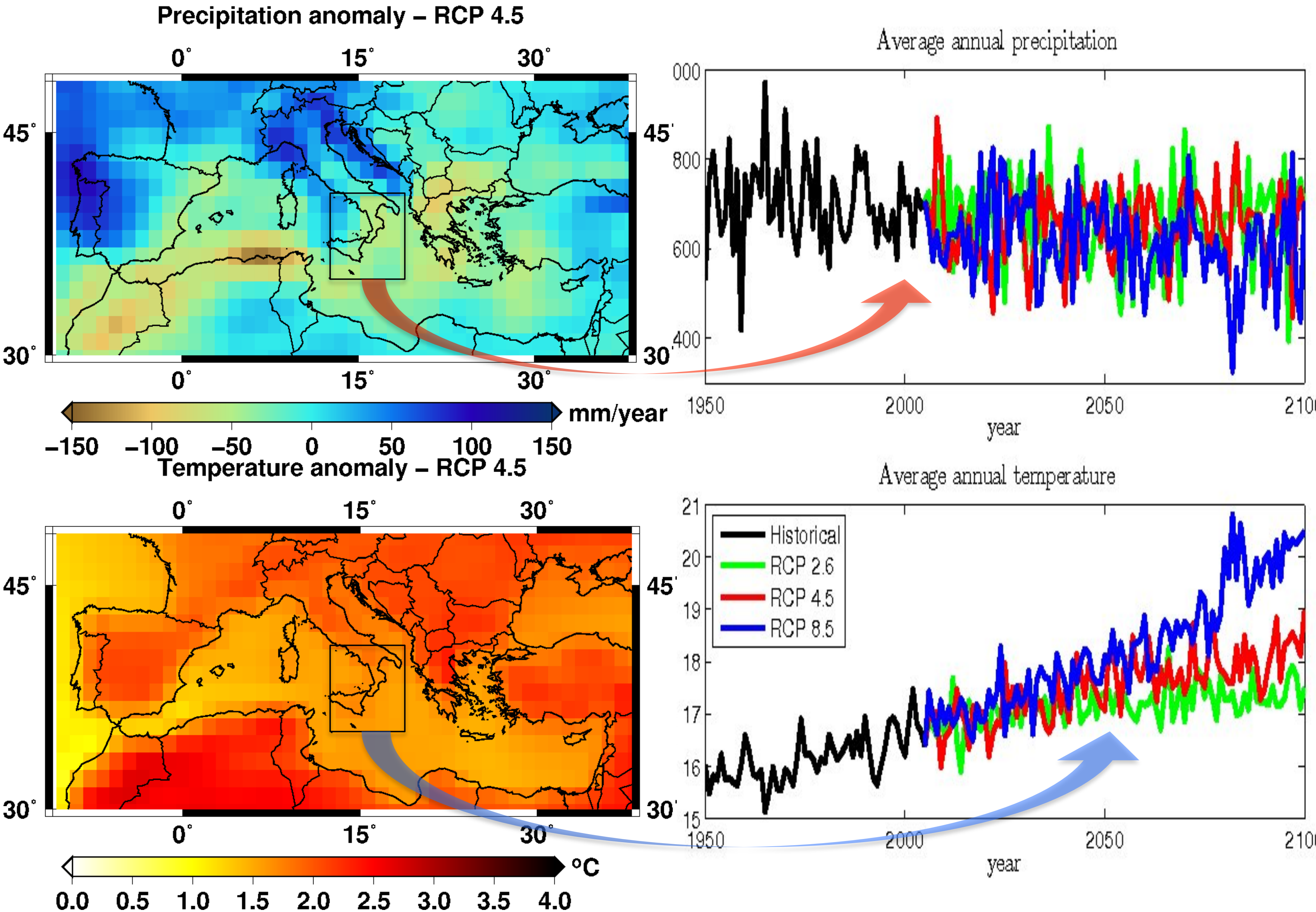
Nucleus for European Modelling of the Ocean

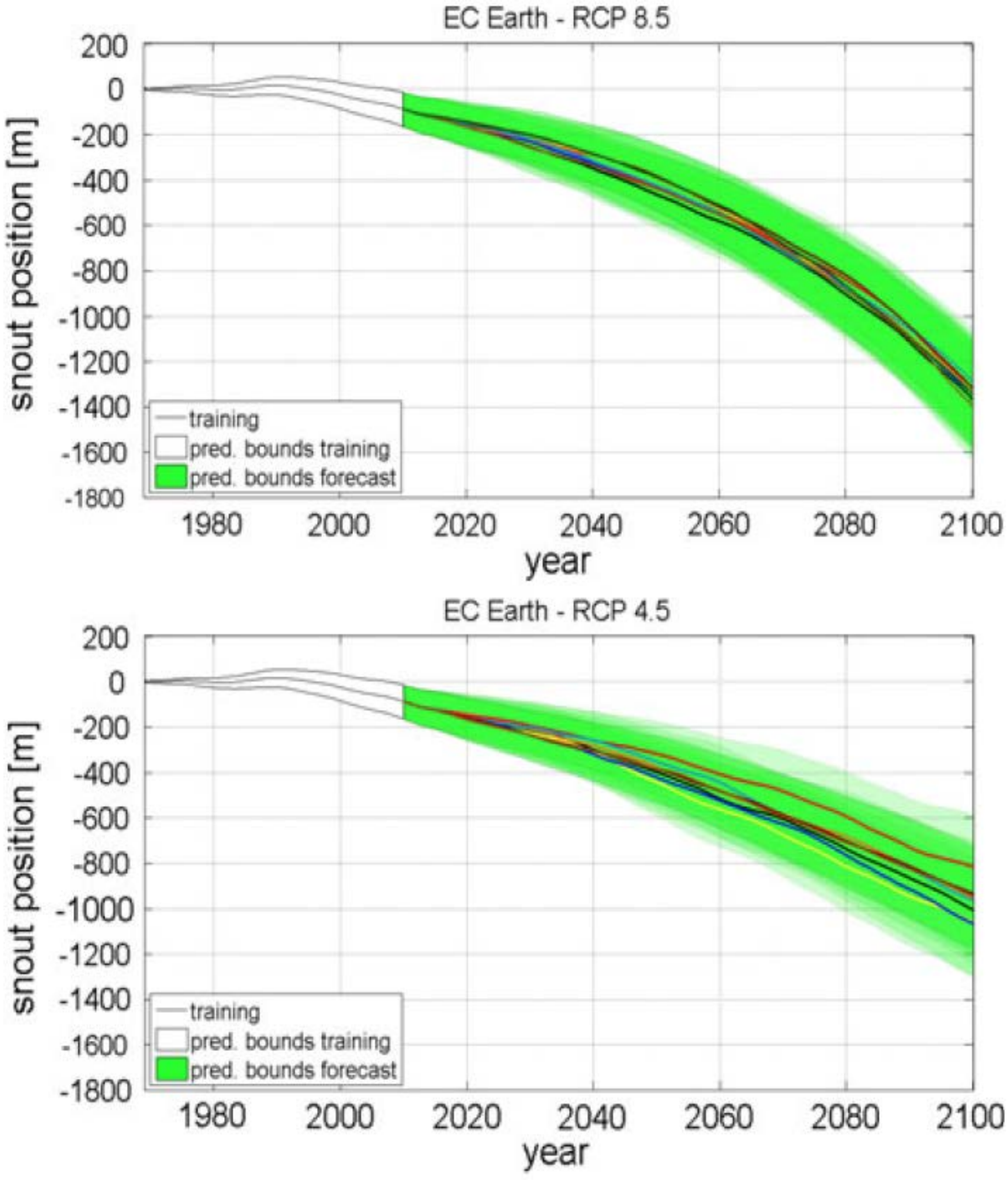


TM5 atmospheric chemistry and transport model

Ref.: Hazeleger, W. et al., 2009. EC-Earth: A Seamless Earth System Prediction Approach in Action. *Bull. Amer. Meteor. Soc.*, in press.

EC-Earth Model, RCP 4.5: [2041-2060] – [1986-2005]

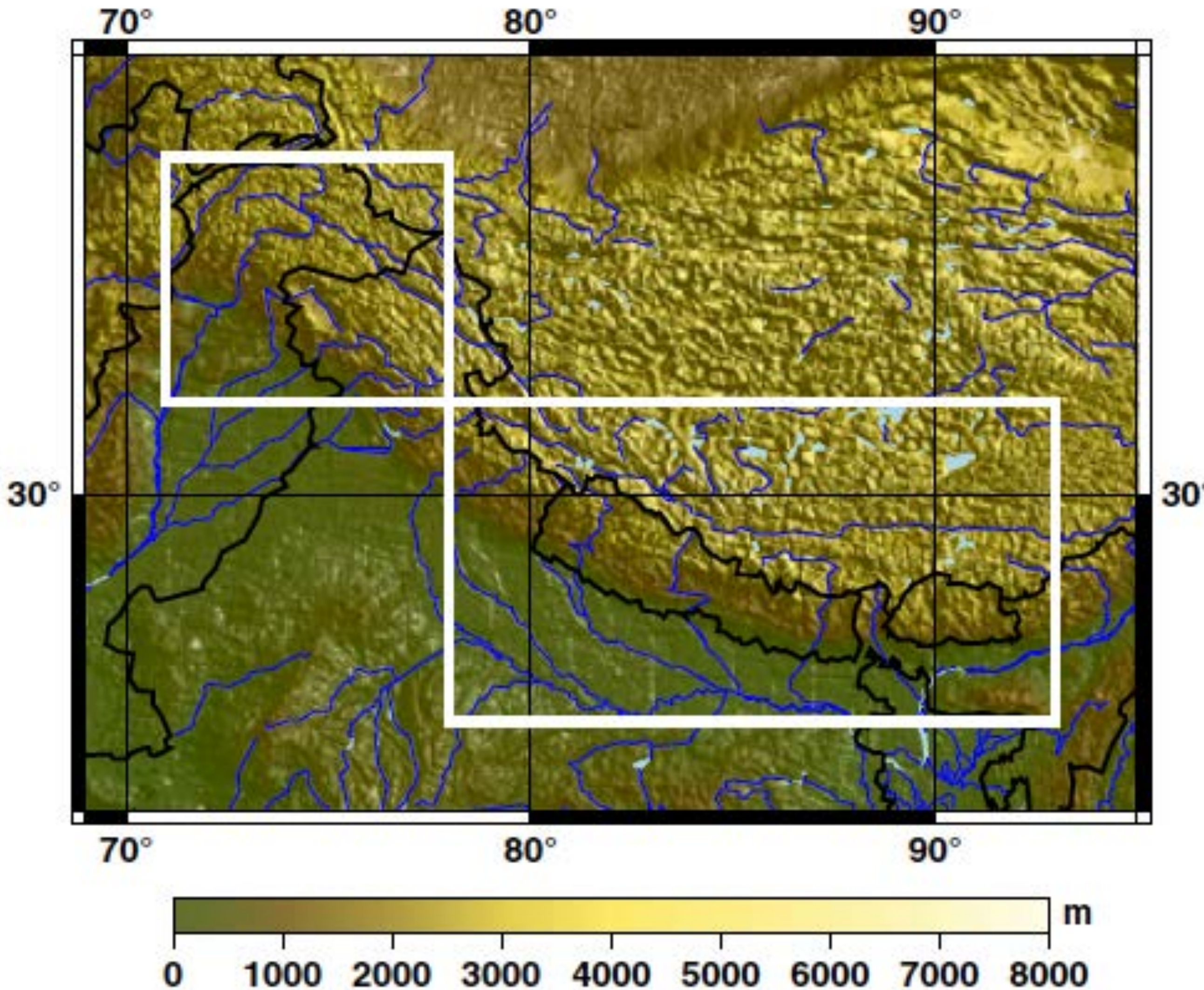


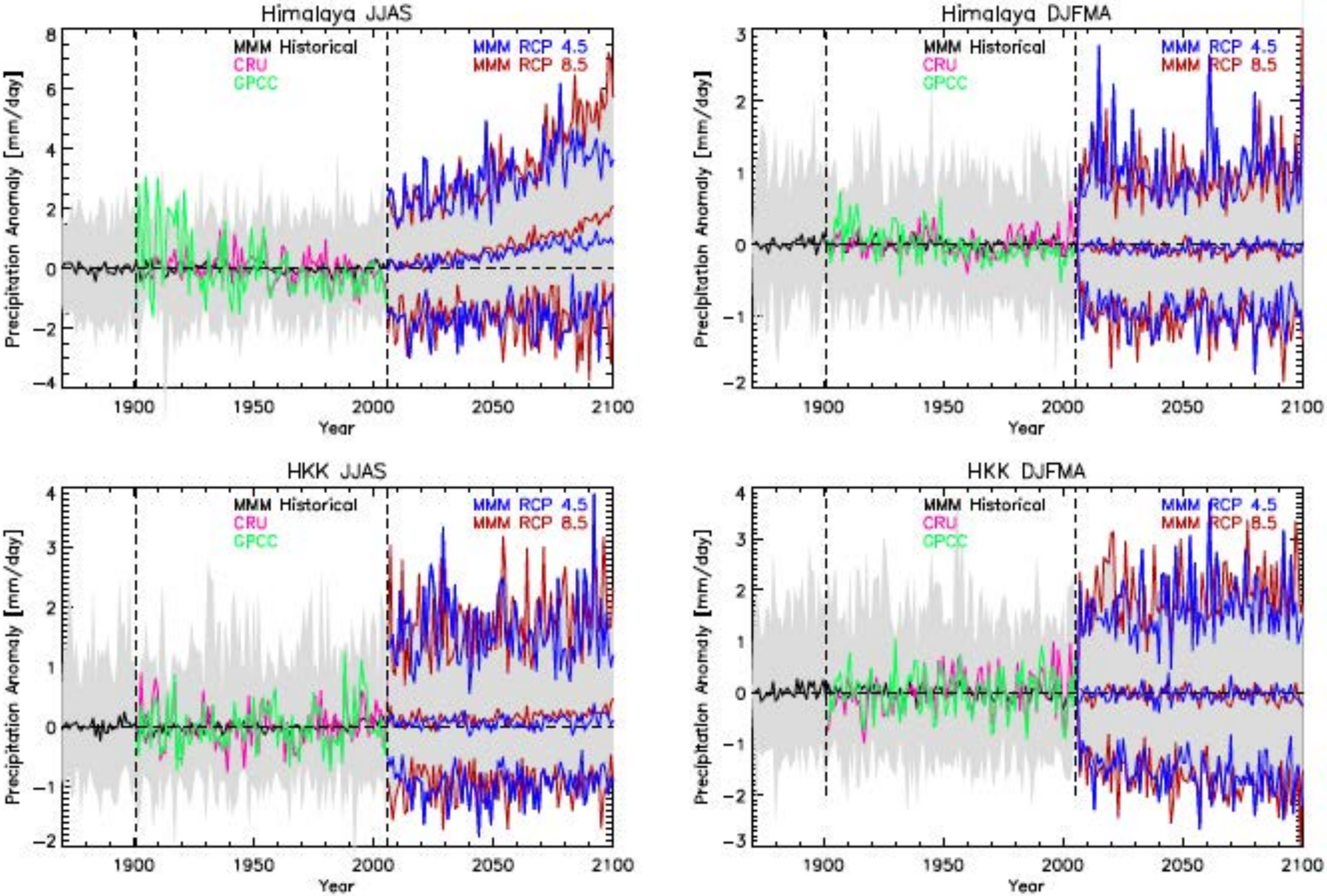


Alpine glacier dynamics (glacier ensembles)

Glacier retreat

Bonanno et al. 2012


70°
80°
90°
30°
30°
70°
80°
90°
m
0
1000
2000
3000
4000
5000
6000
7000
8000



Himalaya JJAS
Himalaya DJFMA
HKK JJAS
HKK DJFMA
MMM Historical
CRU
GPCC
MMM RCP 4.5
MMM RCP 8.5
Precipitation Anomaly [mm/day]
Year

European Research Area for Climate Services

CLIMATE SERVICES:
ERA-NET ERA4CS

“Supporting research for developing better tools, methods and standards on how to produce, transfer, communicate and use reliable climate information to cope with current and future climate variability”

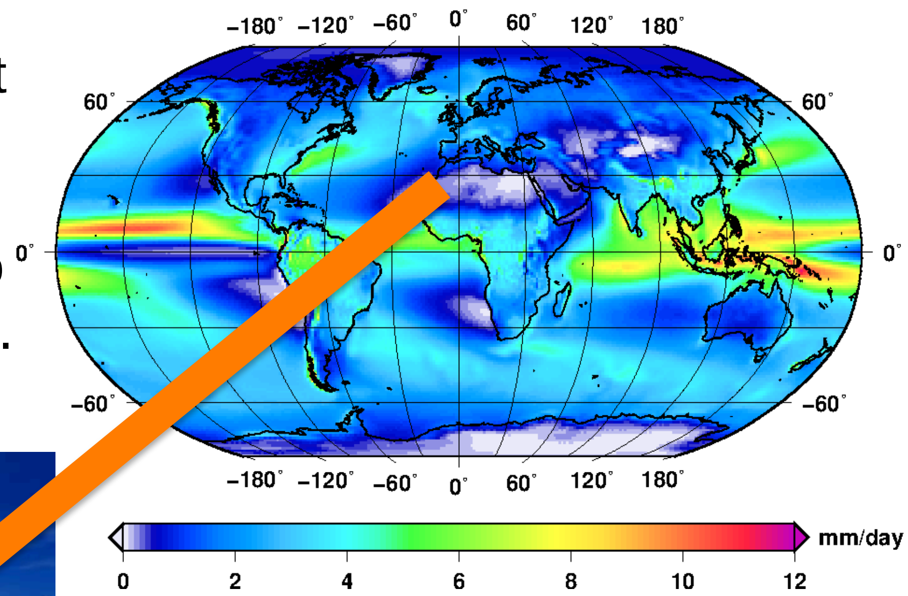
Focus on seasonal to multiannual time scales:
Importance of initial conditions

http://www.jpi-climate.eu/ERA4CS

To estimate future impacts and risks, we need climate and impact models

Global Climate Models: The most advanced tools that are currently available for simulating the global climate system and its response to anthropogenic and natural forcings.

Total precipitation annual mean 1951–2007



Impact models:
Basin response
Ecosystems
Glaciers and snow
Agriculture, Land surface
Water resources

Problem:

Most climate change impacts take place at local scale

Global Climate Models currently provide climate projections spatial resolution between 40 and 100 km

So: **scale mismatch and need for climate downscaling**

Climate downscaling approaches:

Dynamical downscaling

Regional Climate Models

(eg RegCM, Protheus)

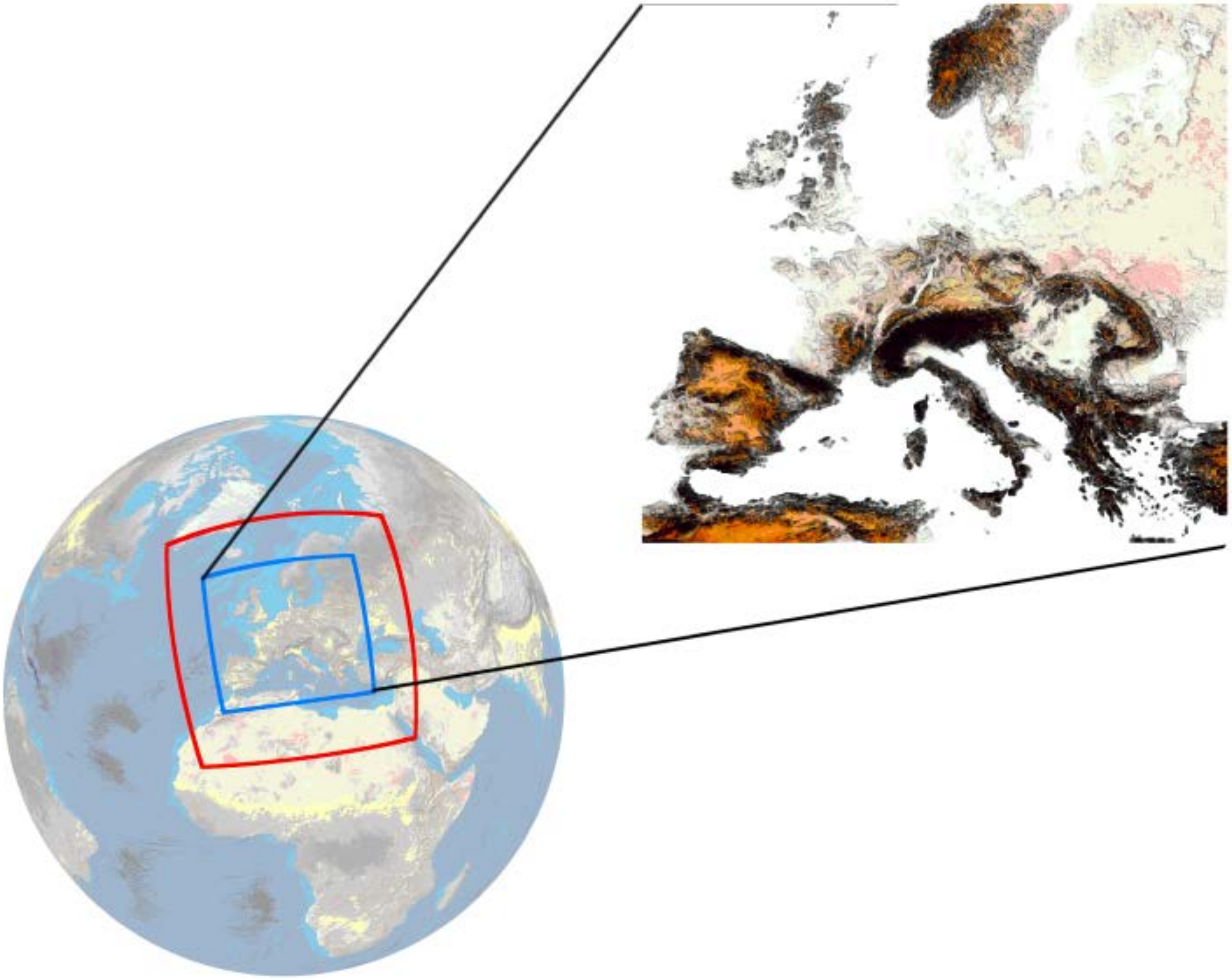
Non-hydrostatic models

(eg COSMO-CLM, WRF)

Statistical downscaling

Stochastic (rainfall) downscaling

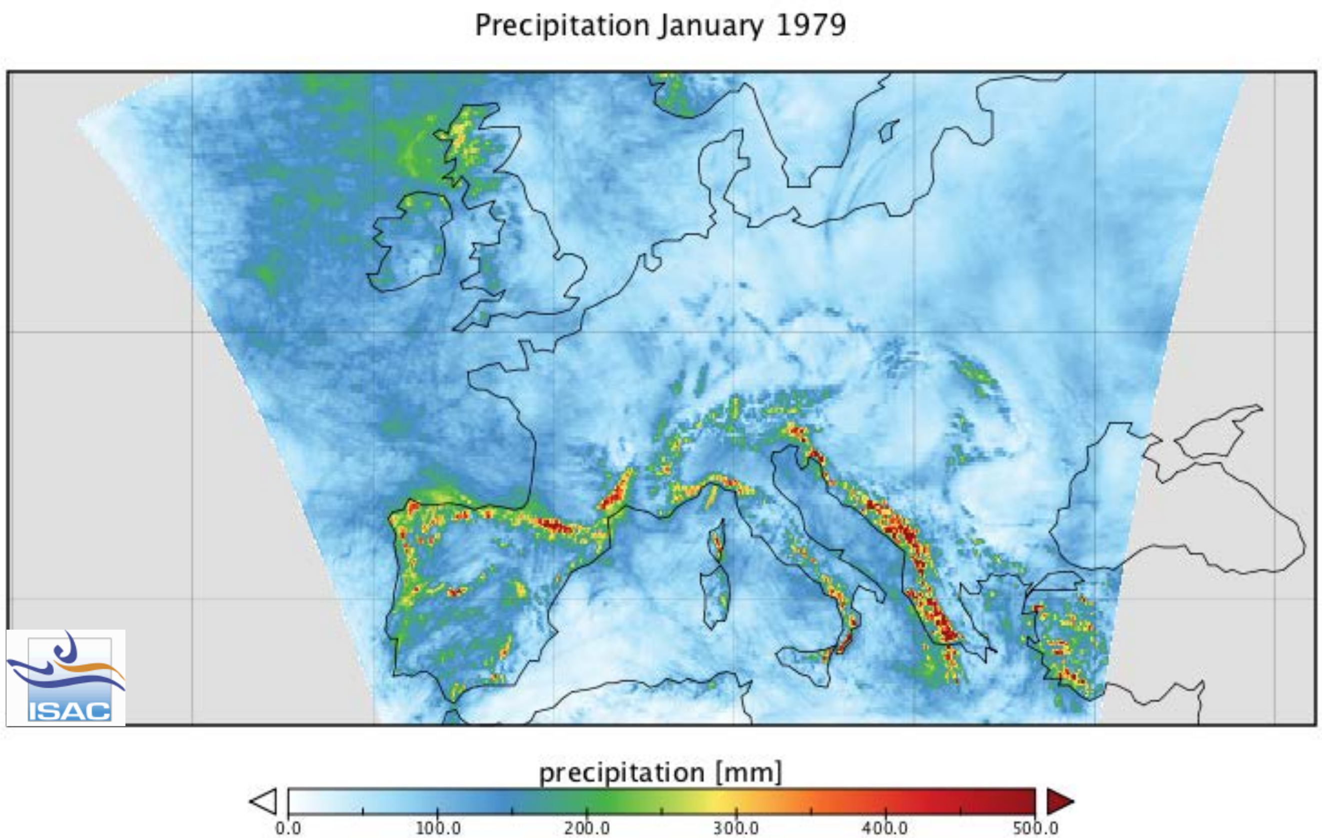
Dynamical downscaling



Non-hydrostatic RCMs: simulations with WRF

WRF - Weather Research & Forecasting Model
http://www.wrf-model.org/index.php

Climate simulations (30 years) with WRF at high spatial resolution (0.11° and 0.04°) nested into reanalyses (to be nested also into the EC-Earth GCM)



Total precipitation

from WRF climate simulations at 4 km January 1979

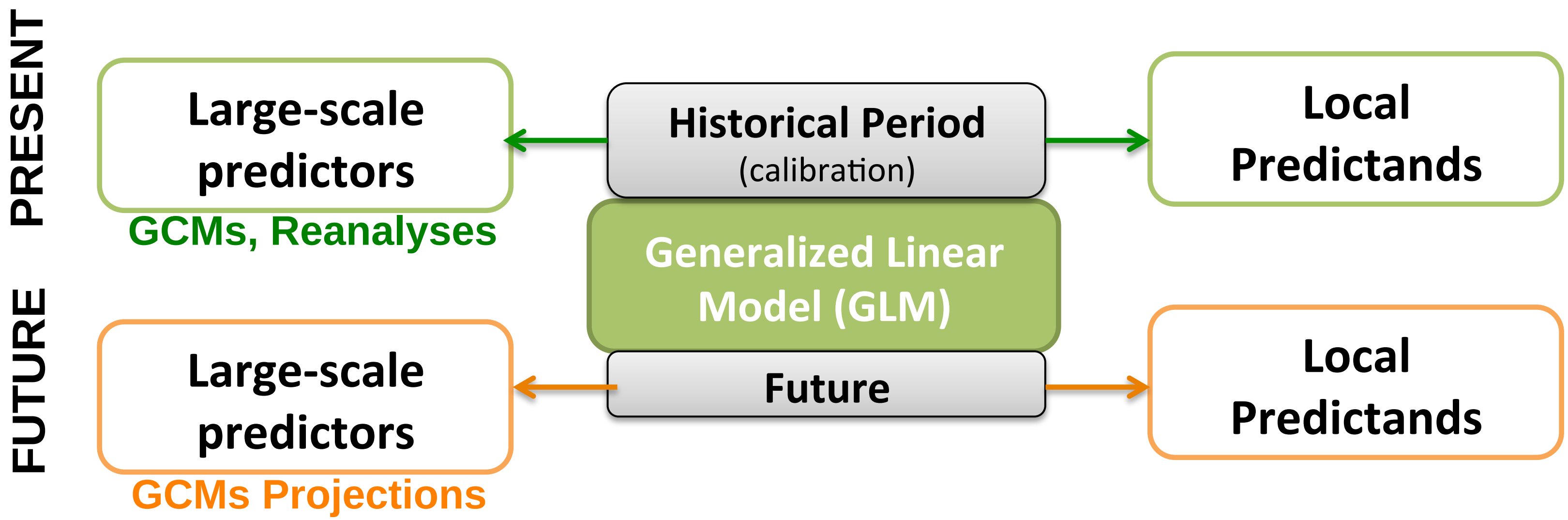
Simulations @ Leibniz-Rechenzentrum (LRZ)/ SuperMUC, Munich

Pieri et al, JHM, 2015

Statistical downscaling

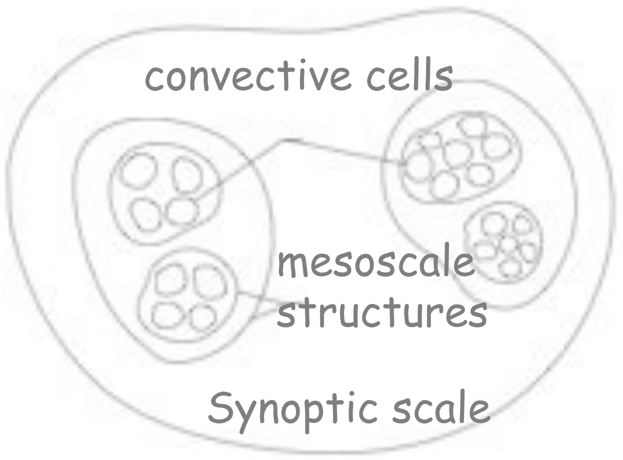
Find statistical relationships between large-scale climate features and fine-scale climate for a give region:

1. Find a large-scale predictor
2. Determine its relation with a predictand
3. Use the projected value of the predictor to estimate the future value of the predictand (assuming stationarity)



Stochastic downscaling

Highly intermittent fields such as rainfall can be difficult to handle with dynamical or statistical downscaling (no simple interpolation is possible).



- Highly **non-homogeneous phenomenon**

- Organized in **hierarchic structures (scaling property of rainfall)**

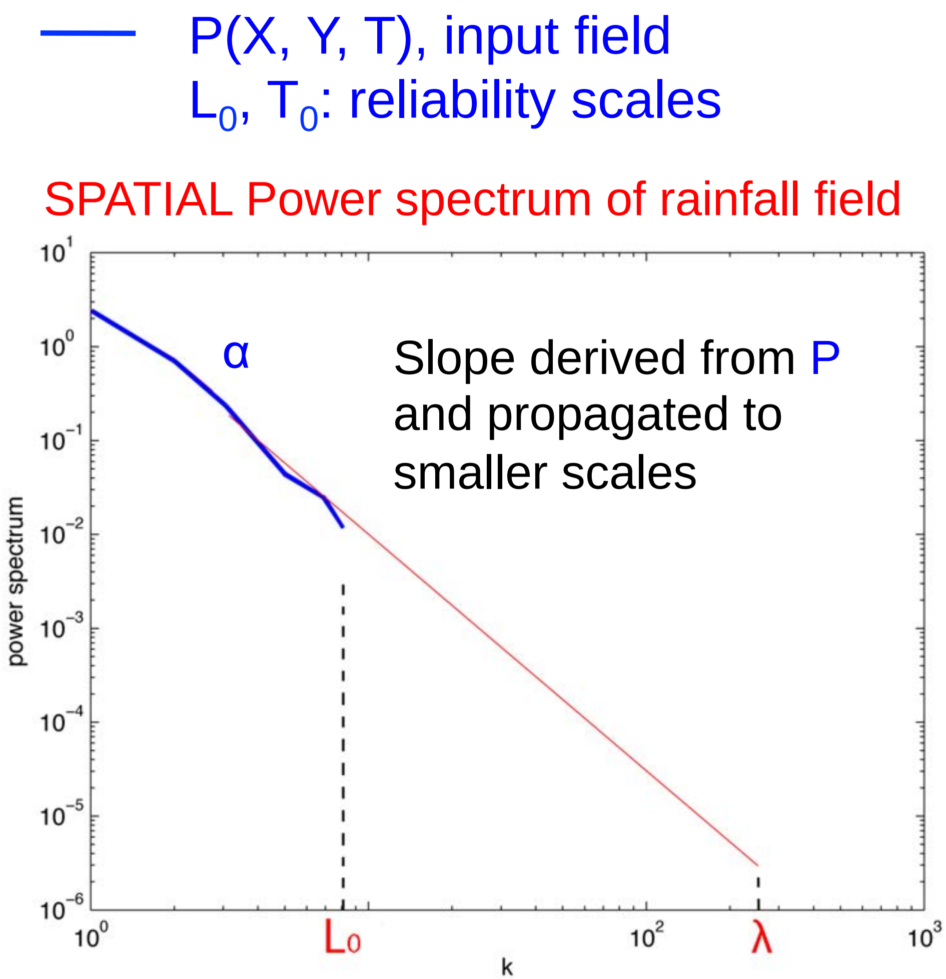
- **Highly intermittent in space and time** (alternating between dry and rainy periods).

An alternate approach is **stochastic downscaling** which leads to ensemble projections

Stochastic downscaling

RainFARM (Rainfall Filtered Auto Regressive Model)

RainFARM uses simple statistical properties of large-scale rainfall fields, such as the **shape of the power spectrum,** and generates small-scale rainfall fields **propagating this information to smaller (unreliable/ unresolved) scales, provided that the input field shows a (approximate) scaling behaviour**



Stochastic downscaling

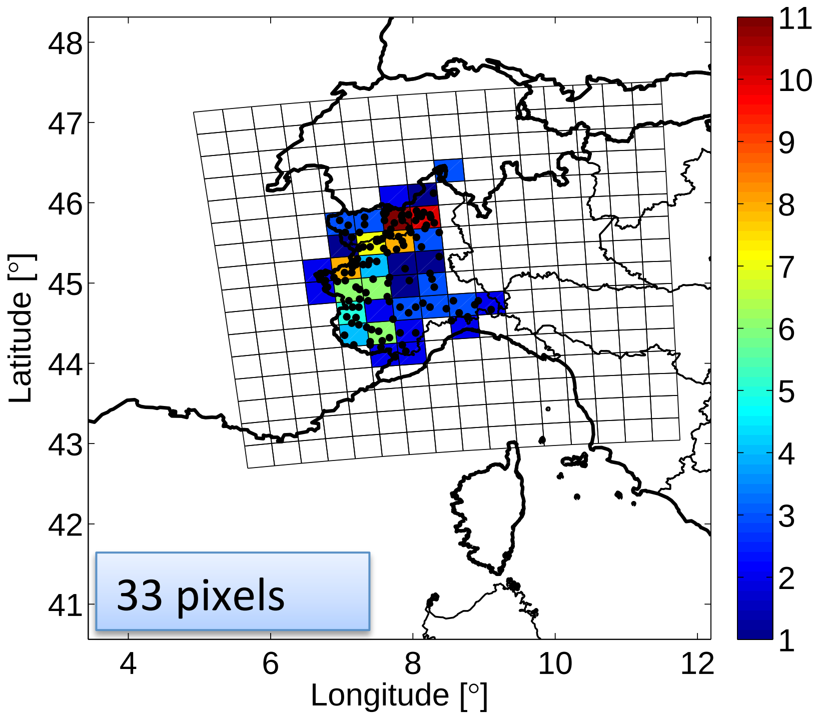
RainFARM (Rainfall Filtered Auto Regressive Model)

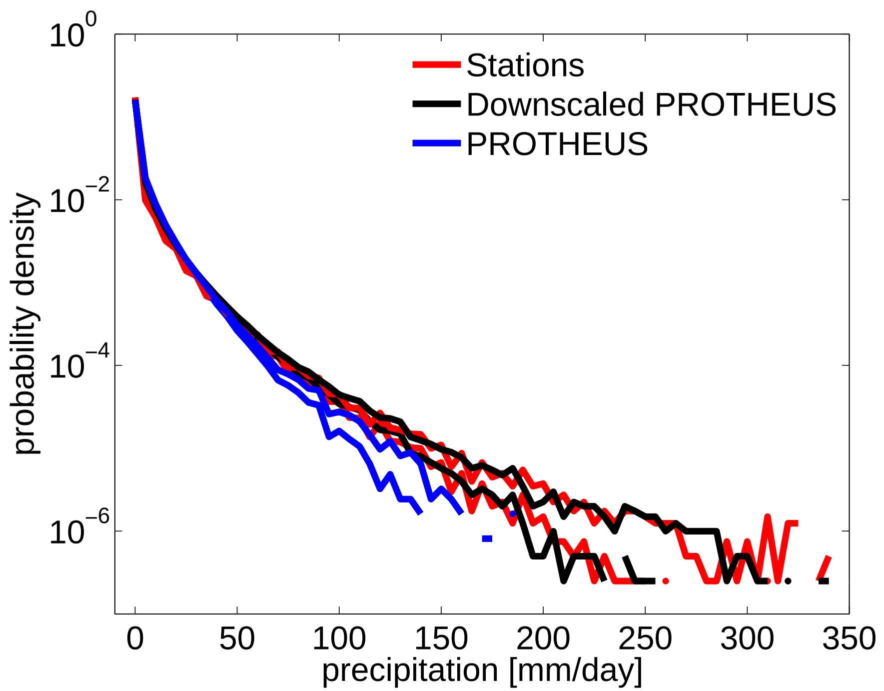
- 122 rain gauges
- 1958-2001
- Daily resolution

- Altitude max: 2526 m
- Altitude min: 127 m

D'Onofrio et al.,
J. Hydrometeor,
15, 830–843, 2014

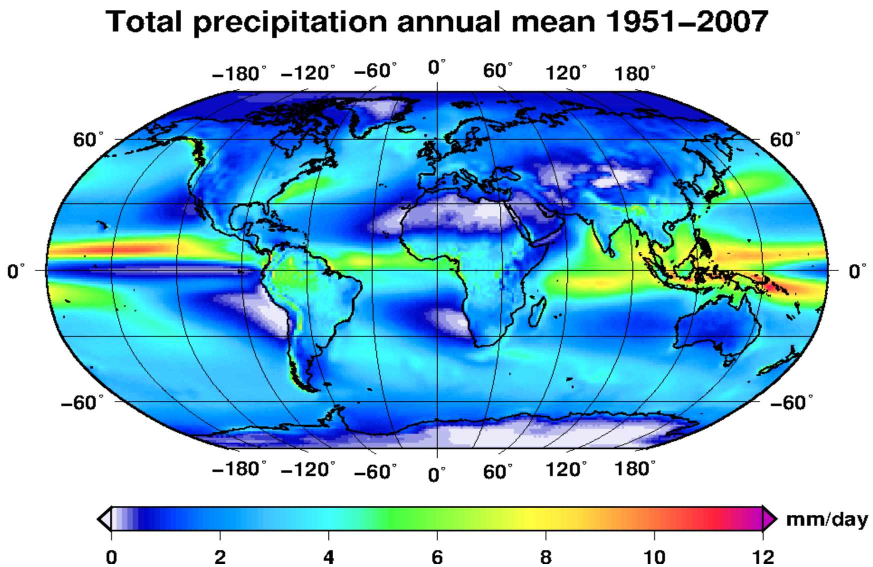
PROTHEUS: Δx≈30km



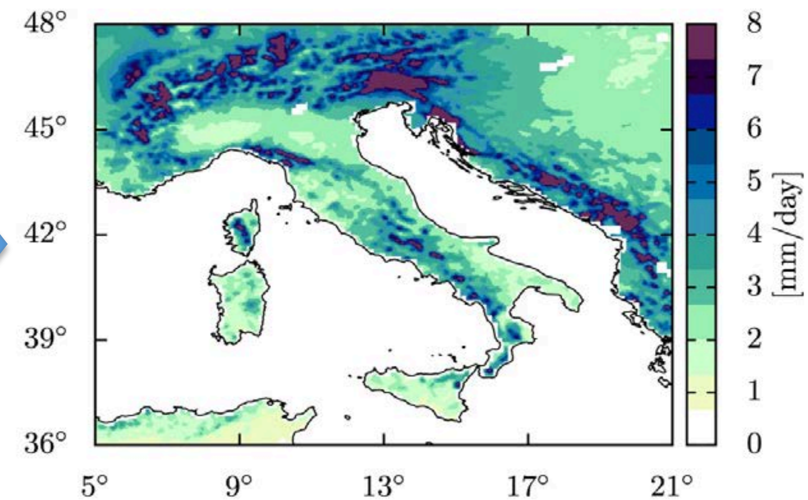


The downscaling-impact chain

Global climate model



Regional climate model



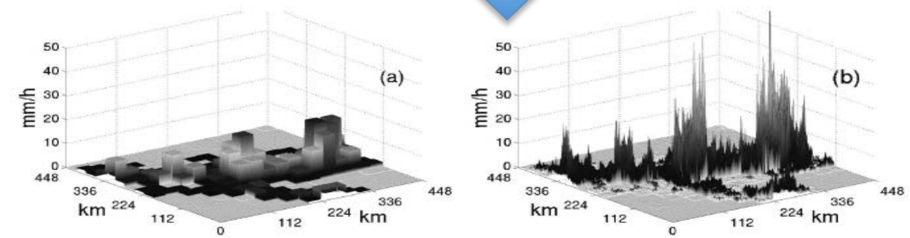


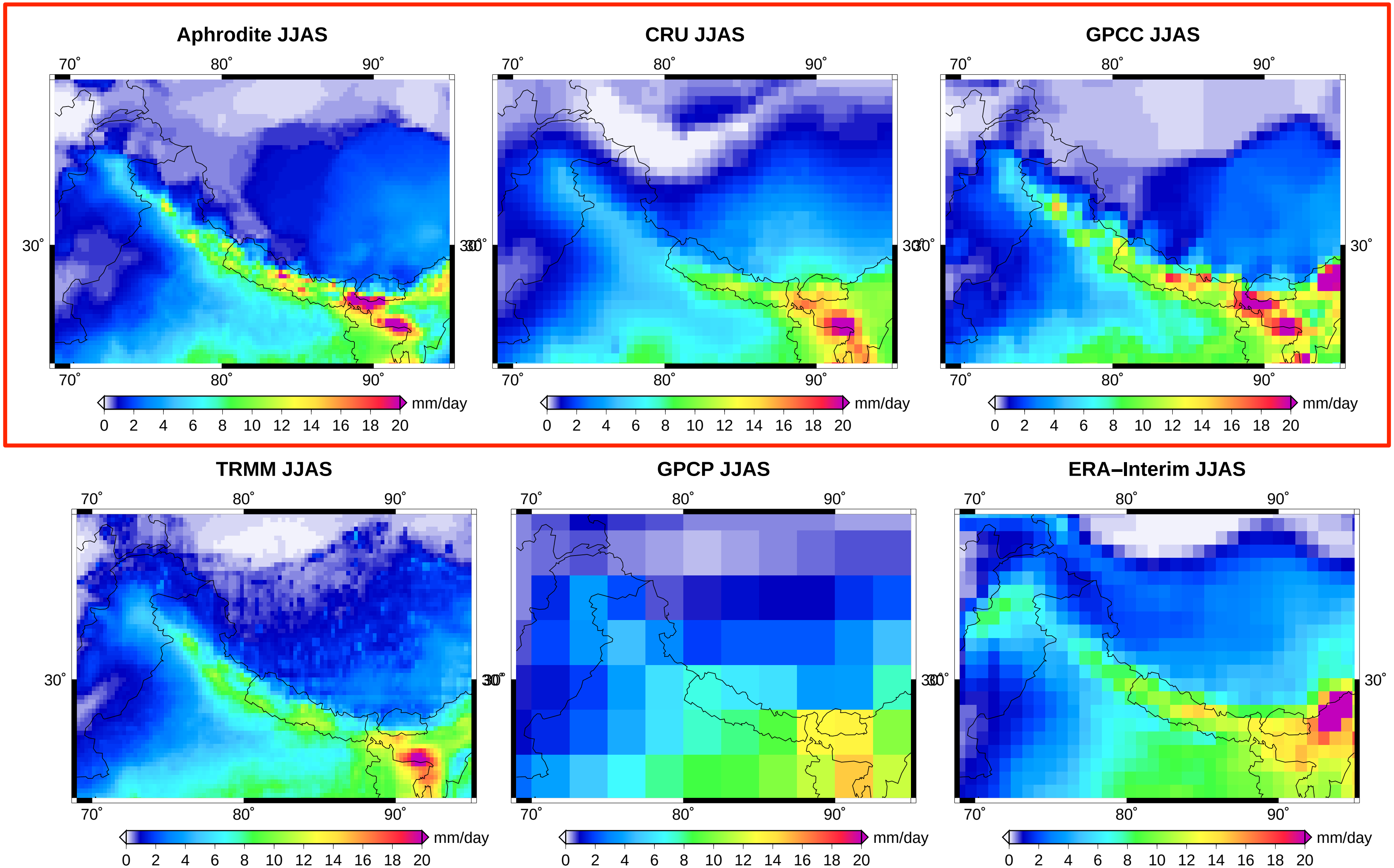
FIG. 10. (a) A snapshot of the forecasted rain field obtained from the LAM forecast and (b) one example of a downscaled field obtained by application of the RainFARM. The vertical scale indicates precipitation intensity (mm h^{-1}) and it is the same for the two fields.

Statistical/stochastic downscaling

Impact on eco-hydrological processes

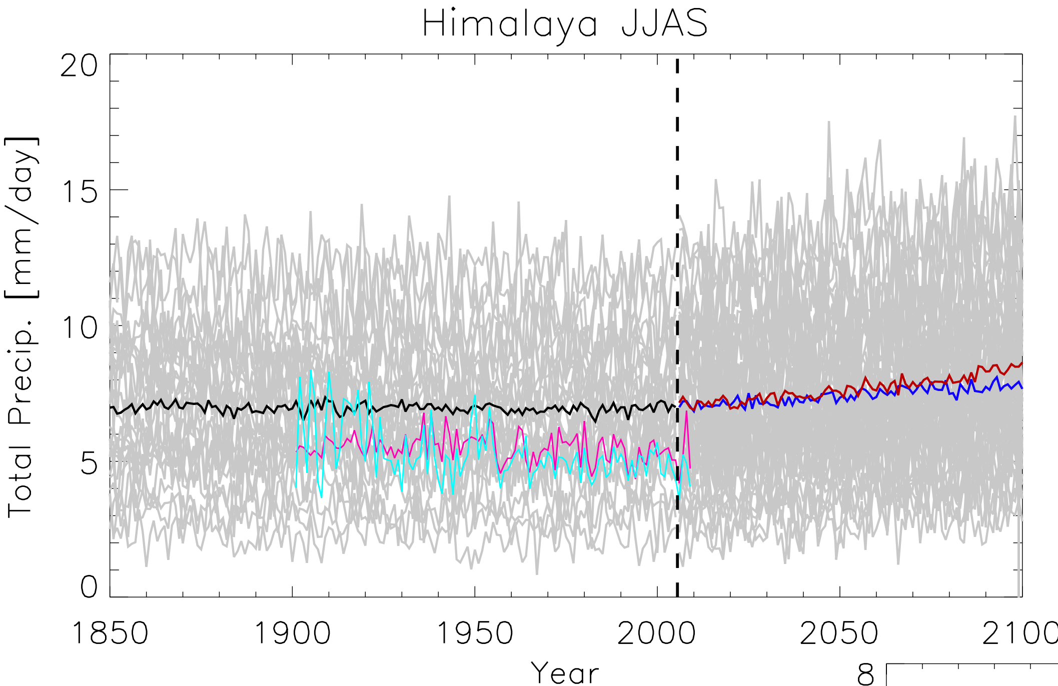

Troubles, oh troubles

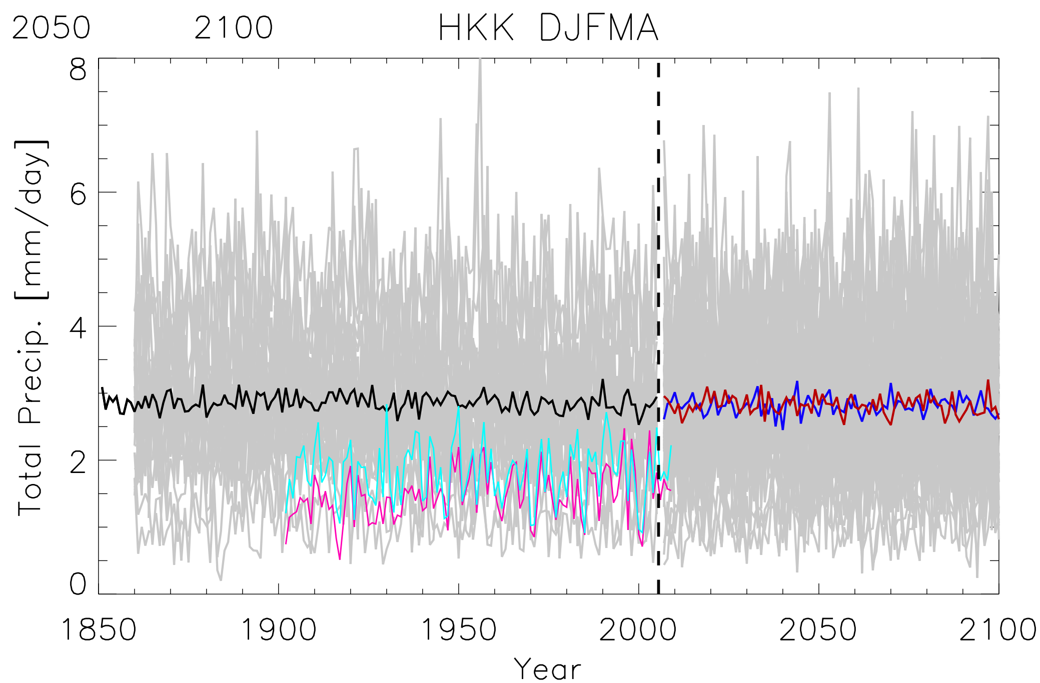
The chain of uncertainties: (1) data for model validation
Summer precipitation (JJAS), Multiannual average 1998-2007



Palazzi E., von Hardenberg J., Provenzale A.: Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, JGR 2013

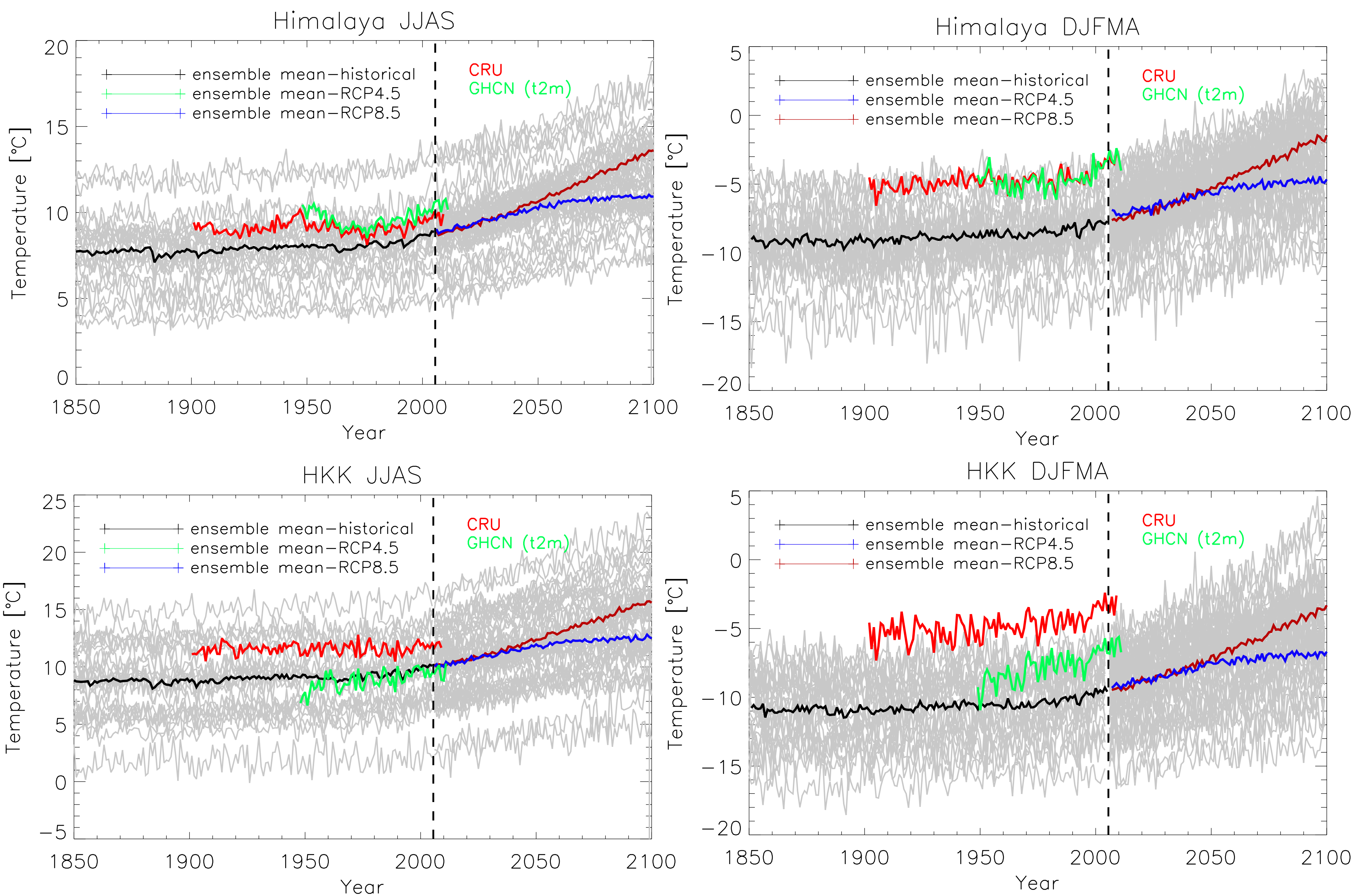
The chain of uncertainties: (2) spread between CMIP5 models



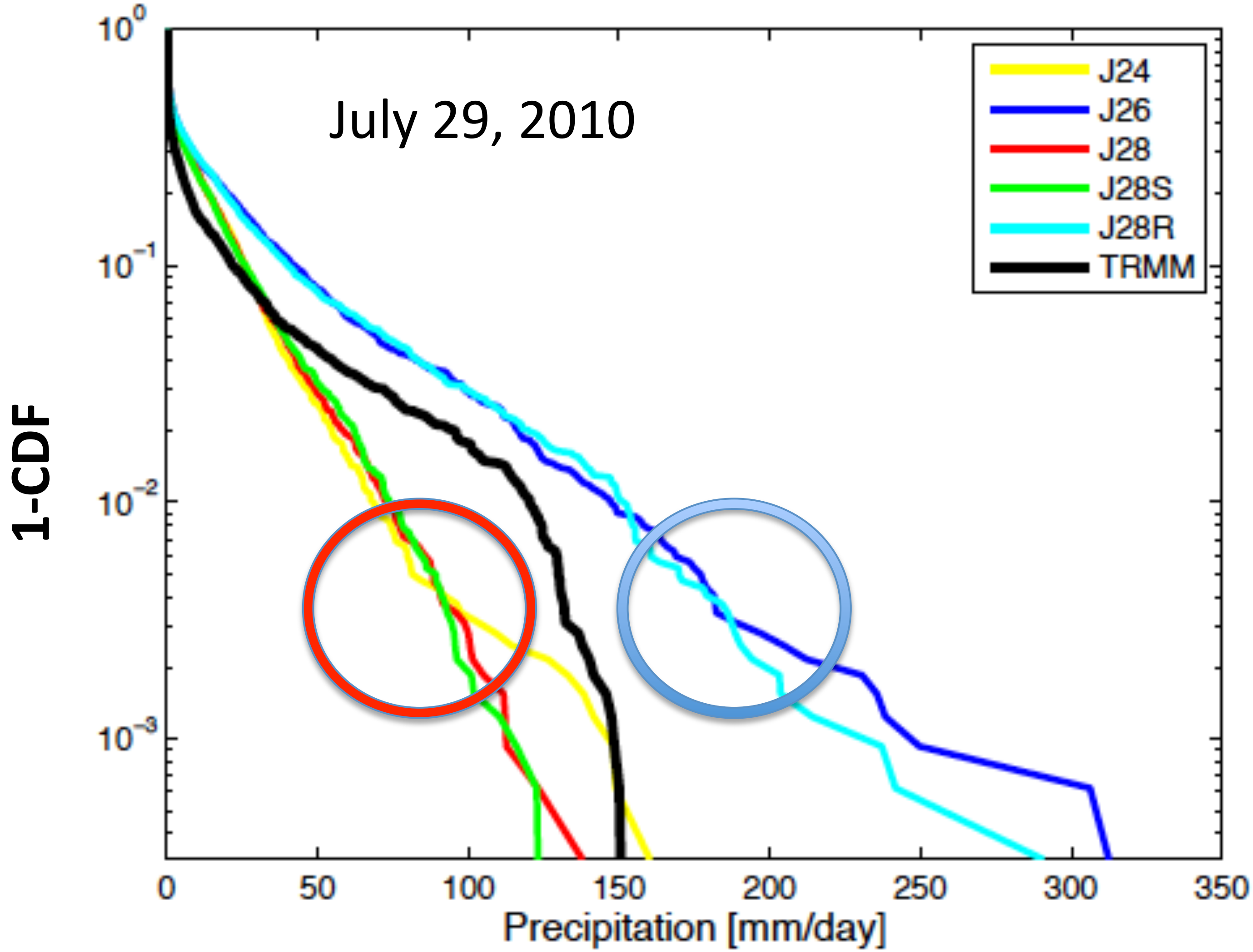


Palazzi E., von Hardenberg J., Terzago S., Provenzale A.: Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, 2014

And the spread of CMIP5 temperatures

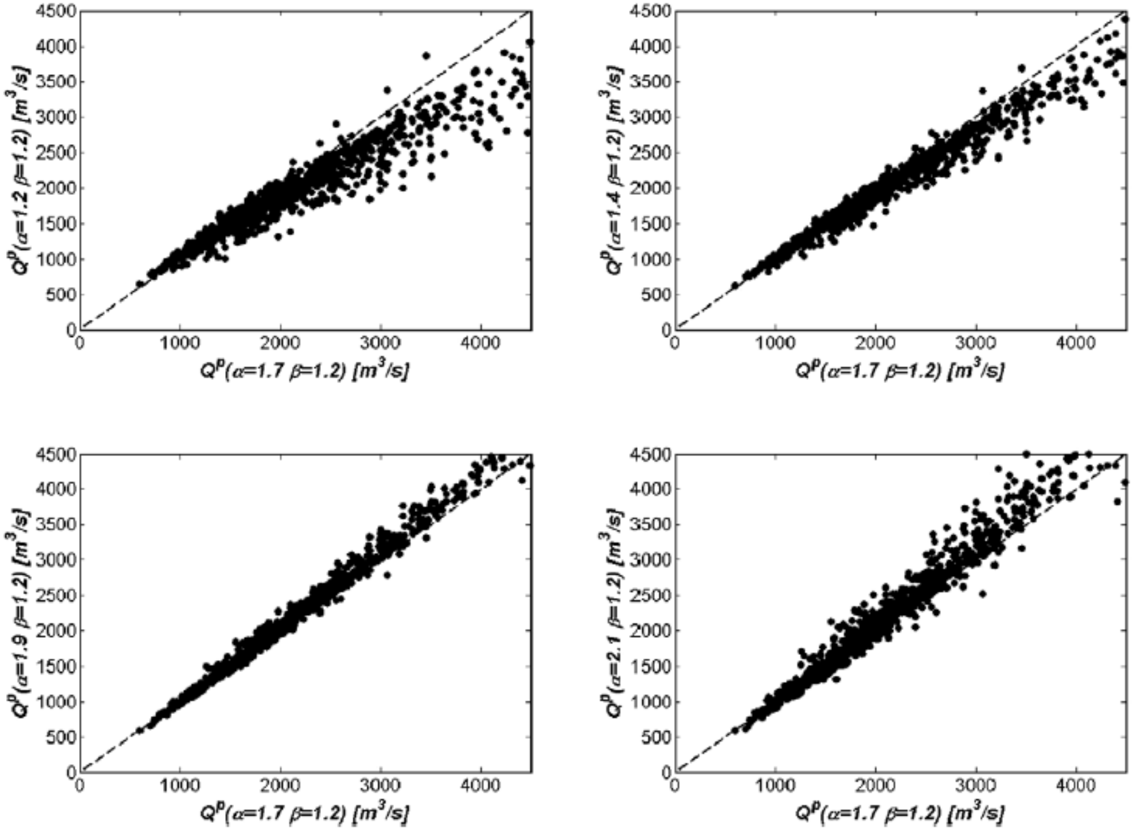


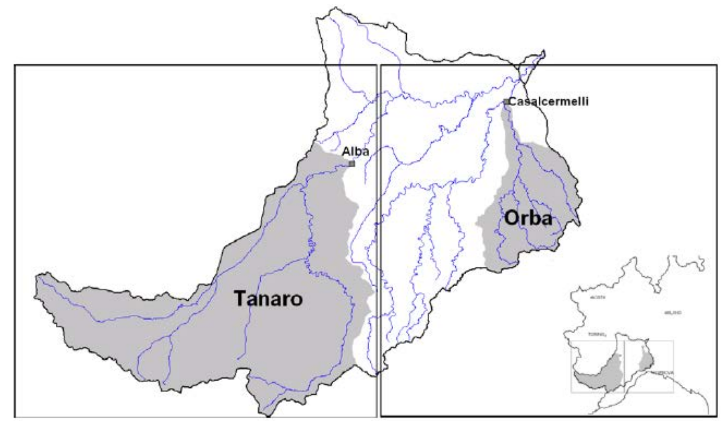
Precipitation statistics from WRF (Pakistan Flood 2010)

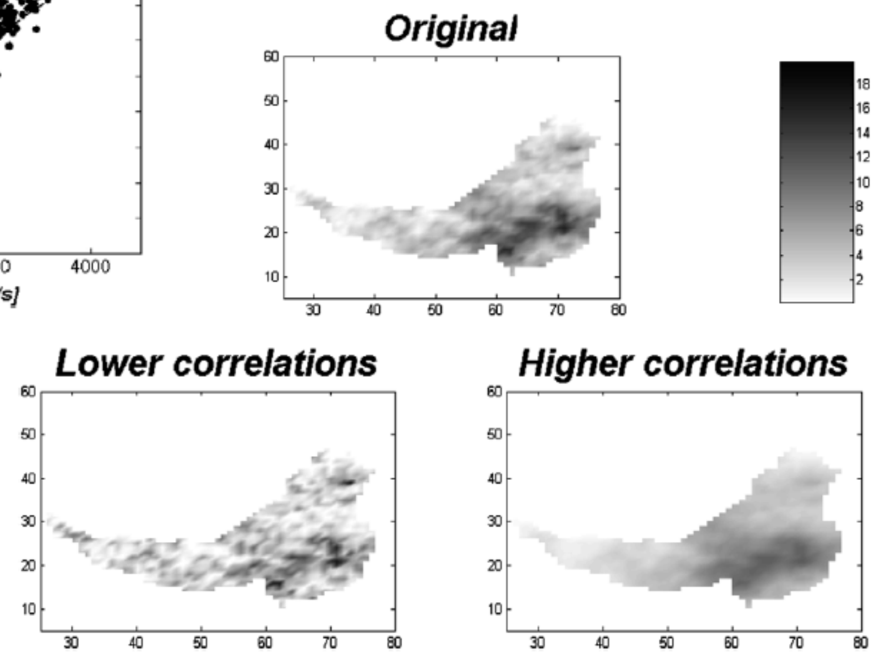


Francesca Viterbo et al., in preparation (2014)

The chain of uncertainties: (3) downscaling

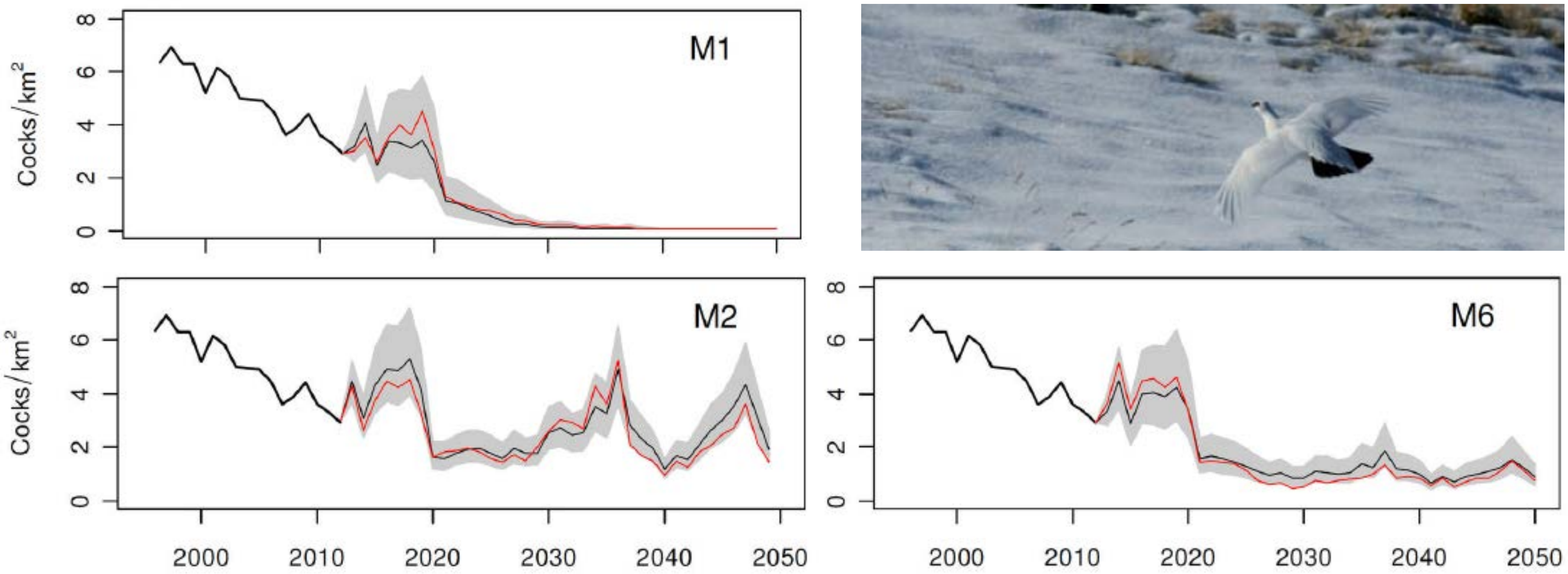






Gabellani, Boni, Ferraris,
von Hardenberg, Provenzale
Adv. Water Res. 2007

The chain of uncertainties: (4) local impact models



Model	Intercept	lnN_{t-1}	lnN_{t-2}	SE_{t-1}	SS_{t-1}	SP_t	$T(July)_{t-1}$	$P(July)_{t-1}$	$T(Jan\text{-}Mar)_t$	$T(Apr\text{-}May)_t$	var.	R^2	AICc
M1	-0.07±0.04			**-0.19±0.04**	**-0.18±0.04**						2	0.78	-50.53
M2	0.34±0.24		-0.25±0.14	**-0.19±0.04**	**-0.19±0.04**						3	0.83	-50.20
M3	-0.07±0.04			**-0.19±0.04**	**-0.18±0.04**			0.05±0.03			3	0.82	-49.28
M4	-0.07±0.04			**-0.19±0.04**	**-0.17±0.04**		-0.05±0.04				3	0.81	-48.51
M5	-0.07±0.04			**-0.20±0.04**	**-0.18±0.04**				-0.03±0.04		3	0.79	-47.28
M6	0.08±0.26	-0.10±0.16		**-0.18±0.04**	**-0.17±0.04**						3	0.78	-46.98

Simona Imperio, Radames Bionda, Ramona Viterbi, Antonello Provenzale,
Alpine rock ptarmigan, PLOS One, 2013

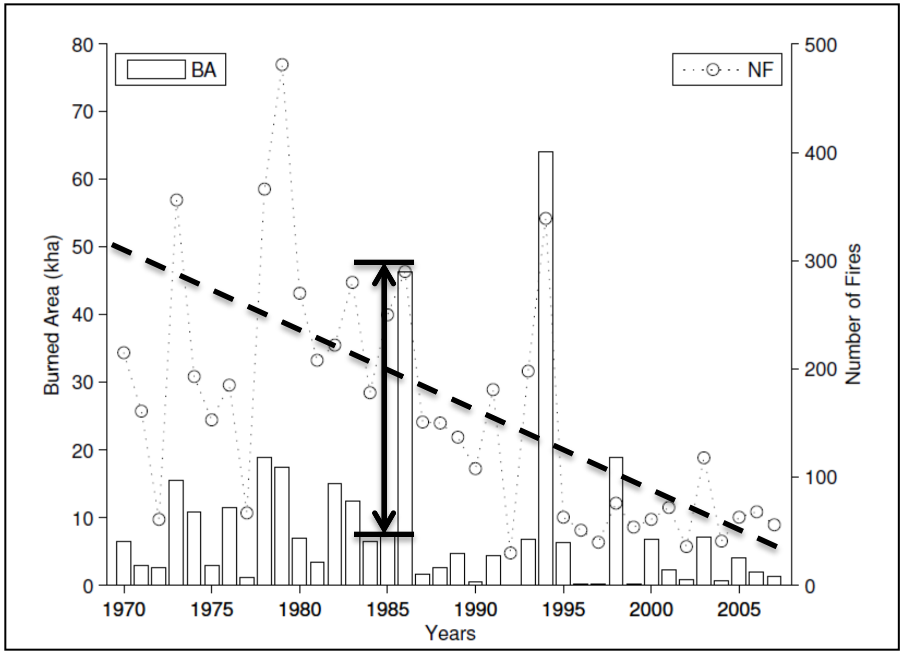
The chain of uncertainties: (4) local impact models

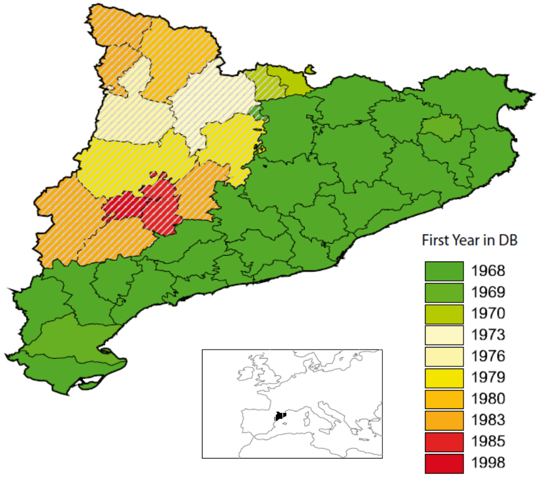
Climate change and forest fires

Long-term changes → human activities, climate trends.

The year-to-year changes in NF and BA are mainly related to **climate variability**.

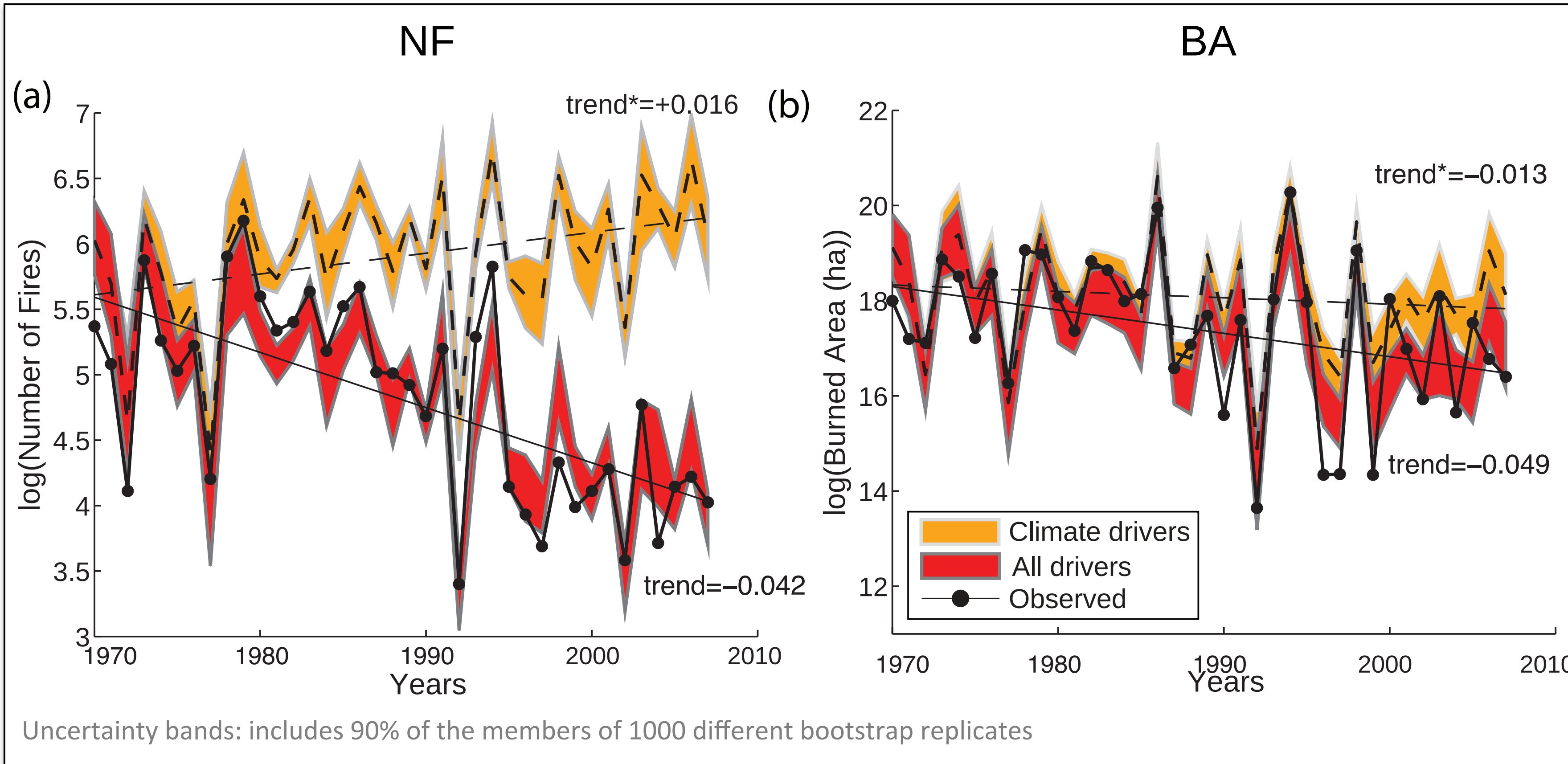
The climate acts mainly on two aspects: (i) **antecedent climate** → fuel to burn; (ii) **coincident climate**→ fuel flammability.





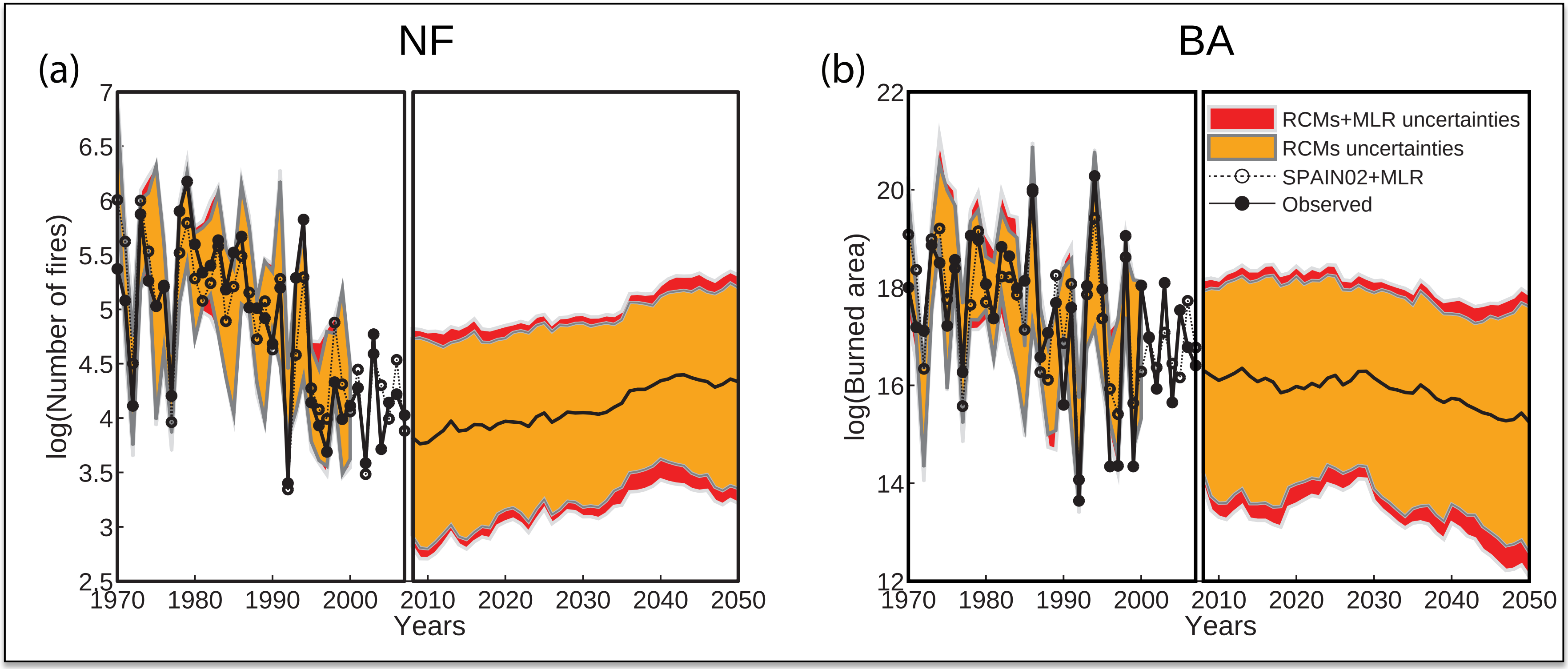
Turco et al. Climatic Change 2013, 2014, NHESS 2013

Fire response to climate trends



Climate drivers = both interannual variability and trends are driven by climate
All drivers= MLR considers the year-to-year climate variation + overall trend

Impact of future climate change on wildfires



- Future response depends on management strategies
- Uncertainty in RCM scenarios is larger than impact model uncertainties for forest fires

Conclusions (from climate to impacts)

Scale mismatch between climate models (and drivers) and land surface response: need for **climate downscaling**

Huge uncertainties in data, climate models, downscaling procedures, impact models: need for **ensemble approaches**, need for **uncertainty estimates**, need for **caution** in providing and interpreting results.

Find the best strategy without ideological constraints