Climate change, modelling and downscaling

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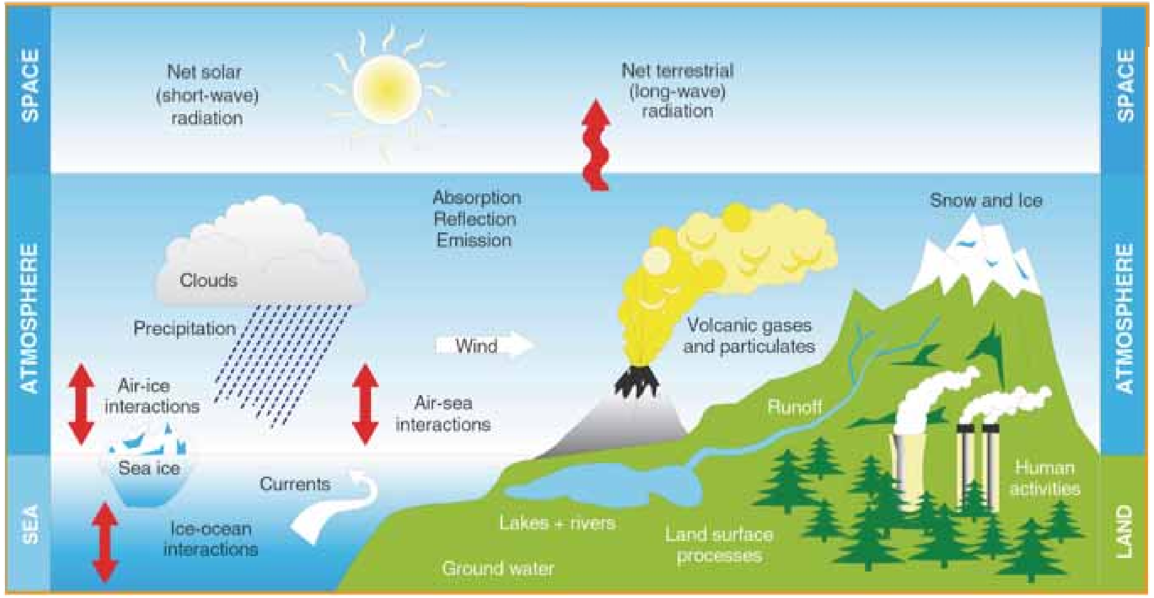
The climate system

The Climate System



GARP (Global Atmosphere Research Programme, WMO) 1975

“as being composed of the atmosphere, hydrosphere, cryosphere, land surface and biosphere”

FCCC (Framework Convention on Climate Change, UN) 1992

“the totality of the atmosphere, hydrosphere, biosphere and geosphere and their interactions”

IPCC AR5 2013

The climate system is the highly complex dynamical system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the lithosphere and the biosphere, and the interactions between them.

Climate system understanding requires the interplay of many different disciplines and approaches.

Climate varies on all spatial and temporal scales, from inter annual variability to the lifetime of the planet, from one slope to another in mountain valleys to the continental scale

The Climate System and climate variability

Variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all spatial and temporal scales beyond that of individual weather events (IPCC)

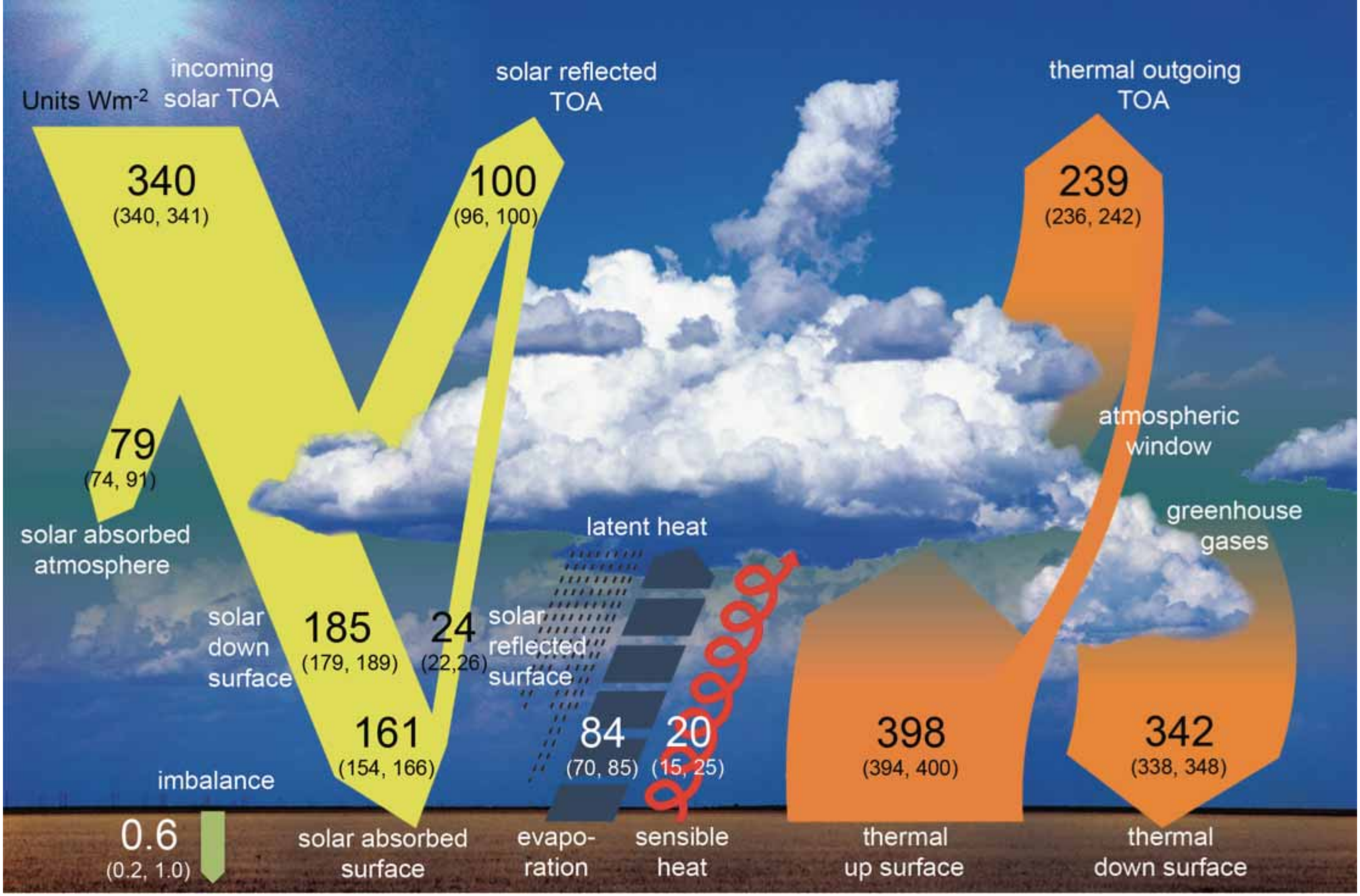
The climate system evolves due to its
- own internal dynamics
- changes in external factors.

- **Internal processes within the climate system - internal dynamics**

atmospheric and oceanic ***circulations****, teleconnection patterns,* ***feedbacks***

- **Variations in natural or anthropogenic external factors - forcings**

-volcanic eruptions, solar variations, insolation changes (**natural**)
-anthropogenic changes in the atmospheric composition, land use change

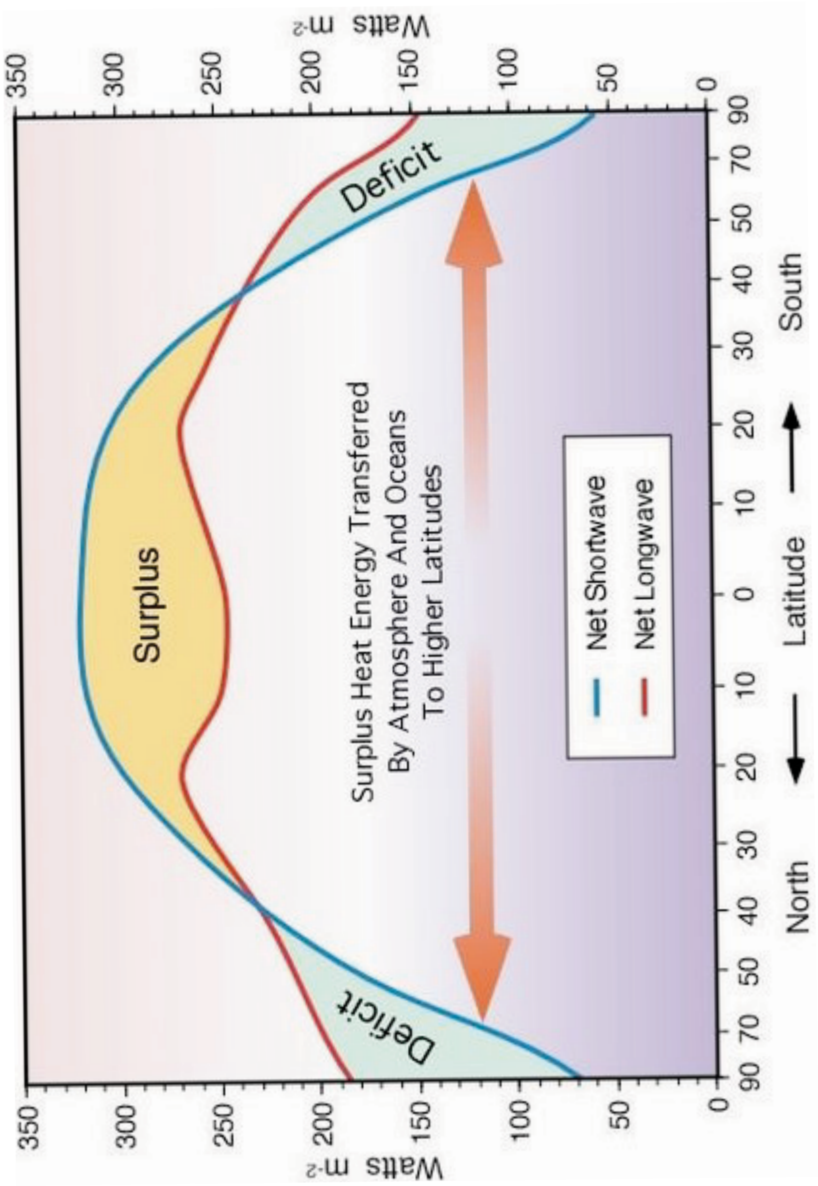


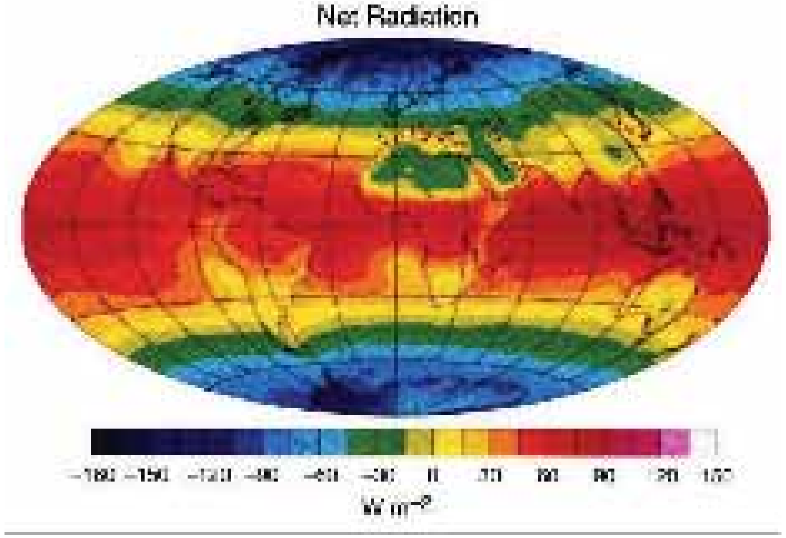
A new diagram of the global energy balance

Martin Wild, Doris Folini, Christoph Schär, Norman Loeb, Ellsworth G. Dutton et al.

Citation: AIP Conf. Proc. **1531**, 628 (2013); doi: 10.1063/1.4804848

Internal climate variability - Circulations



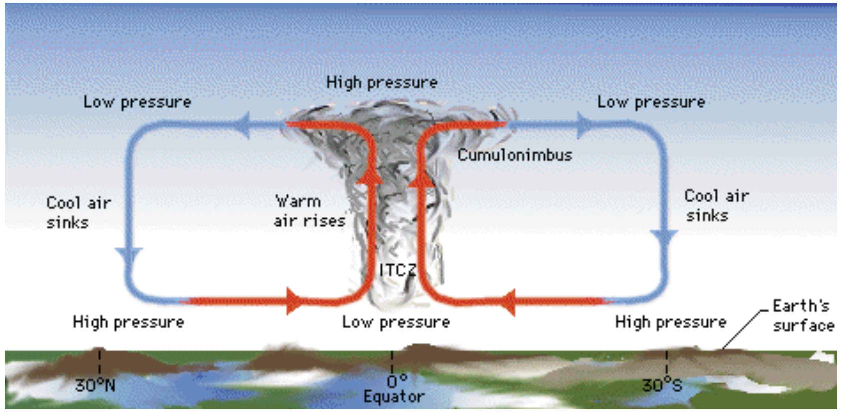


Atmospheric winds and oceanic currents (transport processes) act to to compensate for the surplus of net radiation in the equatorial and tropical regions and the deficit in the polar regions.

Atmospheric and oceanic circulations transport energy polewards and distribute it around the earth, the reducing the resulting equator-to-pole temperature gradient

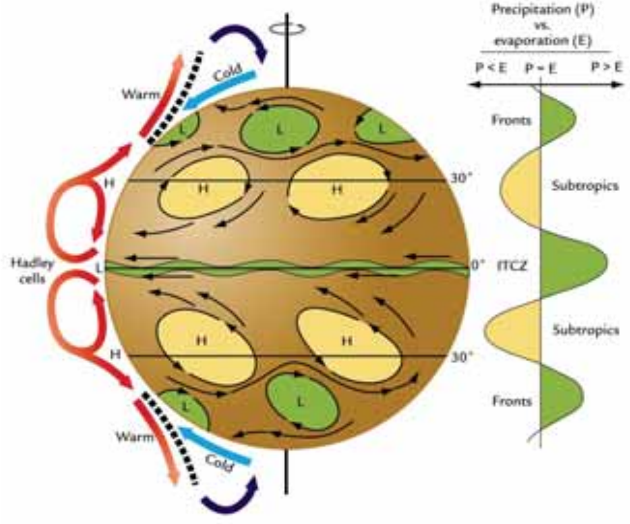
Internal climate variability – Atmospheric circulation

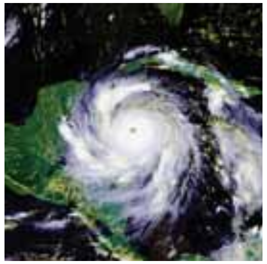
The mechanisms by which atmospheric transport is accomplished differ in tropical and extratropical latitudes.



In the **tropics**, the majority of the atmospheric poleward heat transport is achieved by the **Hadley circulation**.

- rising motion near the equator
- poleward motion near the tropopause
- sinking motion in the subtropics
- equatorward return flow near the surface



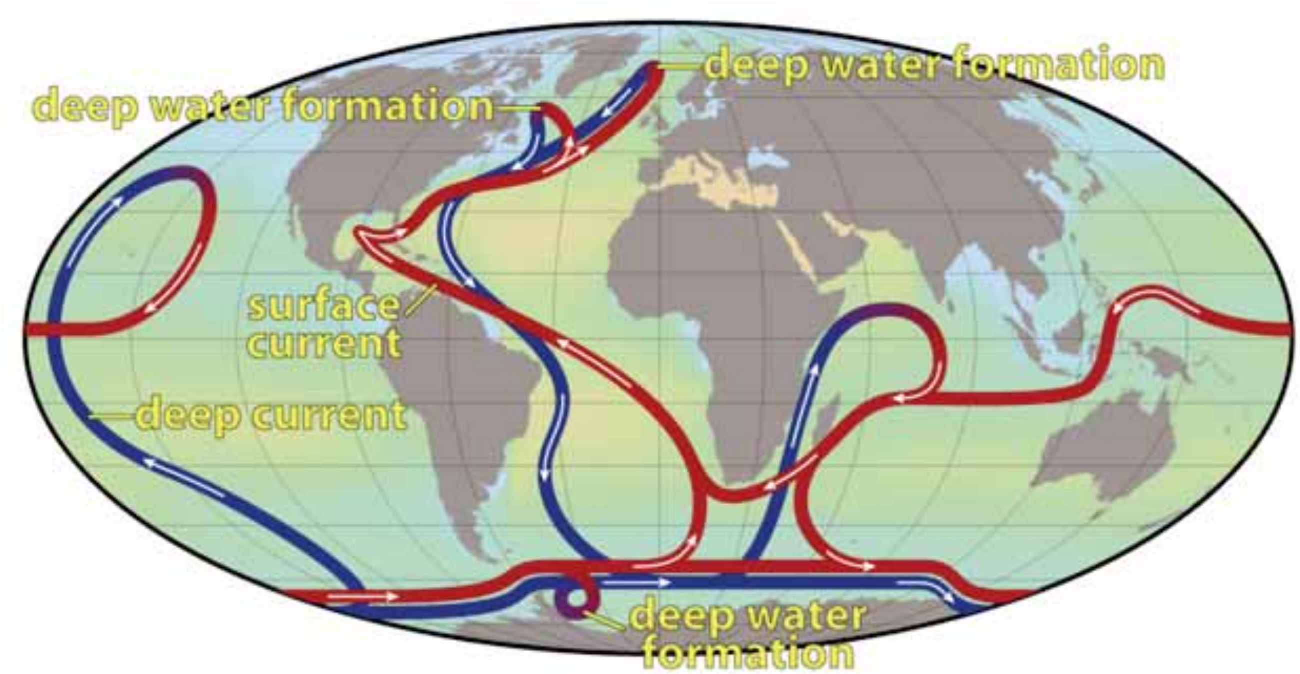


By contrast, in **higher latitudes,** the energy transport is accomplished by **eddies (cyclones and anticyclones)** that cause relatively warm air to move polewards and cold air to move equatorwards.

Internal climate variability – Oceanic circulation

Surface currents are

- driven by winds; their patterns are determined by wind direction, Coriolis force, and the position of landforms
- warm and move polewards (e.g.; Gulf stream)

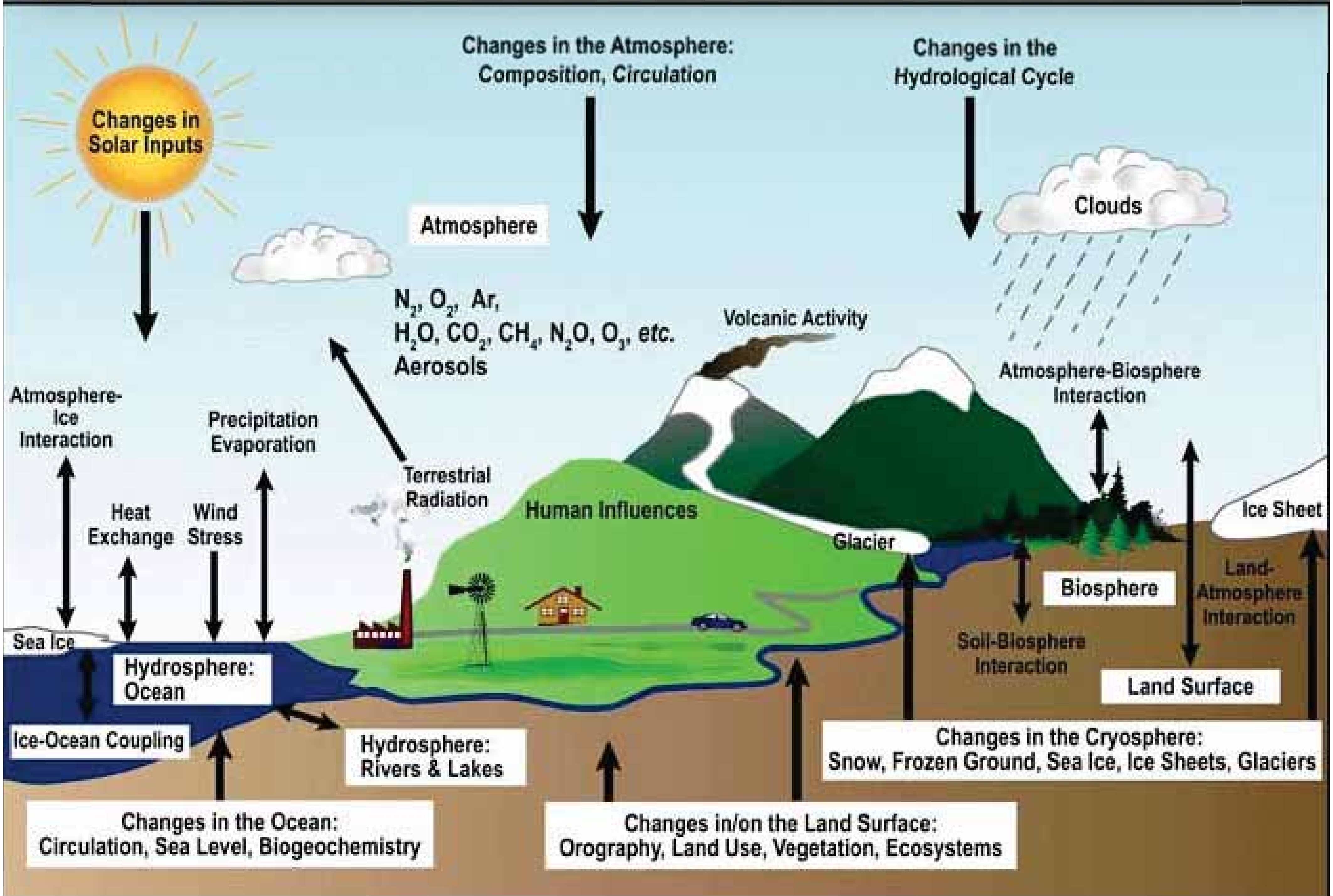


Thermoaline circulation

Deep currents are

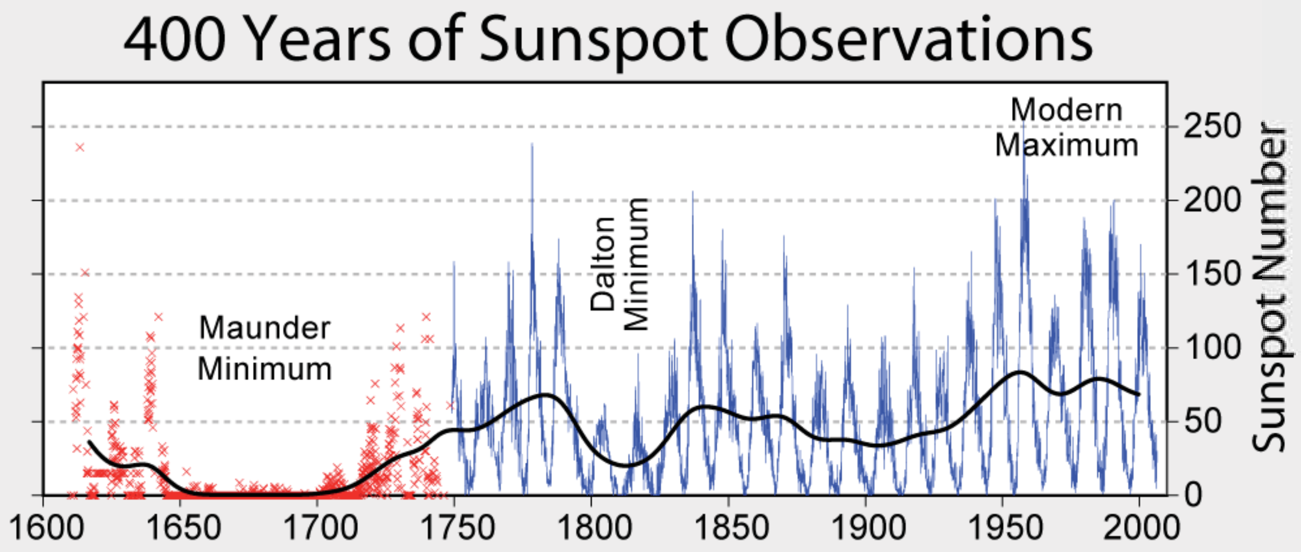
- driven by variations in water density; density is a function of temperature and salinity
- characterized by very long time scales, from decades to thousands of years

The climate system and climate Processes



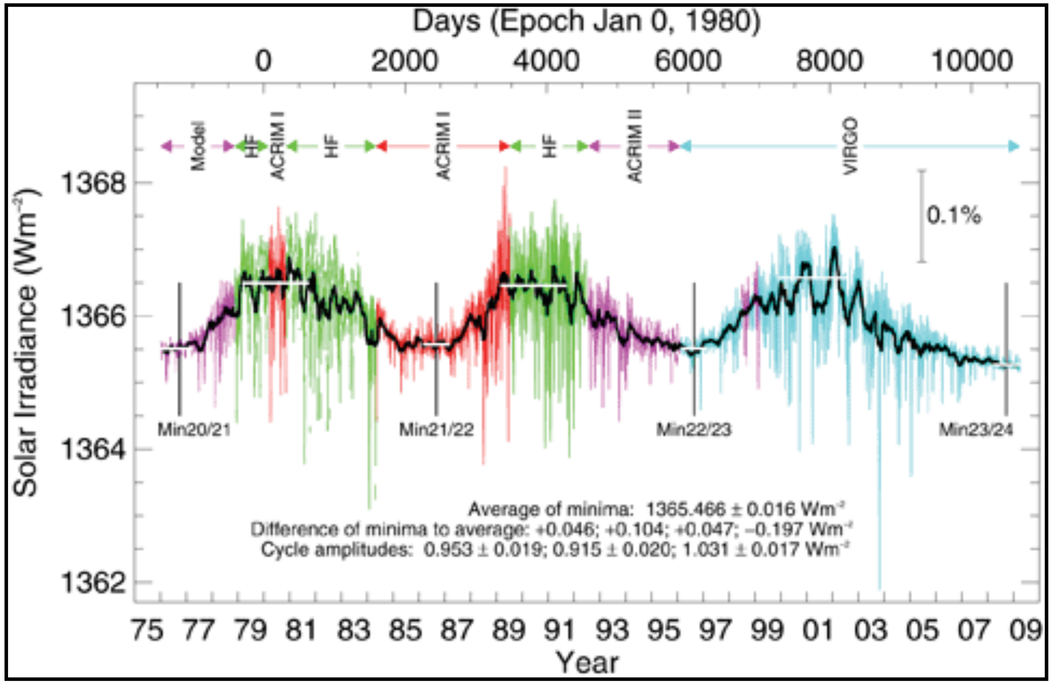
The climate system – external forcings

SOLAR ACTIVITY



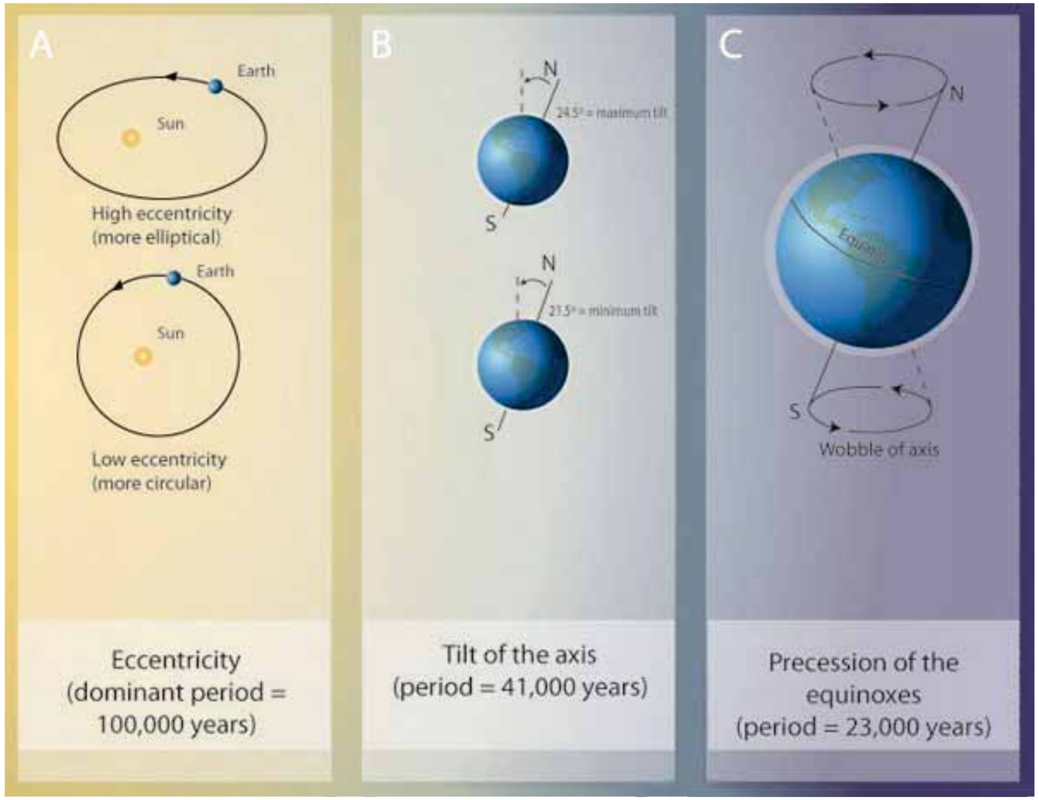
Continuos sunspots observations on a monthly basis from 1749 (average of observations in different parts of the globe). Before 1979, observations were rare and sparse.

Satellite measurements from the late 1970s. The **11-years solar cycle** is associated with the known periodicity of the solar activity, for which sunspots are a proxy.



The climate system – external forcings

ORBITAL FORCINGS



eccentricity

little change in the area-averaged annually averaged sunshine

axial tilt

precession

strong changes in the geographical and seasonal distribution

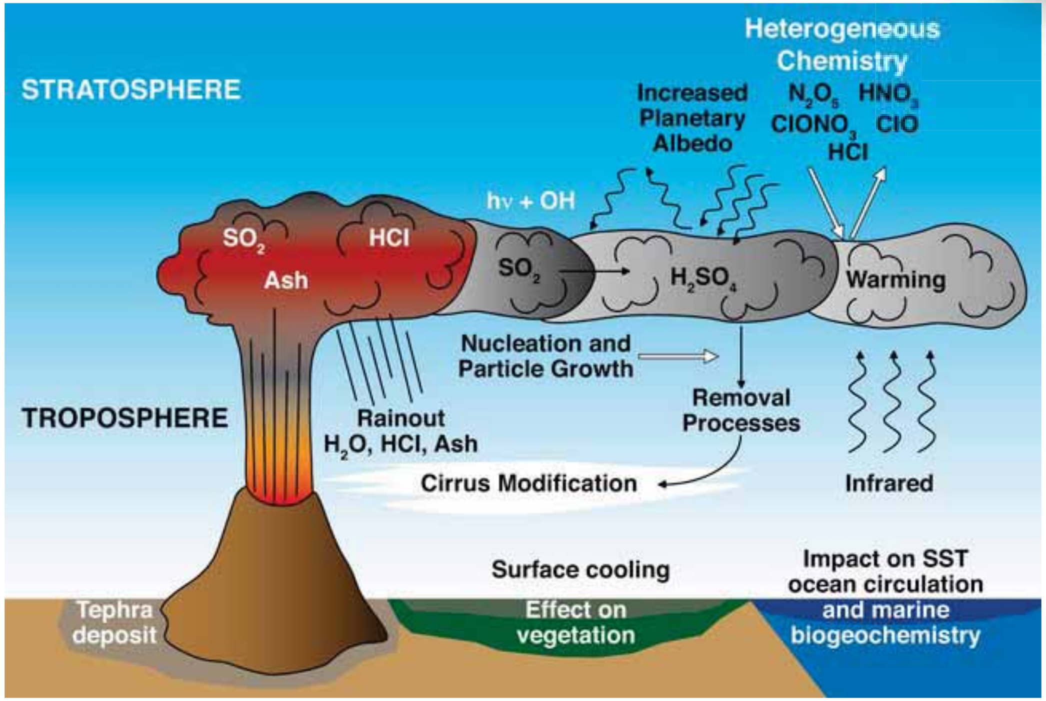
Milankovitch theory describes the effects of changes in the Earth's movements upon its climate.

Variations in **eccentricity**, **axial tilt**, and **precession of the Earth's orbit** determine climatic patterns on Earth through orbital forcing (variation in the amount of radiation received by the sun).

The climate system – external forcings

http://www.mpimet.mpg.de/

VOLCANIC ERUPTIONS



- Amounts of gases and solid particles injected into the atmosphere

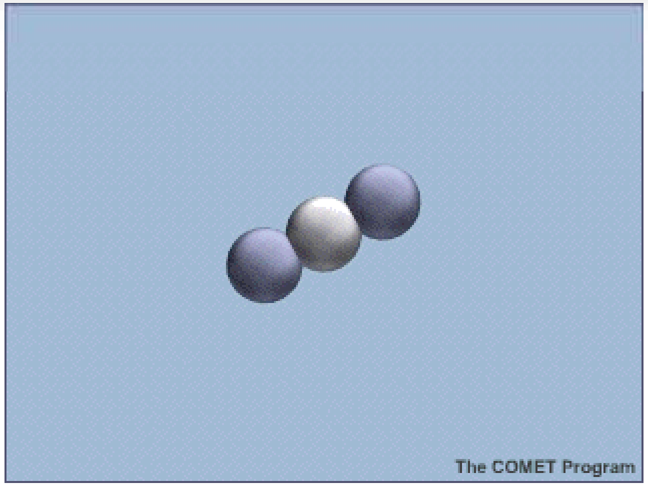
- **The volcanic ash rapidly falls out** (due to its size and mass)
- **Climate response mostly results from the emission of *sulfurous gases*, that *combine with water* to form *sulfuric acid*, which then condenses on particles to form sulphate aerosols. Sulphate aerosol are clear and reflect the incoming solar radiation**

Cause **large although temporary perturbations in the solar forcing**

- **aerosol-containing layers in the stratosphere warm up**
- **near-ground air layers, as well as the ocean, cool down (solar dimming)**

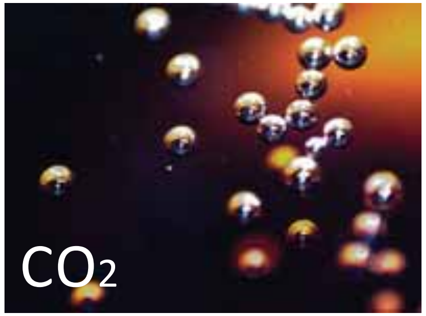
The climate system – external forcings

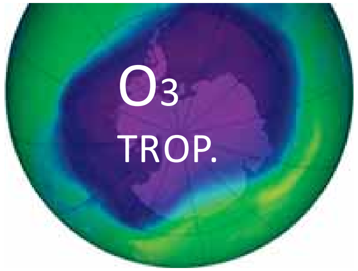
GREENHOUSE GASES



Molecules with three or more atoms, able to induce vibrational motions that change the dipole structure of the molecules making them able to absorb the IR radiation emitted from the Earth's surface.

The most important GHGs directly **emitted by humans (by burning of fossil fuels, changes in land use) include CO2, CH4, nitrous oxide (N2O)**. **Human activities amplify the natural atmospheric concentrations of these gases**





H2O is a natural greenhouse gas.

The climate system – external forcings

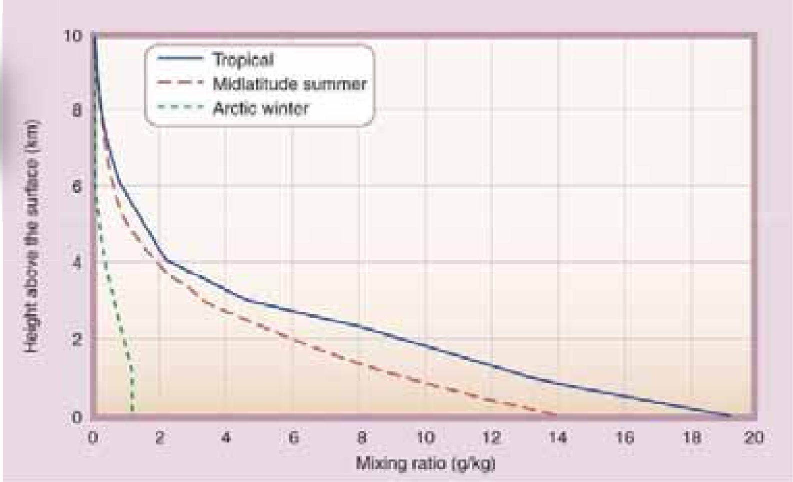
GREENHOUSE GASES - H2O

- Water vapor is the most abundant GHG and the most important in terms of its contribution to the natural greenhouse effect (60%).
- On a global scale, the concentration of water vapor is controlled by temperature (Clausius-Clapeyron law: +1°C => +7% H2O) —> Influence on the overall rates of evaporation and precipitation.

Atmosphere

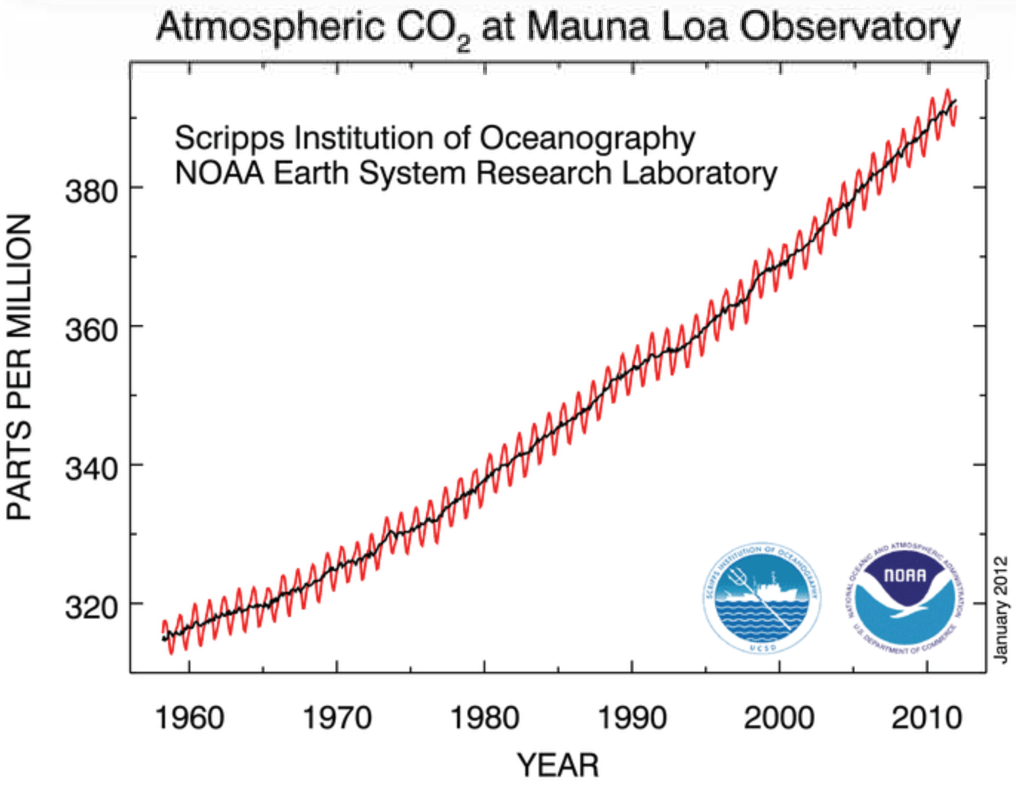
Vegetation

Cryosphere



The climate system – external forcings

GREENHOUSE GASES - CO2



CO2 is absorbed and emitted naturally as part of the carbon cycle, through **animal and plant respiration, volcanic eruptions, and ocean-atmosphere exchange**

Human activities, such as the **burning of fossil fuels and changes in land use,** release large amounts of carbon to the atmosphere, causing CO2 concentrations in the atmosphere to rise.

CO2 concentration has risen from pre-industrial levels of 280 ppmv to about 390 ppmv in 2010. The current CO2 level is higher than it has been in at least 800,000 years (from the EPICA ice core)

Aerosols

coal power plants (BC, OC, SU, Nitrates)

volcanic eruptions
(volcanic ash and SU)

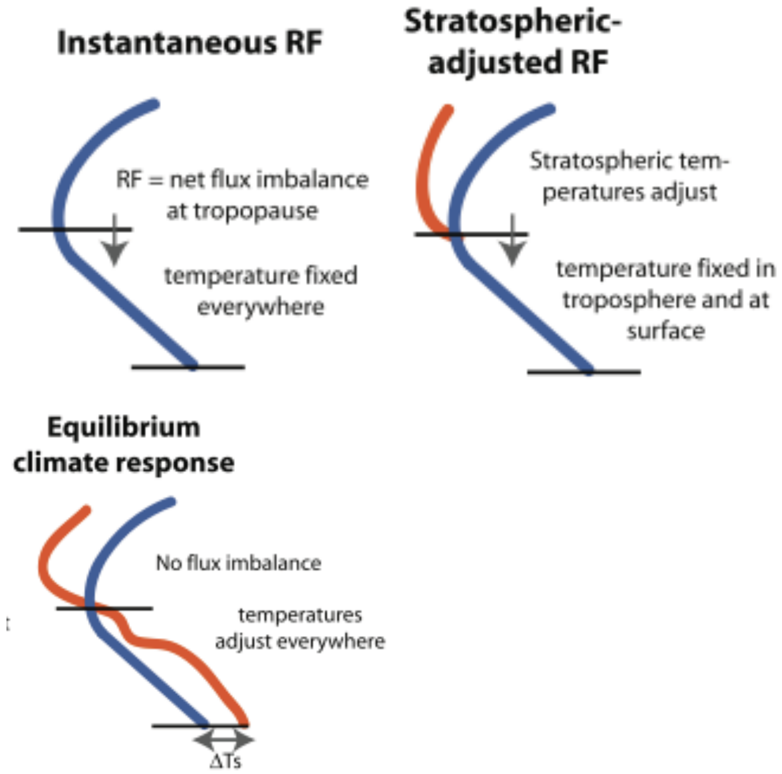
sea spray (SS, SU)

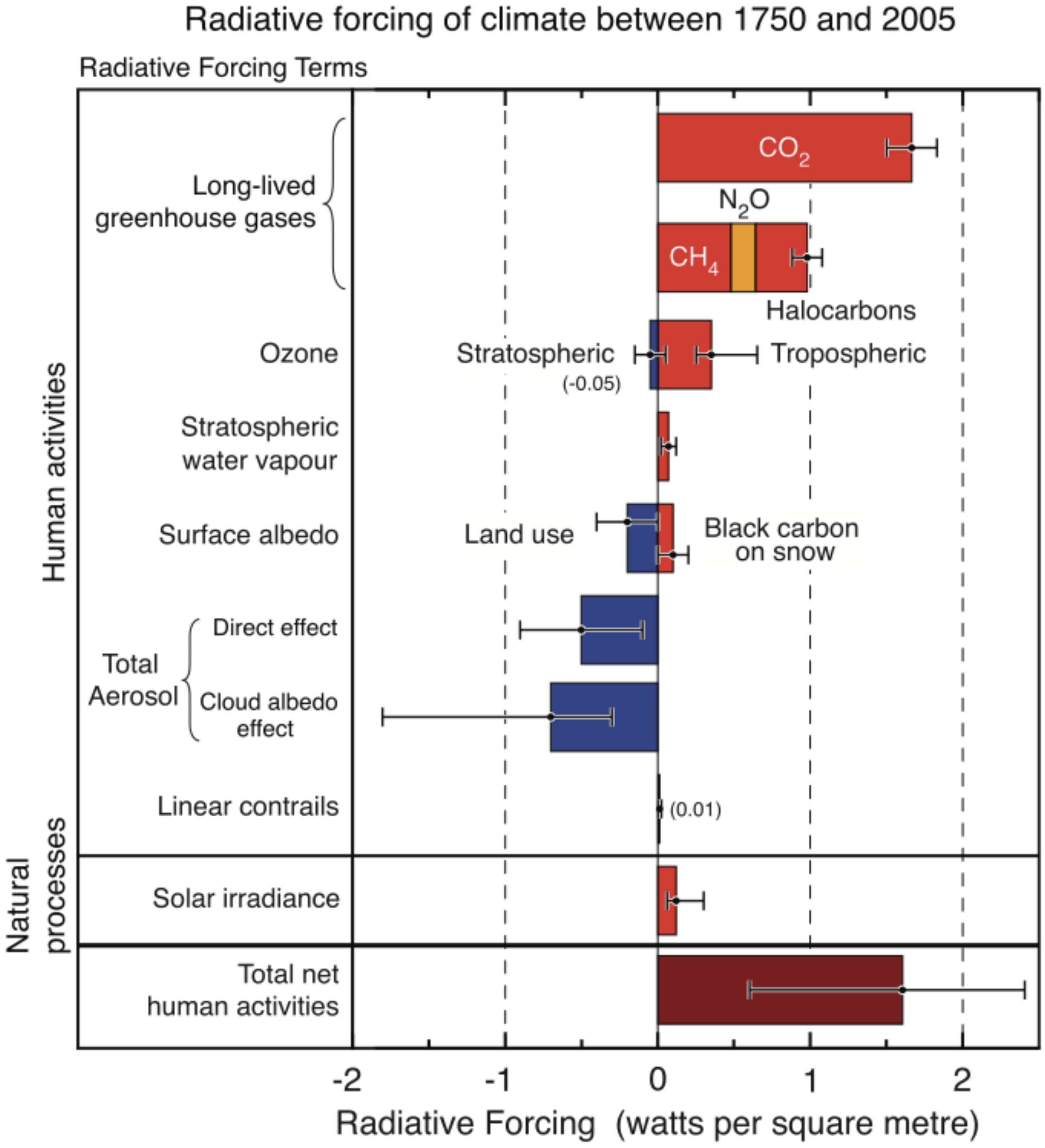
desert storms (DU)

Others: ships (BC, OC, sulphates, nitrate), cooking* (domestic BC and OC), road transport (sulphate, BC, VOCs yielding OC)

biomass burning (BC, OC)

Radiative forcing:
“the change in net (down minus up) irradiance (solar plus longwave; in W m–2) at the tropopause after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values” *(IPCC TAR)*



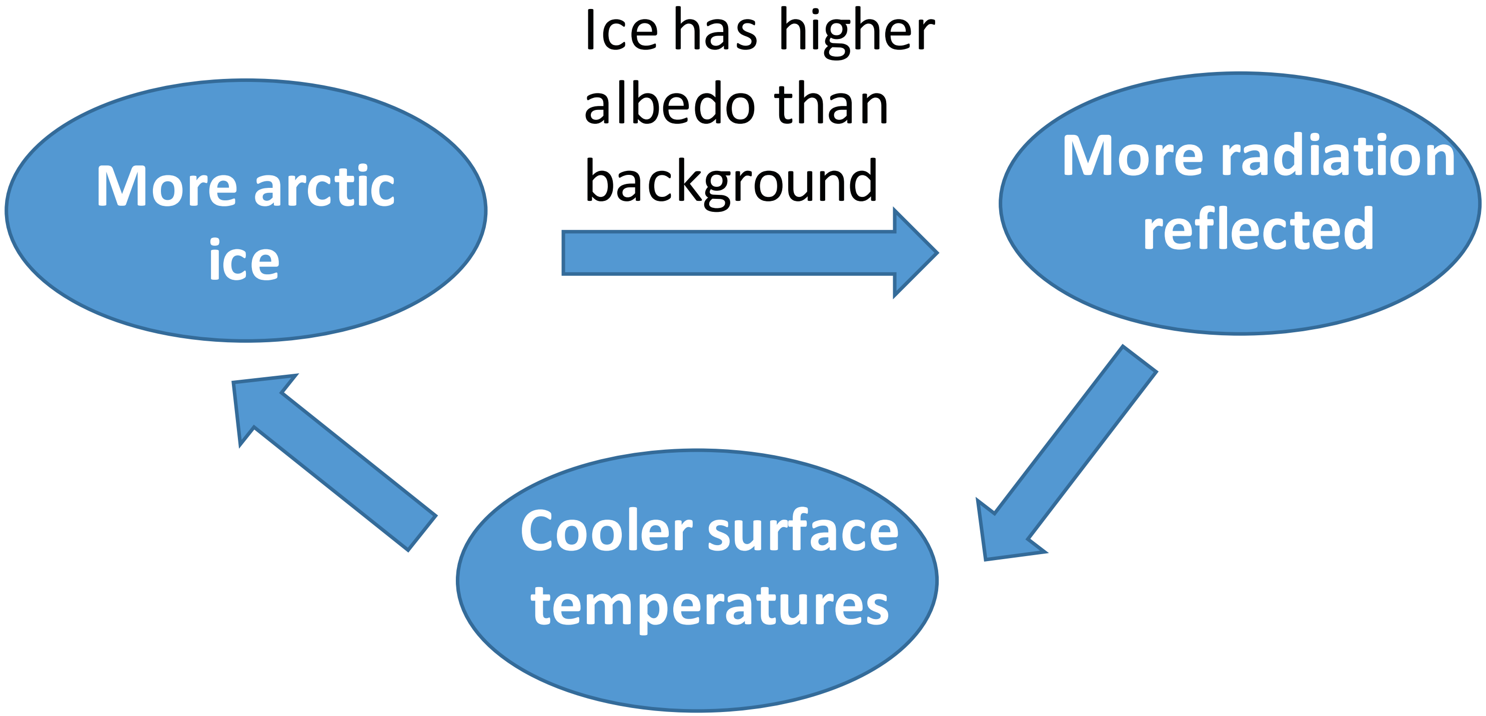


FAQ 2.1, Figure 2. *Summary of the principal components of the radiative forcing of climate change. All these radiative forcings result from one or more factors that affect climate and are associated with human activities or natural processes as discussed in the text. The values represent the forcings in 2005 relative to the start of the industrial era (about 1750). Human activities cause significant changes in long-lived gases, ozone, water vapour, surface albedo, aerosols and contrails. The only increase in natural forcing of any significance between 1750 and 2005 occurred in solar irradiance. Positive forcings lead to warming of climate and negative forcings lead to a cooling. The thin black line attached to each coloured bar represents the range of uncertainty for the respective value. (Figure adapted from Figure 2.20 of this report.)*

Forster, P. et al..*In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC AR4)

Climate feedbacks: Ice-albedo feedback

Ice-albedo feedback

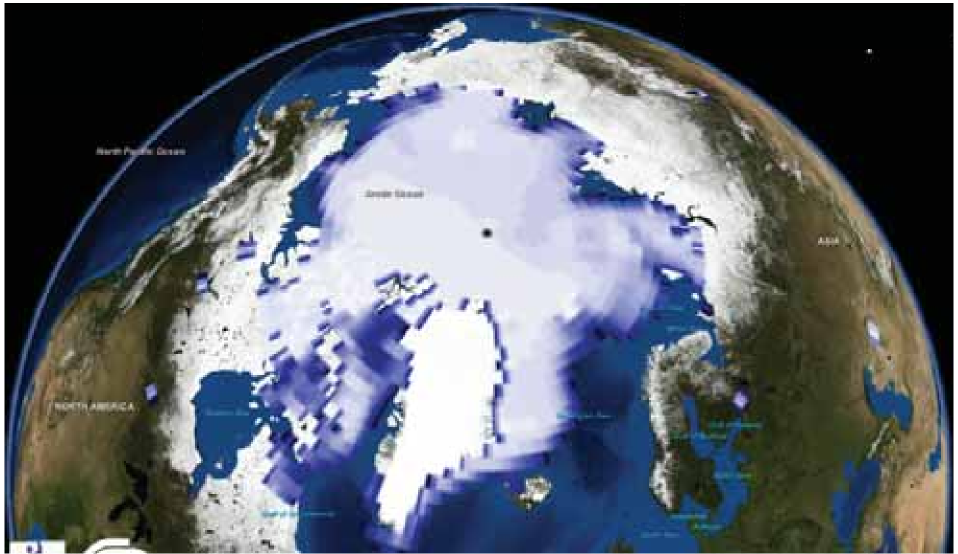


More arctic ice

Ice has higher albedo than background

More radiation reflected

Cooler surface temperatures

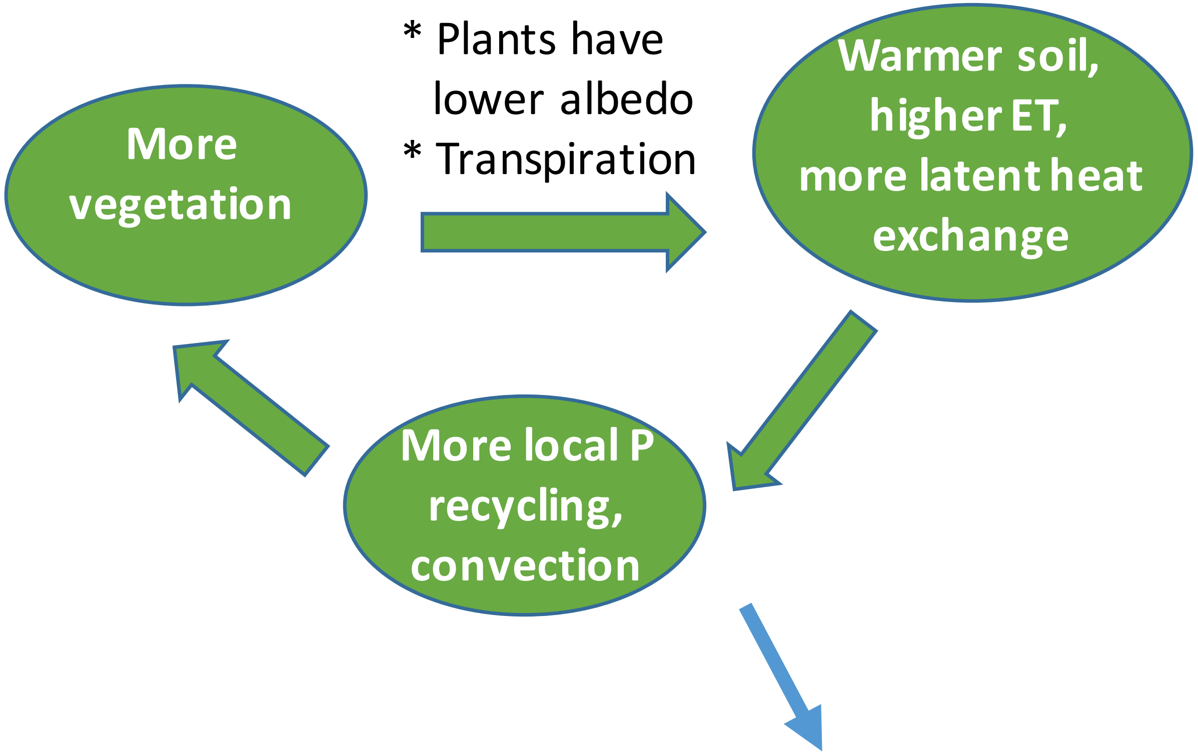


Climate feedbacks: vegetation

Atmospheric exchanges of vegetation+soil moisture:

- Surface roughness → momentum transfer
- Biogeochemical fluxes (e.g. CO_2, VOC)
- Evapotranspiration, latent heat
- Albedo, radiative fluxes

Vegetation feedback



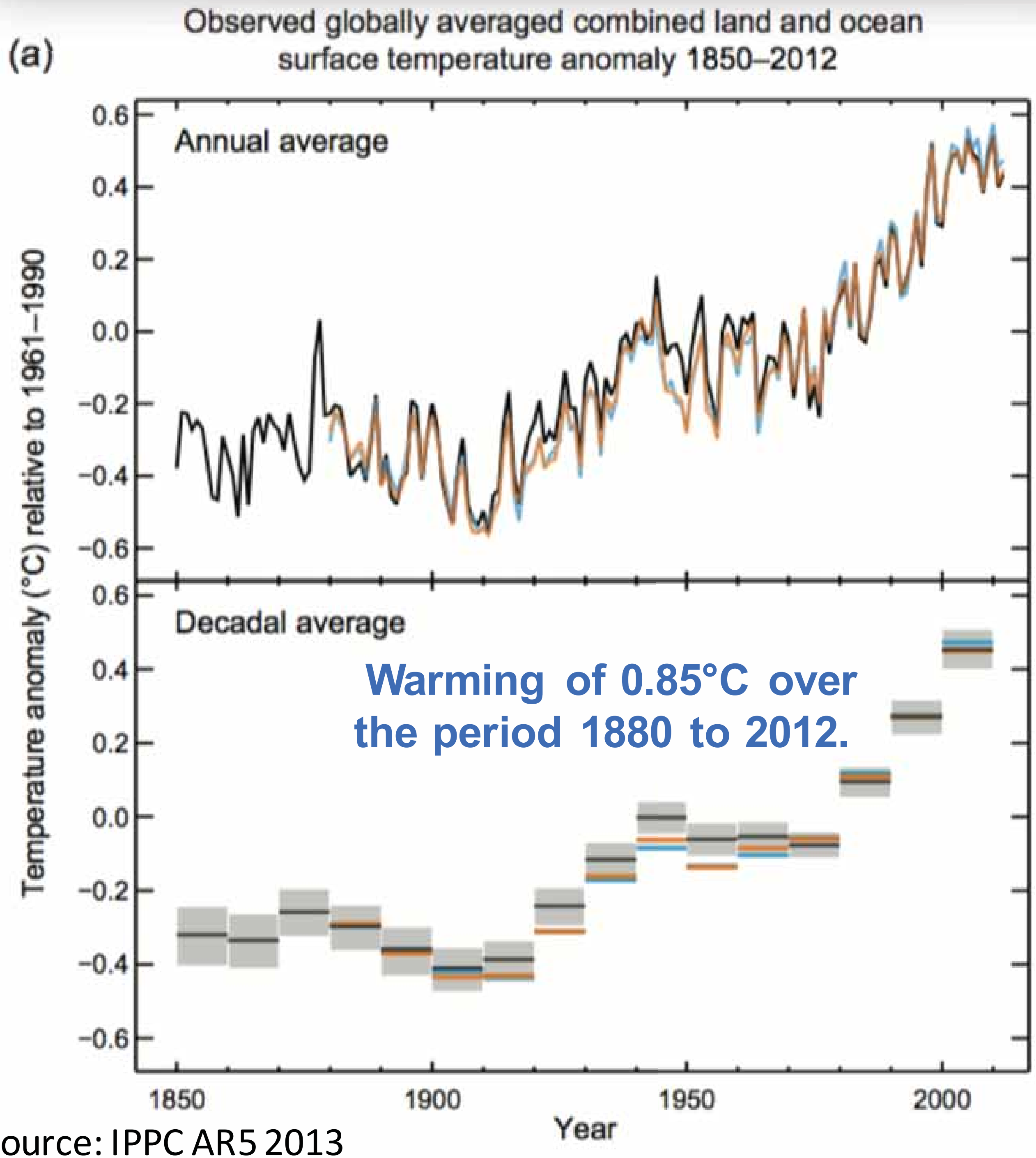
Nonlinear interaction, possibility of coexistence of multiple states

Examples:

- Wet Sahara (6k-10k BC)
- Wet and dry regimes in the Sahel (Charney effect)
- Heat waves in continental US and Europe
- Different regimes and forest-savanna shifts in the Amazons

Observed climate change

Observations of the recent changes



(a) Observed globally averaged combined land and ocean surface temperature anomaly 1850–2012

Warming of 0.85°C over the period 1880 to 2012.

Source: IPPC AR5 2013

TEMPERATURE

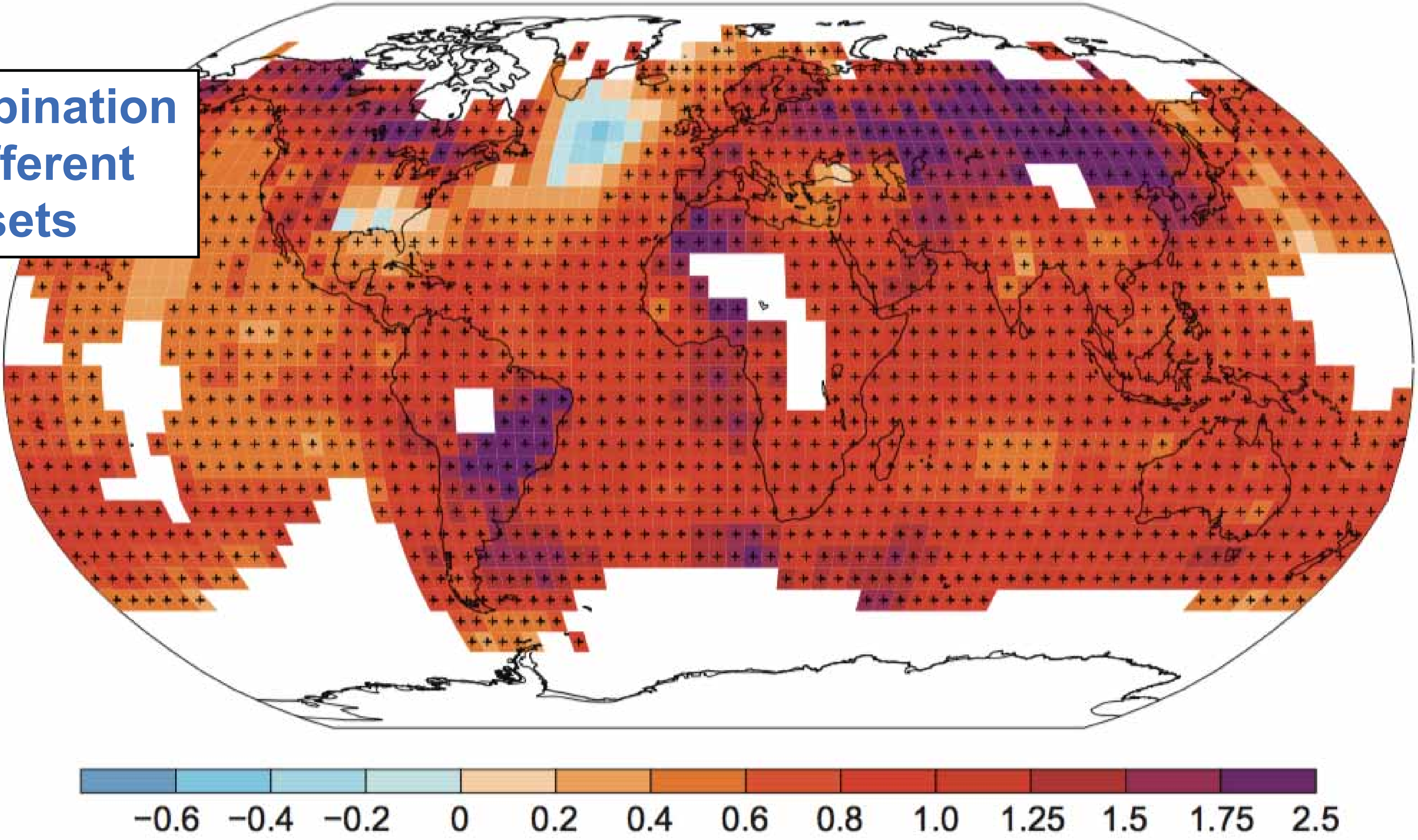
Temperature anomalies, relative to the mean of 1961−1990.

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. In the Northern Hemisphere, ***1983-2012 was <u>very likely</u> the warmest 30-year period of the last 800 years and <u>likely</u> the warmest 30-year period of the last 1400 years***

Observations of the recent changes

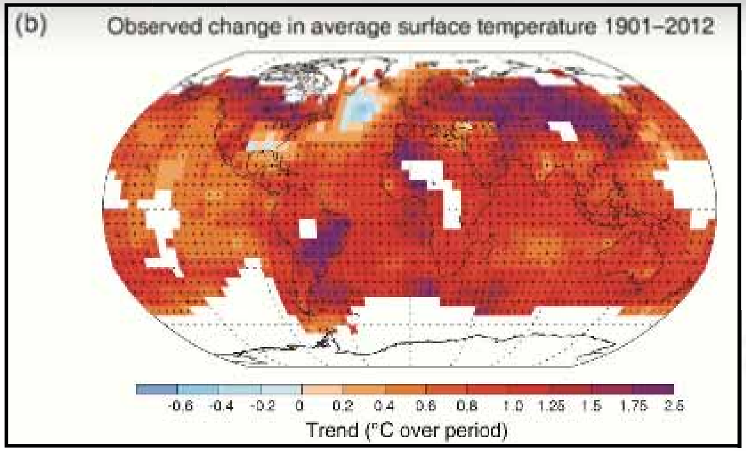
Combination of different datasets

Observed change in surface temperature 1901–2012

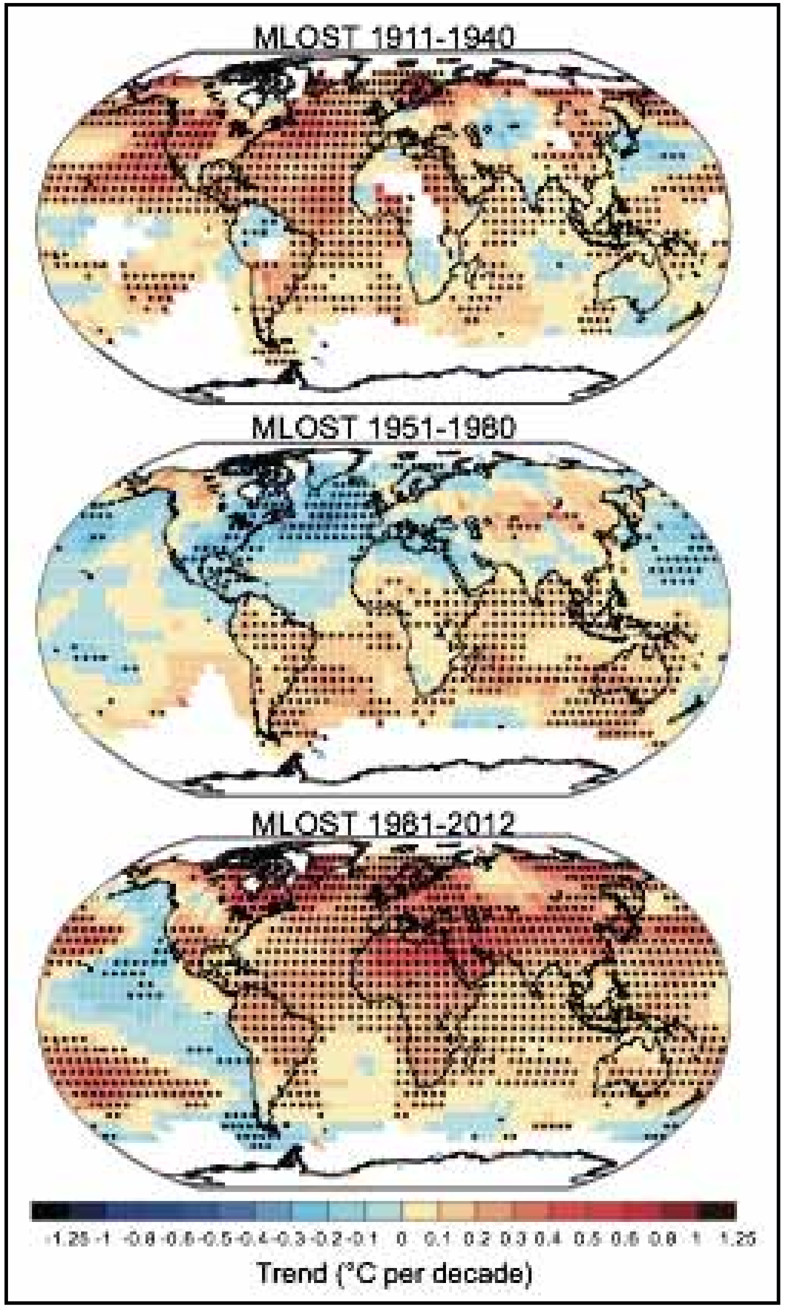


For the longest period when calculation of regional trends is sufficiently complete (1901 to 2012), almost the entire globe has experienced surface warming.

Observations of the recent changes



TEMPERATURE

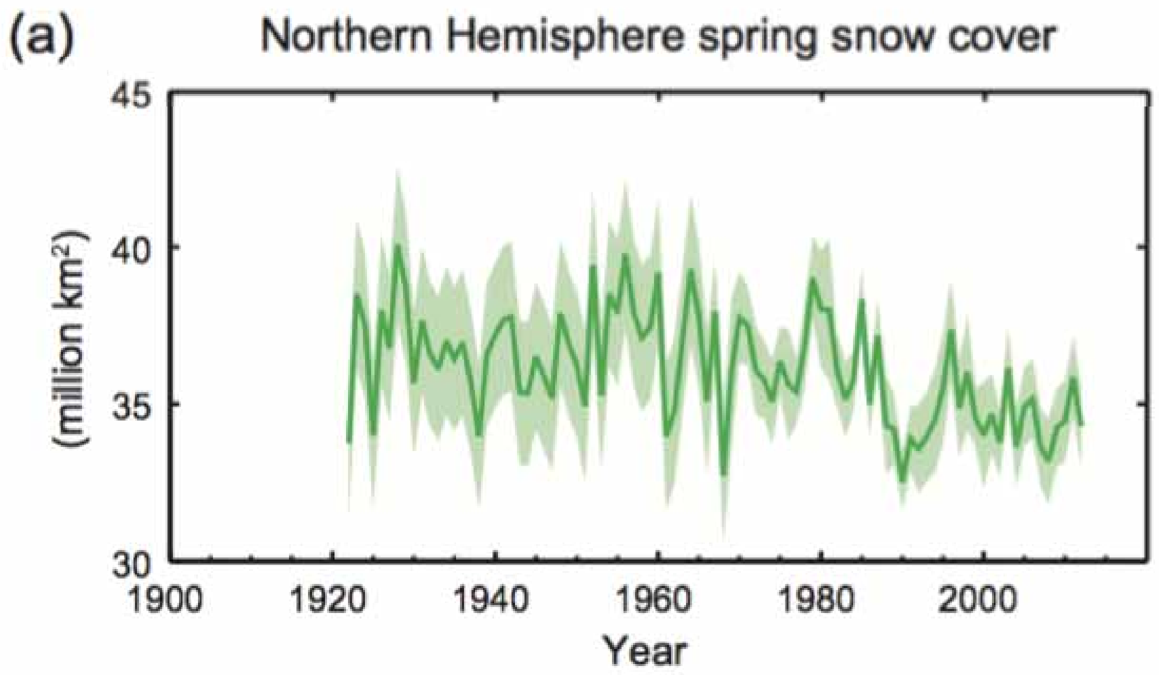


However, **warming has not been linear in time; most warming occurred in two periods: around 1900 to around 1940 and around 1970 onwards**.

The early 20th century warming was largely a NH mid- to high-latitude phenomenon, whereas the more recent warming is more global in nature.

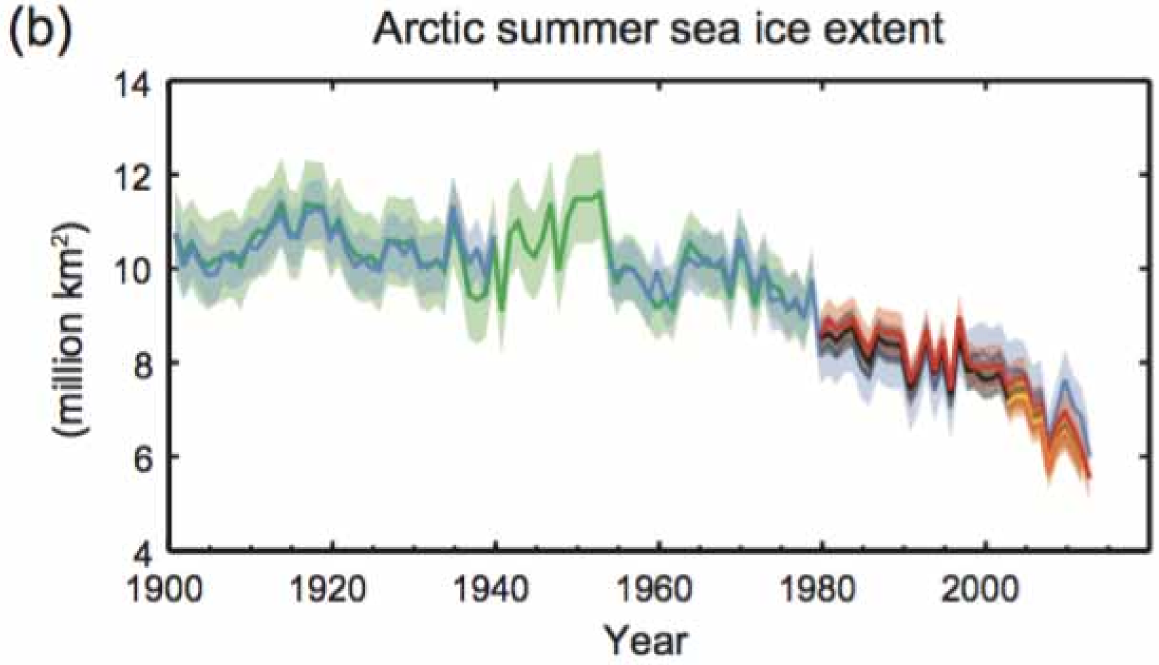
Observations of the recent changes

SNOW COVER



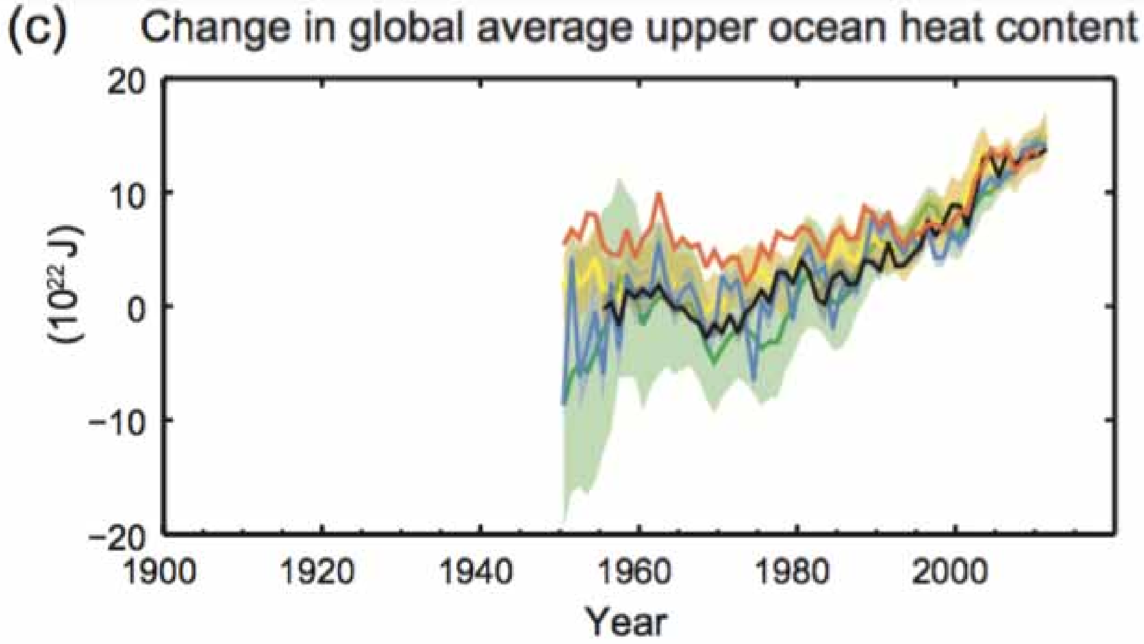
(a) Northern Hemisphere spring snow cover

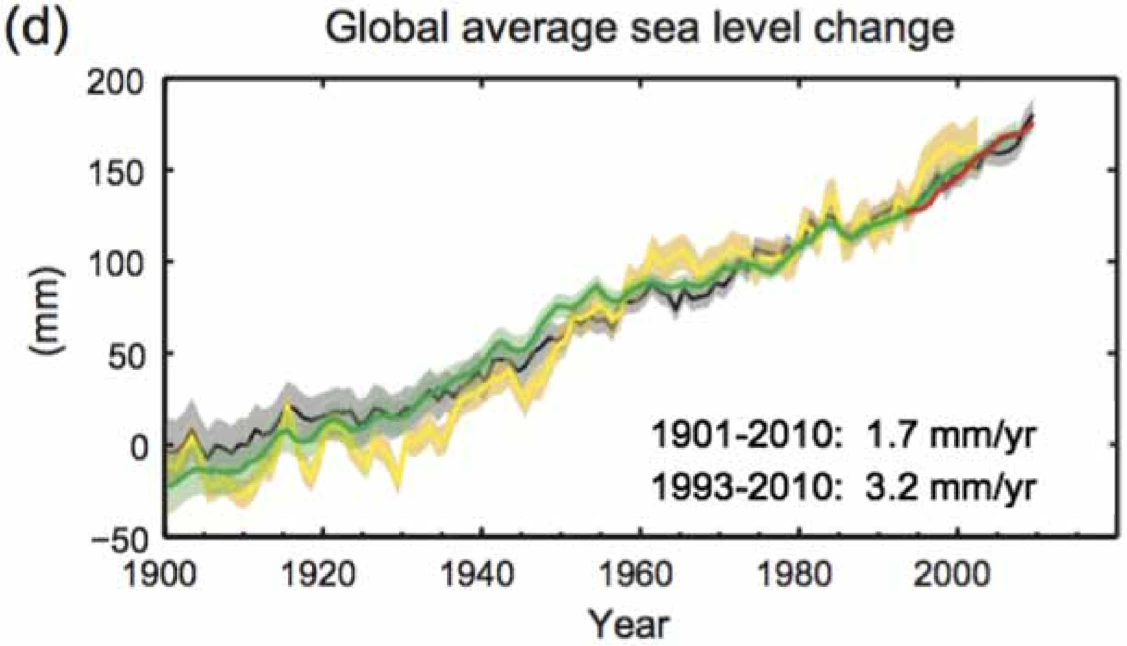
SEA ICE EXTENT



(b) Arctic summer sea ice extent

Observations of the recent changes





UPPER OCEAN HEAT CONTENT

The oceans have warmed, accounting for more than 90% of the extra energy stored by the earth system since 1971

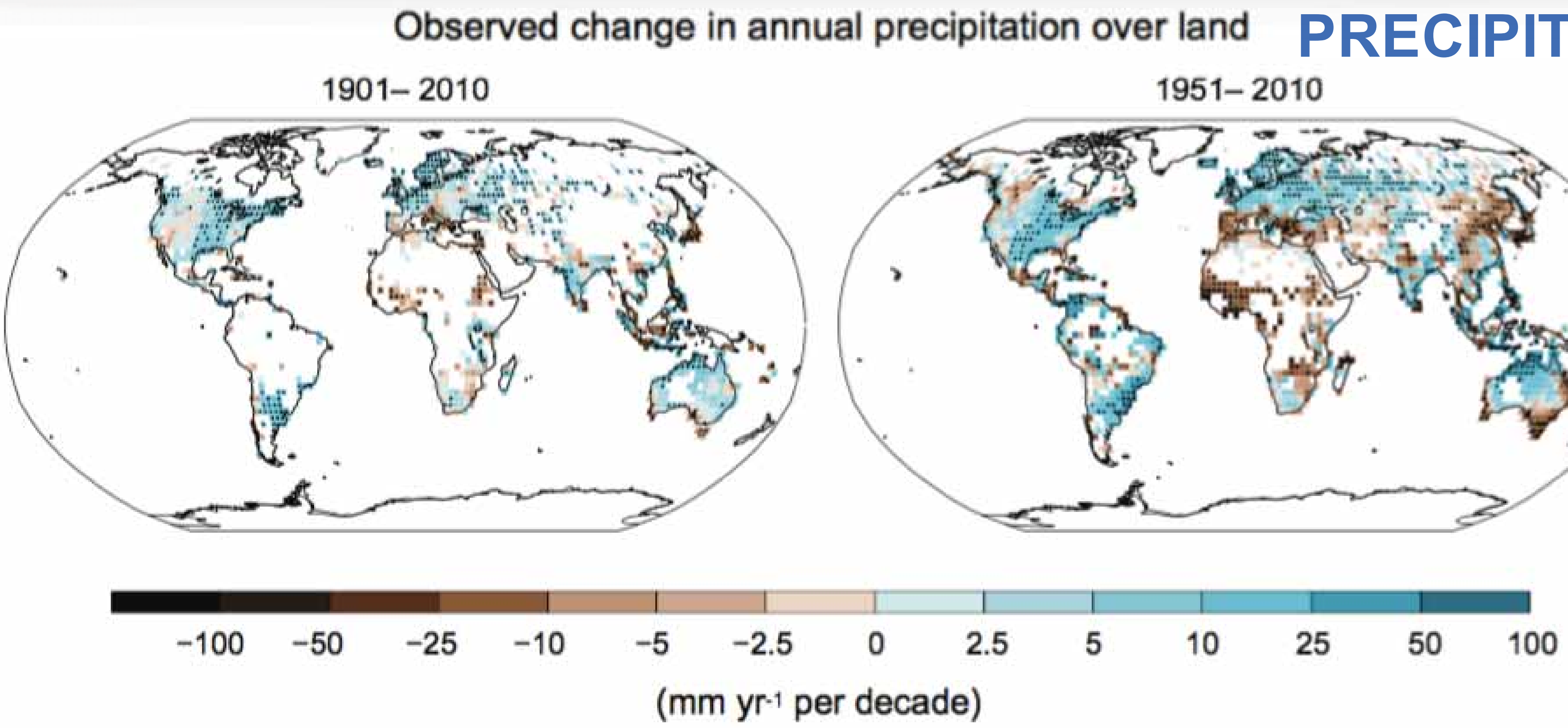
SEA LEVEL

Global mean sea level increased by 19 cm between 1901 and 2010 (**ocean thermal expansion** in the upper 700 m + **glacier mass loss** **—> dominant contributors during the 20th century**)

Measured by gauges since the 1700s and by satellites since 1992

Observations of the recent changes

PRECIPITATION



Confidence in precipitation change averaged over global land areas **since 1901 is low prior to 1951 and medium afterwards.**

Averaged over the mid-latitude land areas of the Northern Hemisphere, precipitation has increased since 1901.

For other latitudes area long-term trends have low confidence.

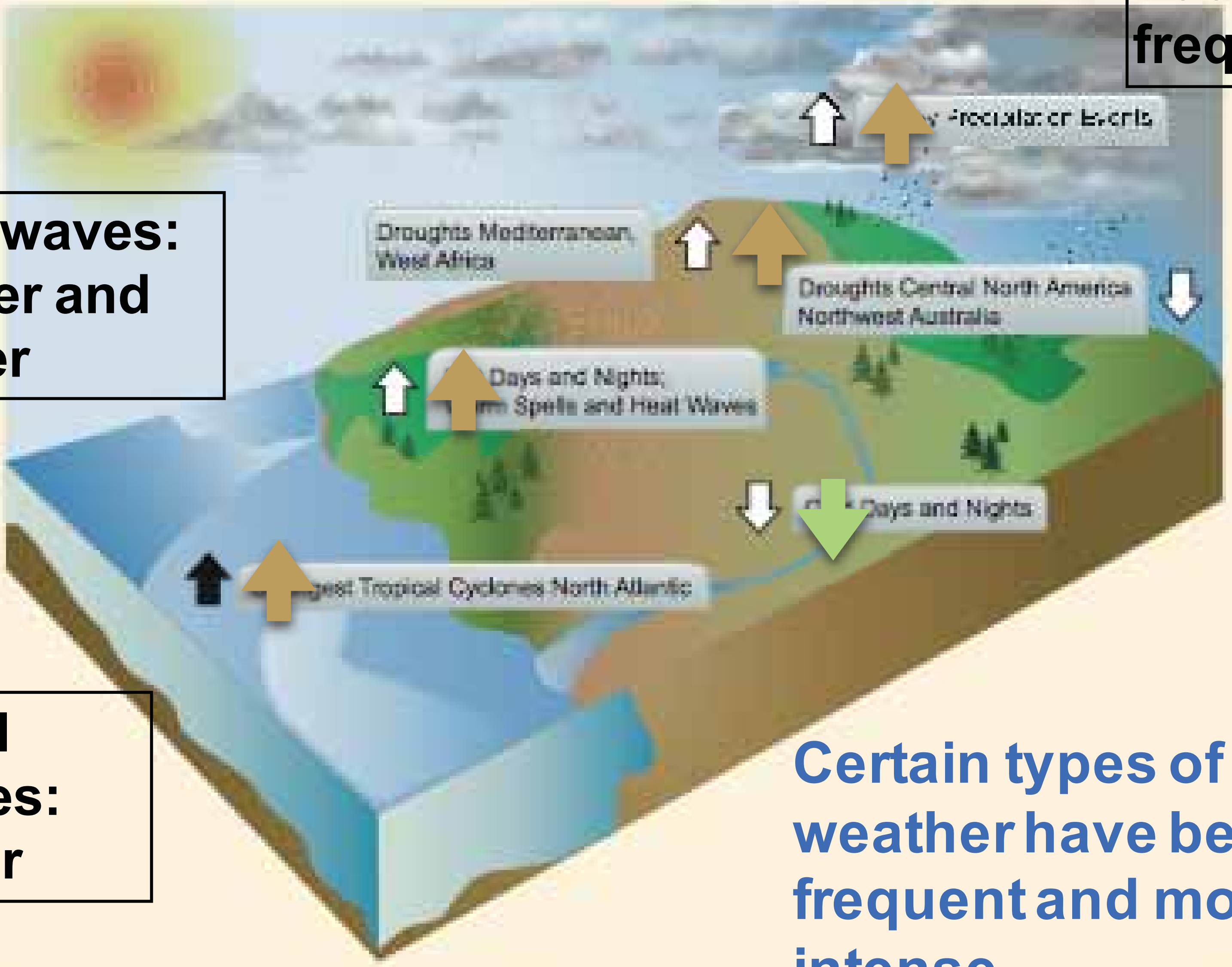
Observations of the recent changes

CLIMATE EXTREMES

heavy rain and floods: more frequent

heat waves: longer and hotter

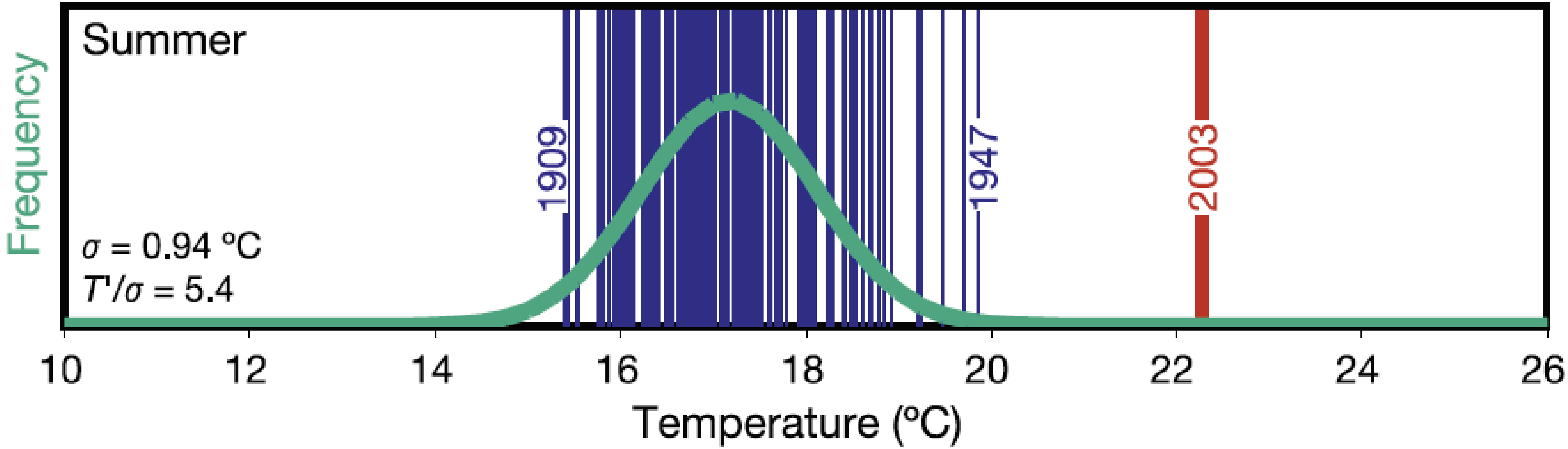
Tropical Cyclones: stronger



Certain types of extreme weather have been more frequent and more intense

FAQ 2.2, Figure 2 | Trends in the frequency (or intensity) of various climate extremes (arrow direction denotes the sign of the change) since the middle of the 20th century (except for North Atlantic storms where the period covered is from the 1970s).

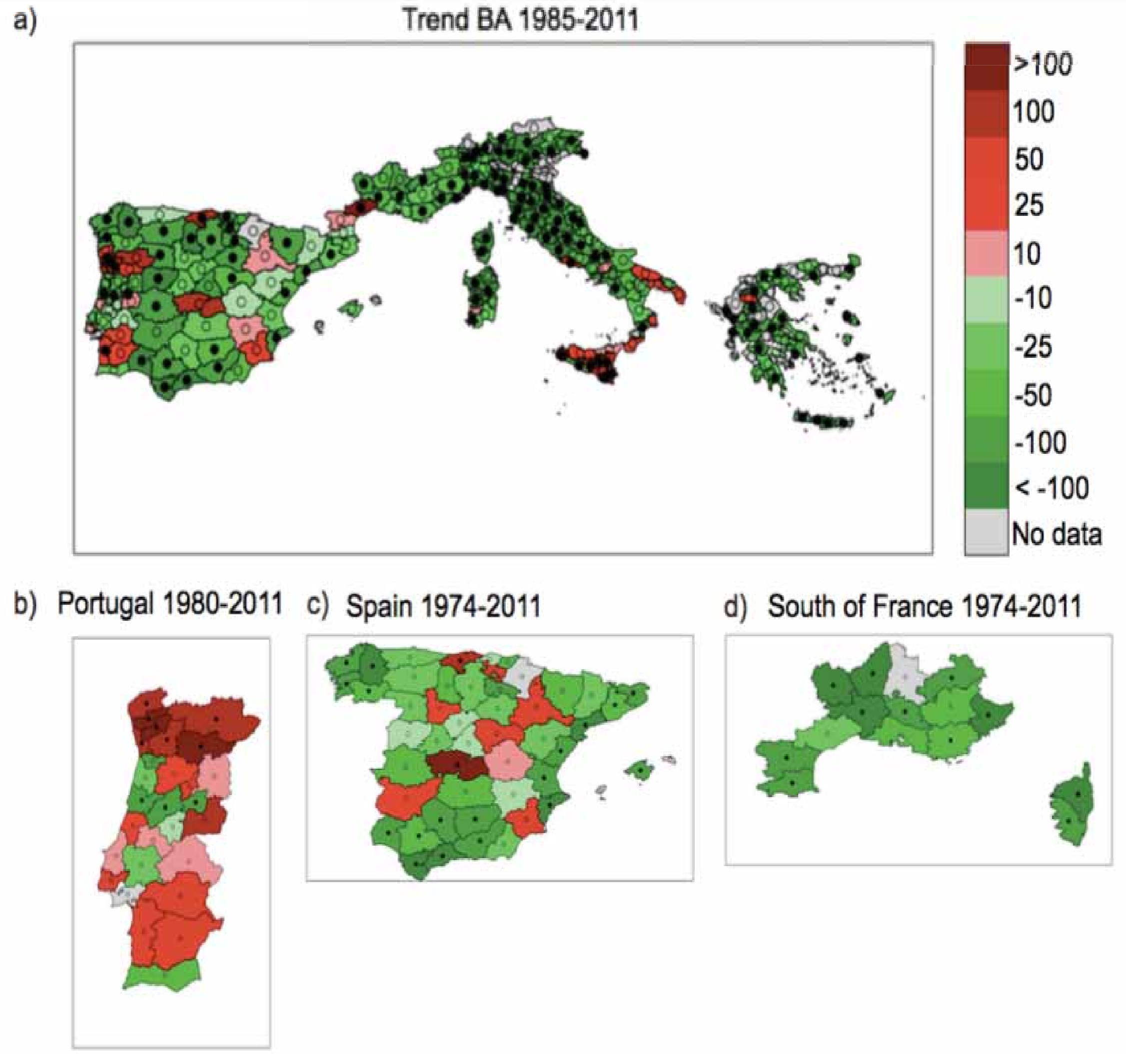
Climate extremes



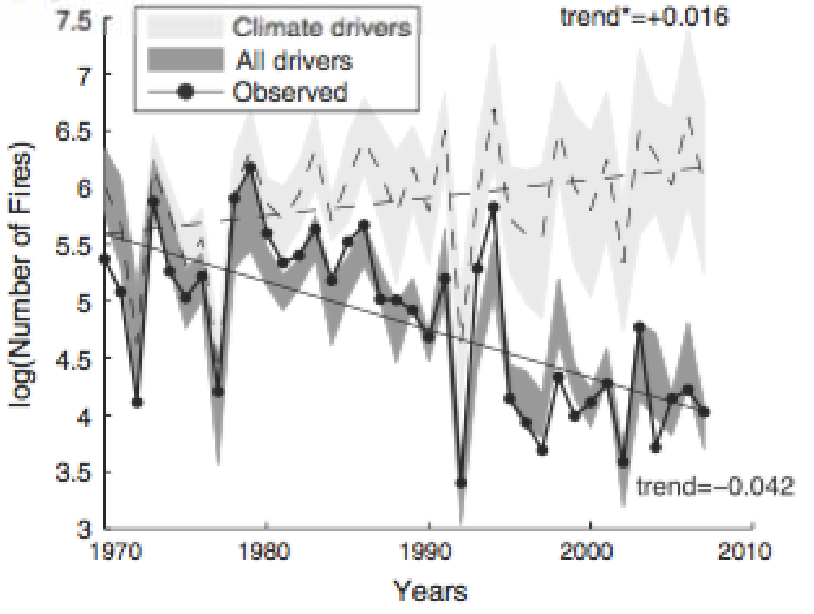
2003 European Heat Wave: The Hottest Summer in 140 Years (1864-2003). Each vertical line represents the average summer temperature for a single year from the average of four locations in Switzerland over the period 1864-2003.

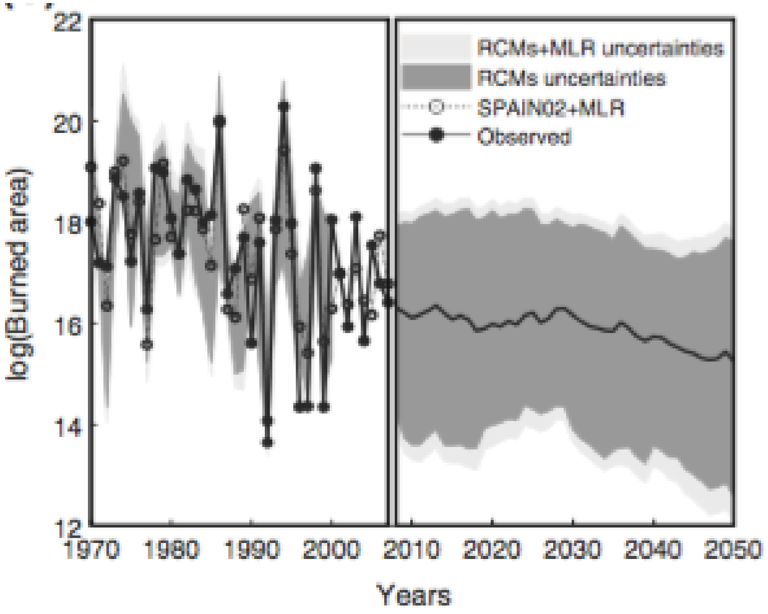
This illustrates how far outside the normal range the summer of 2003 was.
[Schär et al. 2004]

Wildfires in the Mediterranean



In Catalunya:





- Turco, M., Llasat, M.-C., von Hardenberg, J. and Provenzale, A (2014) Climate change impacts on wildfires in a Mediterranean environment. Climatic Change 125, 369–380, doi:10.1007/s10584-014-1183-3.
- Turco et al., Decreasing fires in Mediterranean Europe, PlosOne, under review

Climate change hotspots

"climate change hotspot" = areas with largest variations in multiple statistics (mean, variability and extremes) of climate variables → where climate is changing most

$$\mathrm{SED_{tot}} = \sqrt{\sum_{i}^{N_{\mathrm{indicators}}} \sum_{j}^{4} \left(\frac{\Delta_{ij}}{p_{95}(|\Delta_{ij}|)} \right)^2}$$

(1) absolute change in mean temperature

(2) percentual change in mean precipitation

(3) percentual change in the interannual standard deviation of detrended temperature

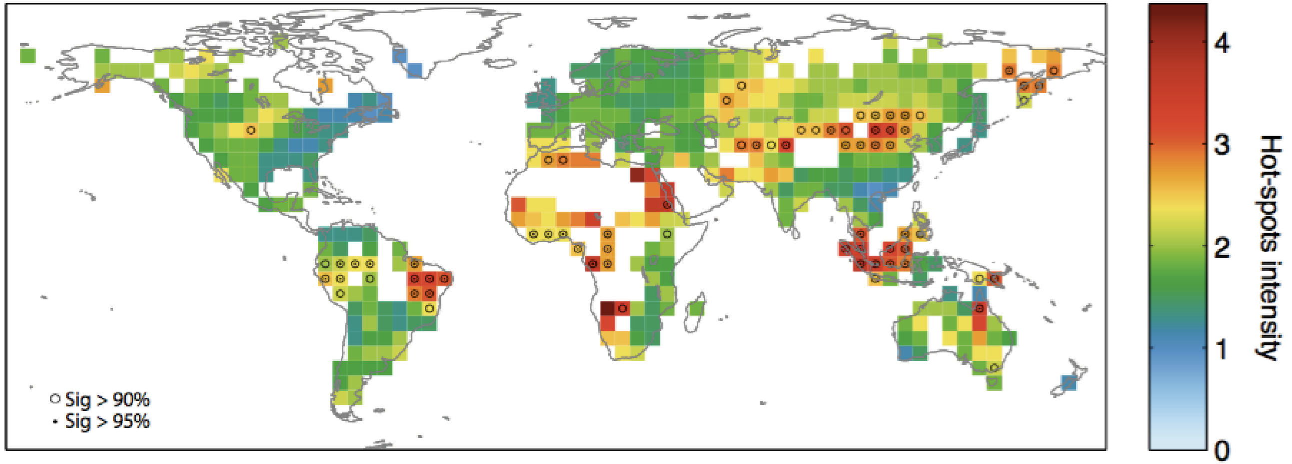
(4) percentual change in the interannual coefficient of variation of detrended precipitation

(5) frequency of seasons exceeding past temperature maximum

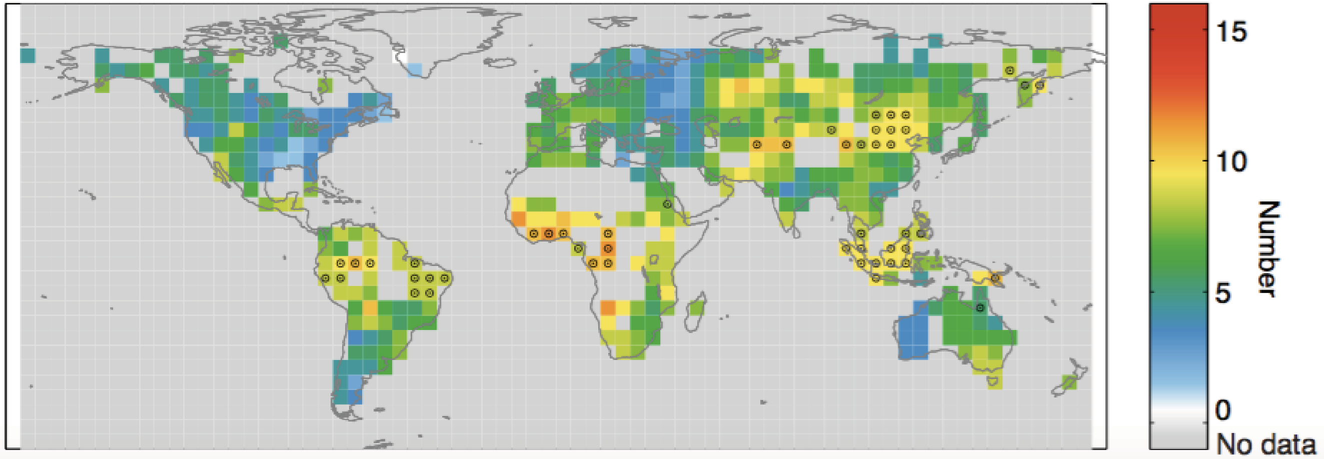
(6) frequency of seasons exceeding past precipitation maximum

(7) frequency of seasons below past minimum seasonal precipitation

Observed climate change hot-spots



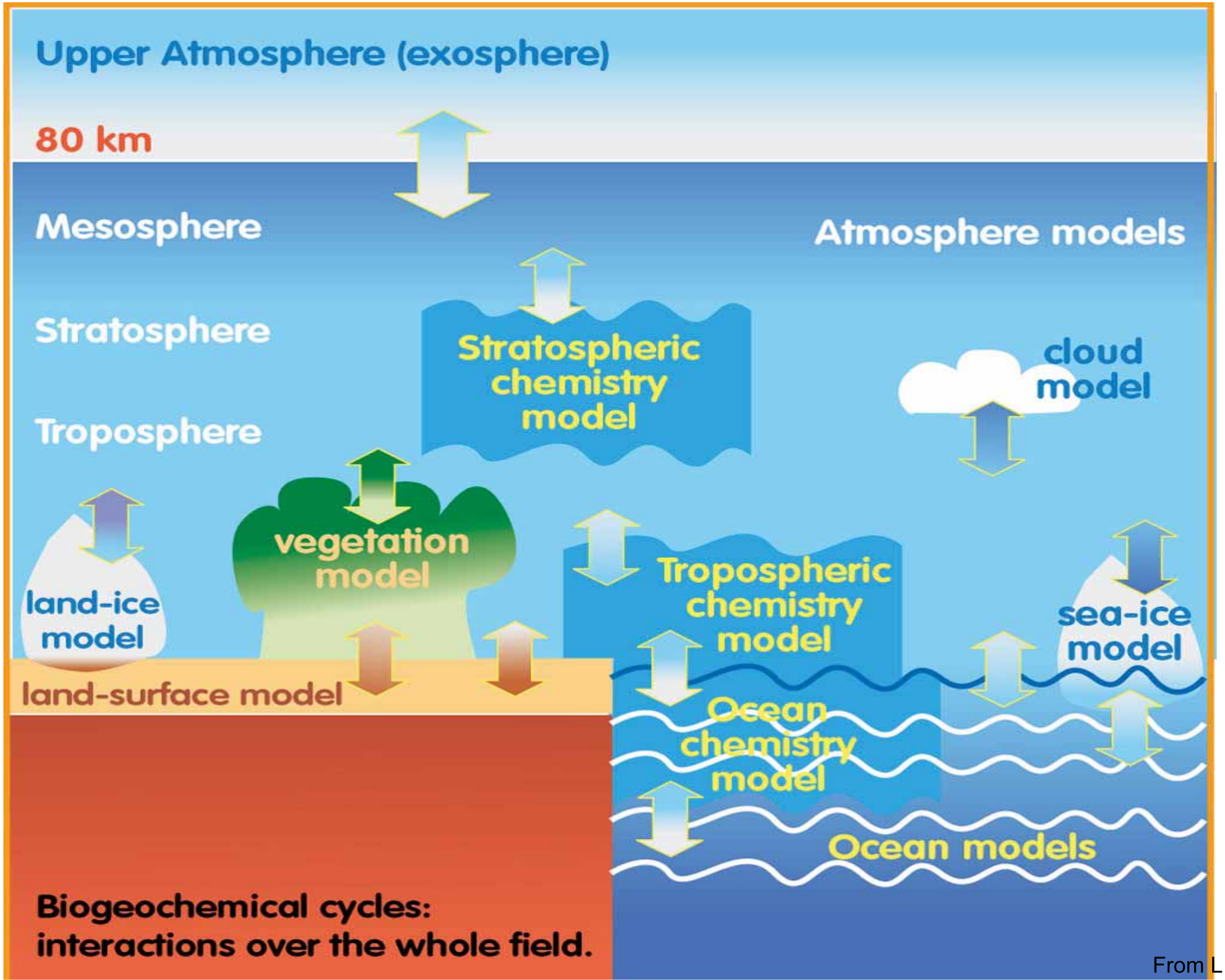
Number of indicators with significant changes



M. Turco, E. Palazzi, J. von Hardenberg, and A. Provenzale. Observed climate change hotspots, Geophysical Research Letters (2015) 10.1002/2015GL063891

Climate models

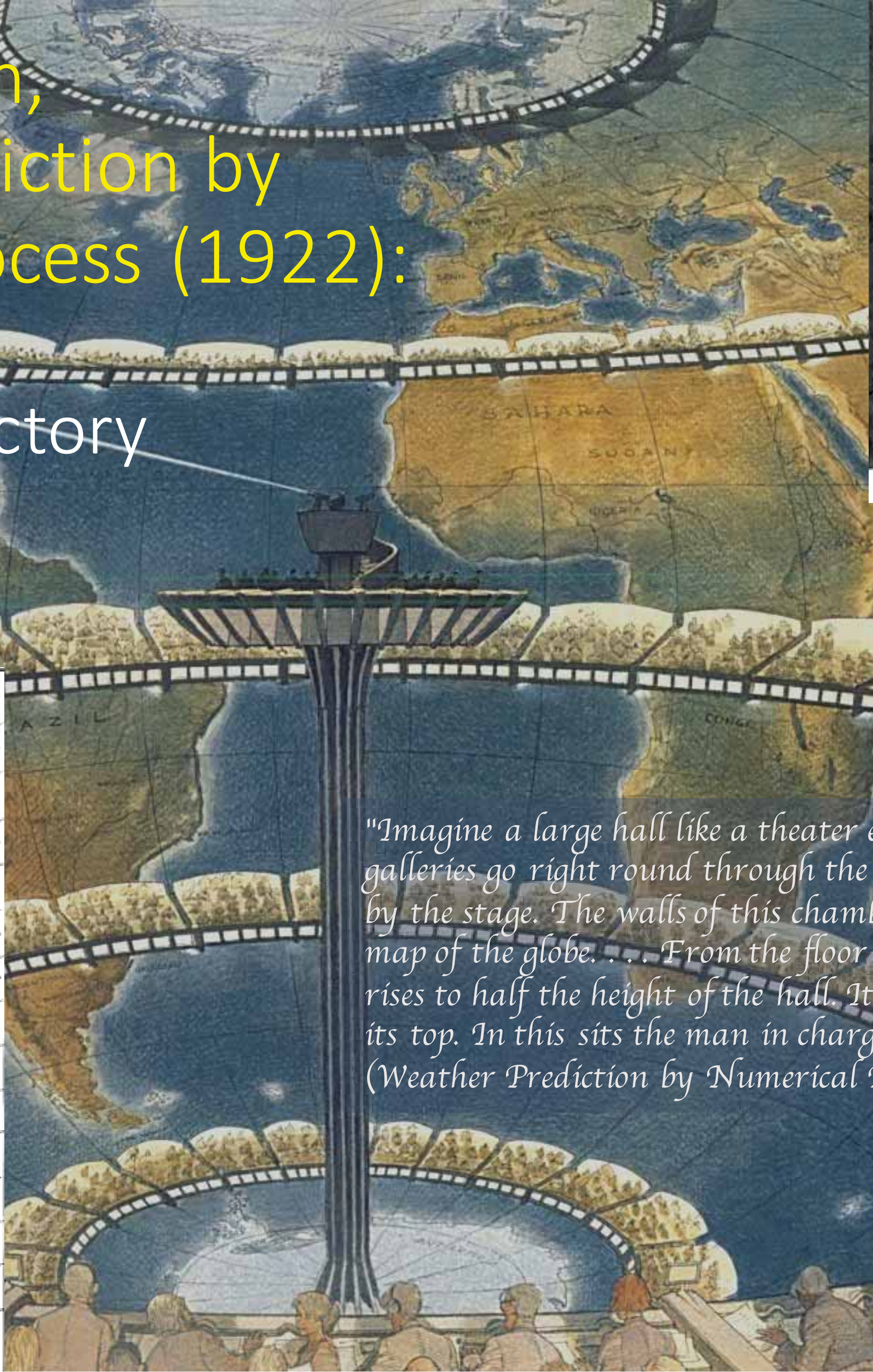
Main components of a global earth-system model



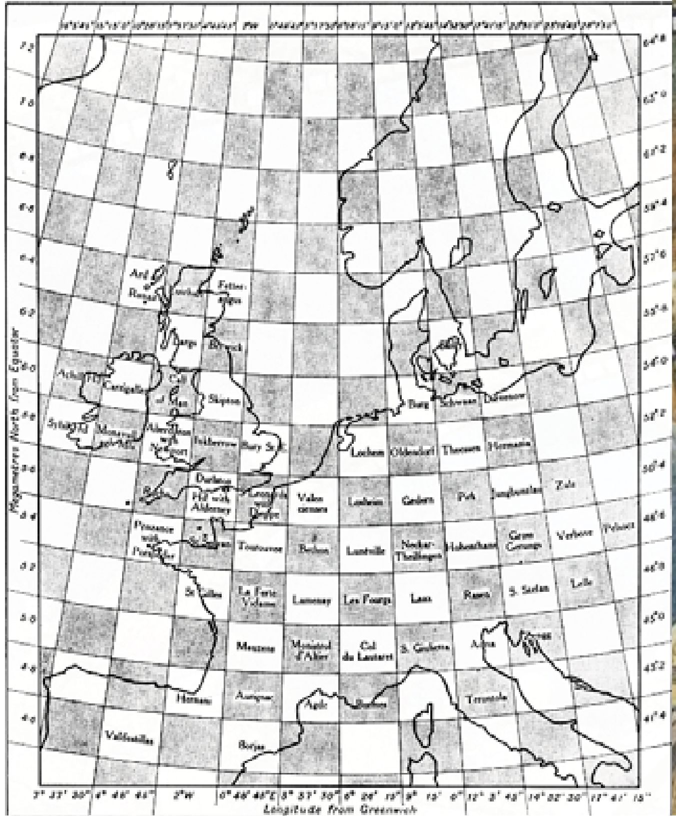
From L. Bengtsson, 2005

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

The forecast factory

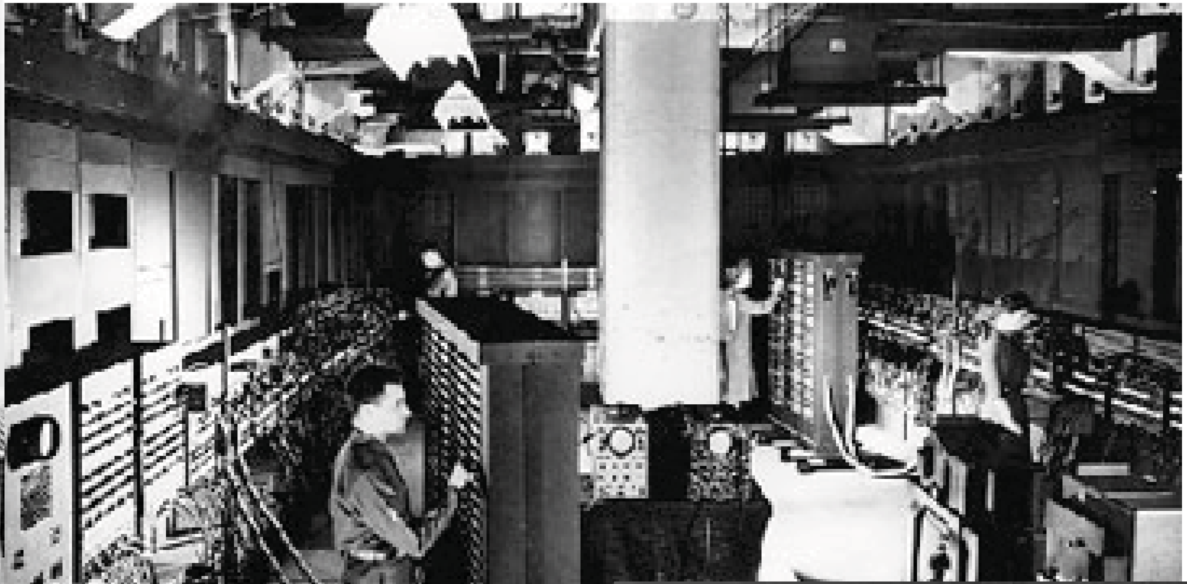


L. F. Richardson, 1931



"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

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

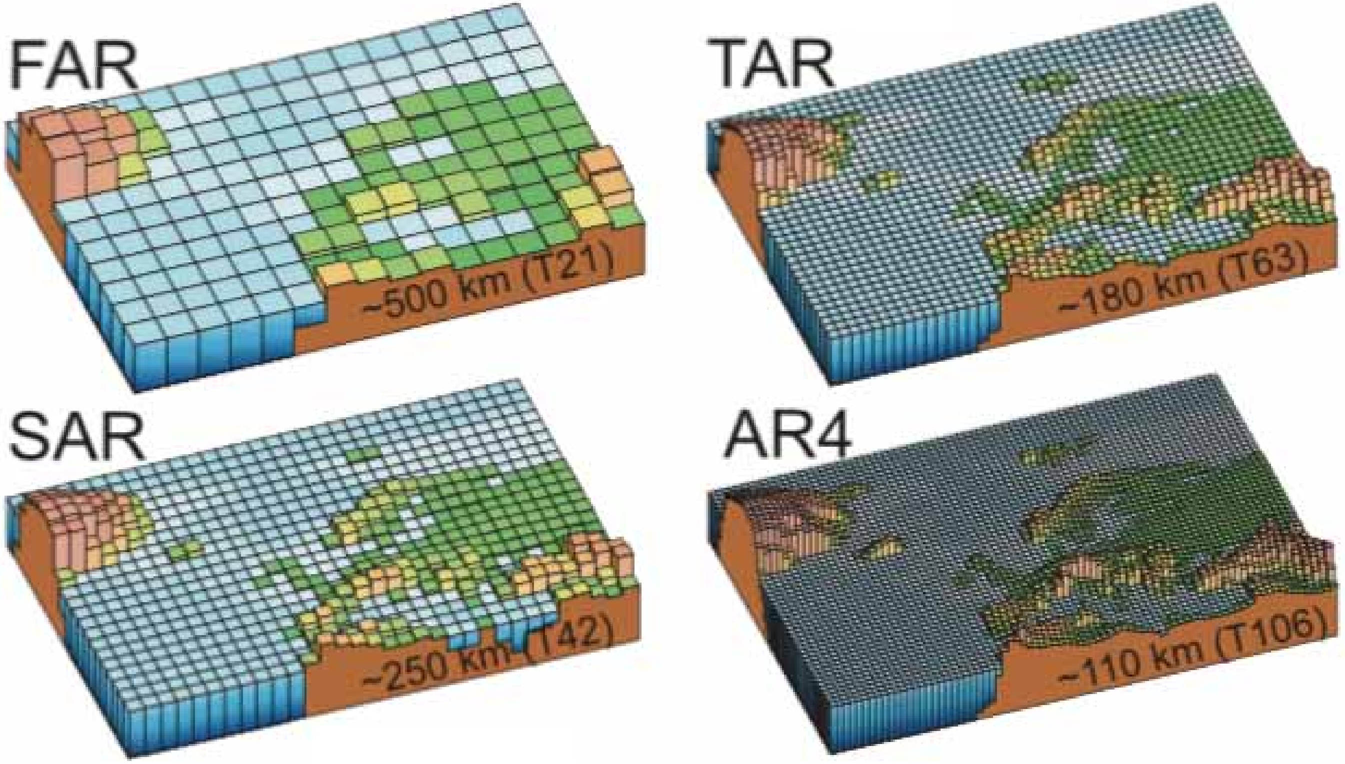
Fig. 1. Visitors and some participants in the 1950 ENIAC computations. (left to right) Harry Wexler, John von Neumann, M. H. Frankel, Jerome Namias, John Freeman, Ragnar Fjørtoft, Francis Reichelderfer, and Jule Charney. (Provided by MIT Museum.)

1950: First numerical meteorological prediction (24h lead time) using one of the first electronic calculators (ENIAC) and simplified equations for atmospheric motion (QG)

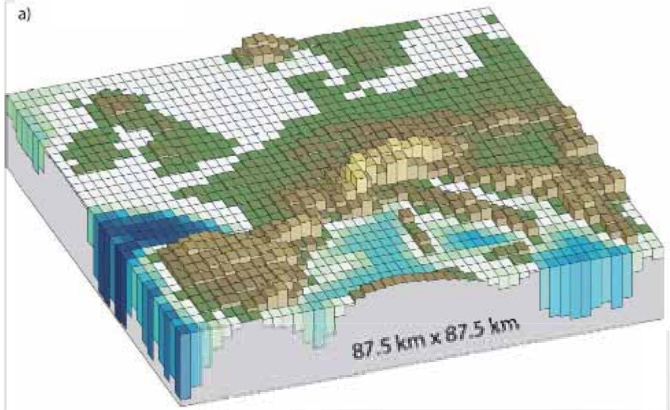
Increasing Climate Model Resolution

Global Climate Models (GCMs) - resolution

500 km

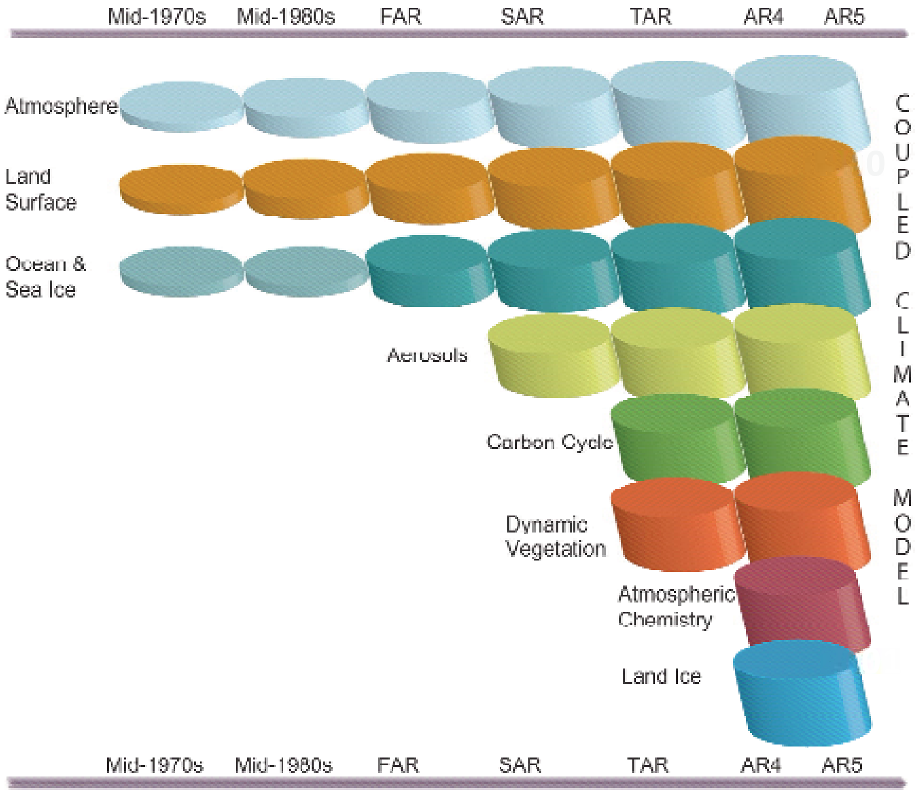


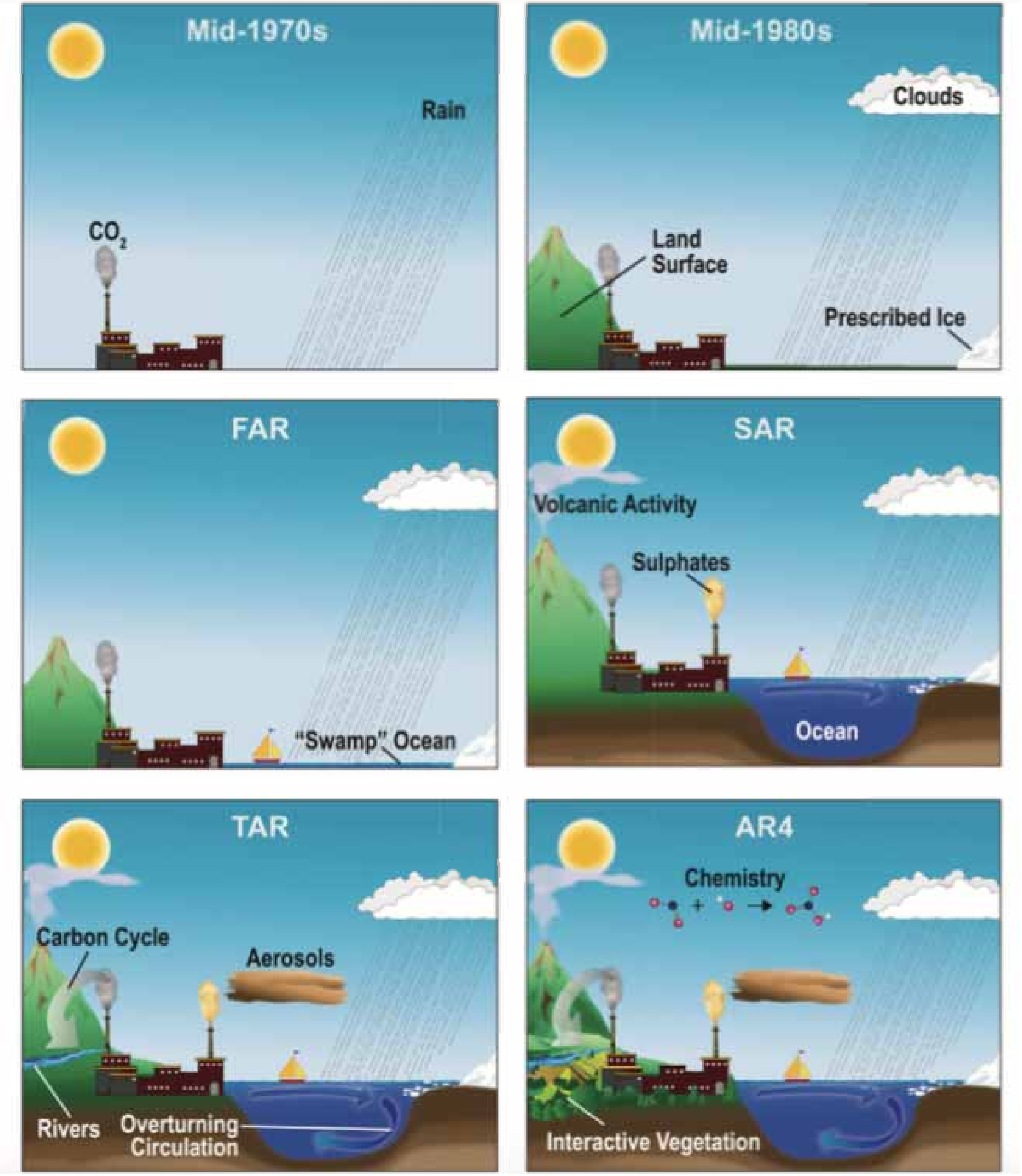
AR5



87 km

Increasing Climate Model Complexity



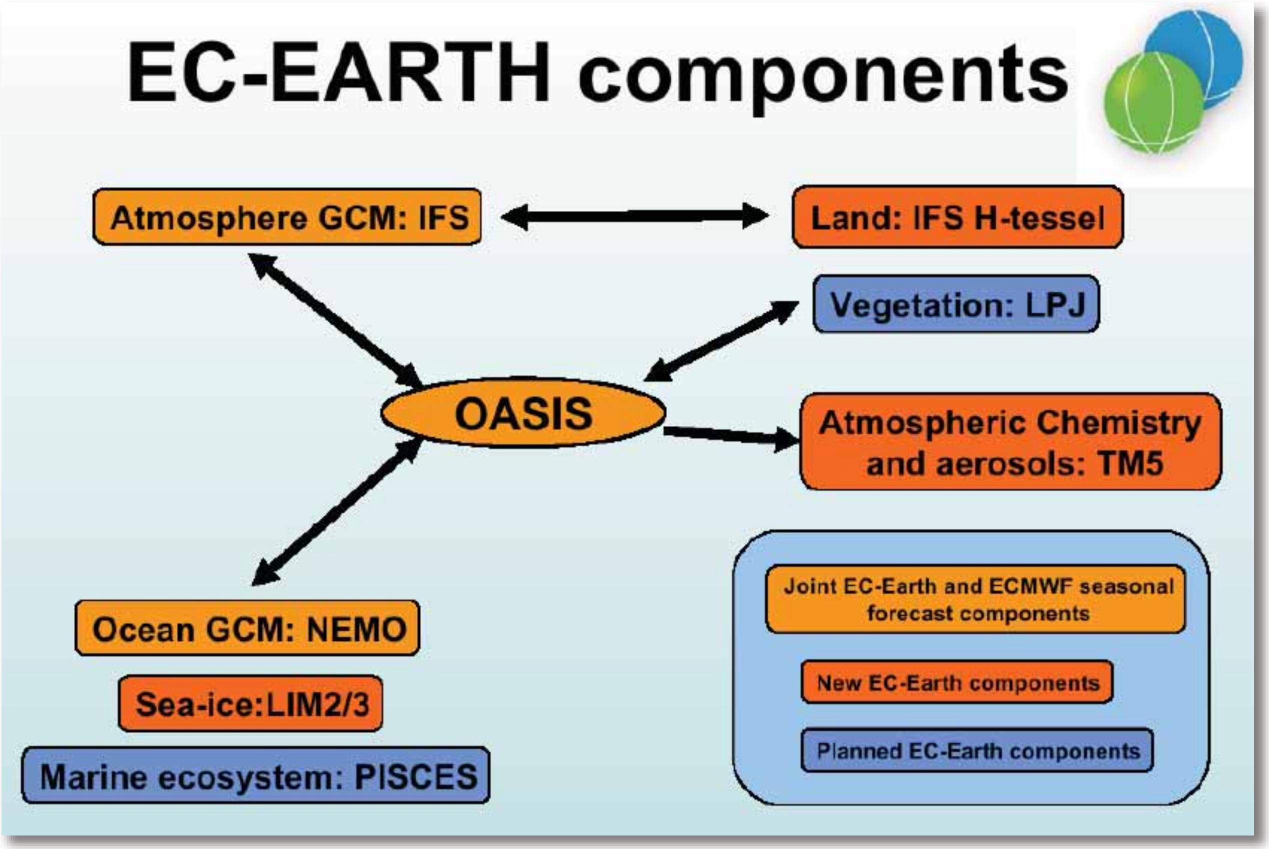


Le Treut et al. 2007, IPCC 2013

Example: the EC-Earth Earth System 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°)



EC-EARTH components

Atmosphere GCM: IFS

Land: IFS H-tessel

Vegetation: LPJ

OASIS

Atmospheric Chemistry and aerosols: TM5

Ocean GCM: NEMO

Sea-ice:LIM2/3

Marine ecosystem: PISCES

Joint EC-Earth and ECMWF seasonal forecast components

New EC-Earth components

Planned EC-Earth components

Integrated Forecast System
ECMWF

Nucleus for European Modelling of the Ocean

TM5 atmospheric chemistry and transpor model

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

The Atmosphere: IFS

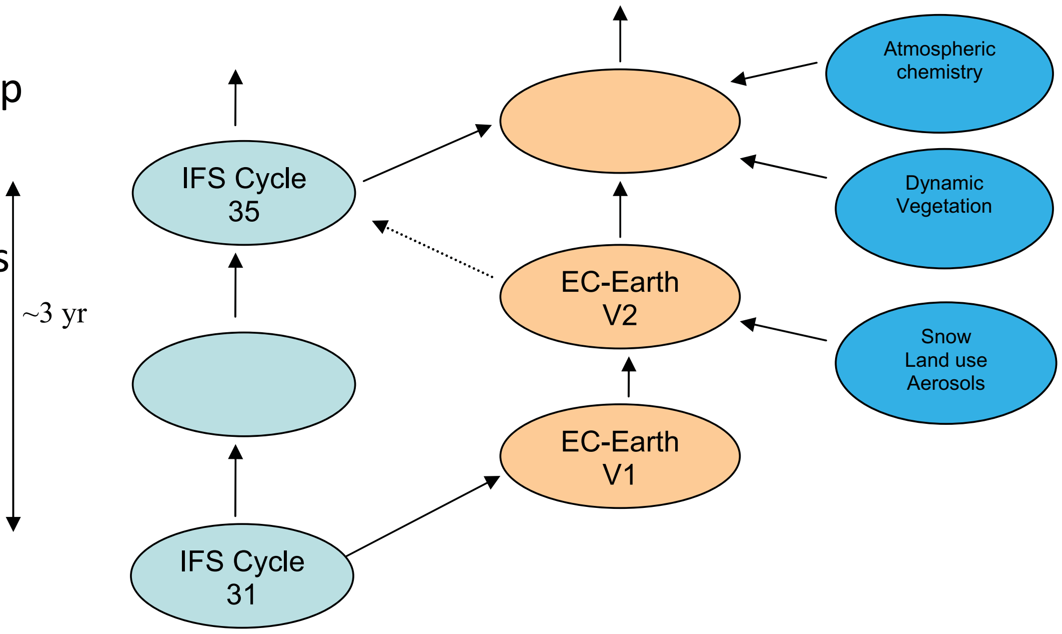
- The “Integrated Forecast System” is the NWP system in use at the European Centre for Medium-Range Weather Forecasts
- Spectral primitive equation model
- Semi-Lagrangian advection , 1h time step
- Current resolution for EC-Earth:
  T159 / N80 (1.125° ~ 125 km) reduced Gaussian grid /
  62 vertical levels up to 5 hPa.
- Cloud and radiation physics + aerosol direct and indirect effects.
- Based on IFS cycle 31r1, some changes:

✓ Better description of entrainment in deep convecting plumes
(from cycle 32r3) →
better precipitation patterns over tropics

✓ Better mass conservation correction scheme from cy33R2 →
better mean atmospheric state

✓ Time-varying aerosols

✓ Ocean wave model not used



Ref.: Hazeleger et al. EC-Earth V2: description and validation … http://ecearth.knmi.nl/index.php?n=PmWiki.Papers

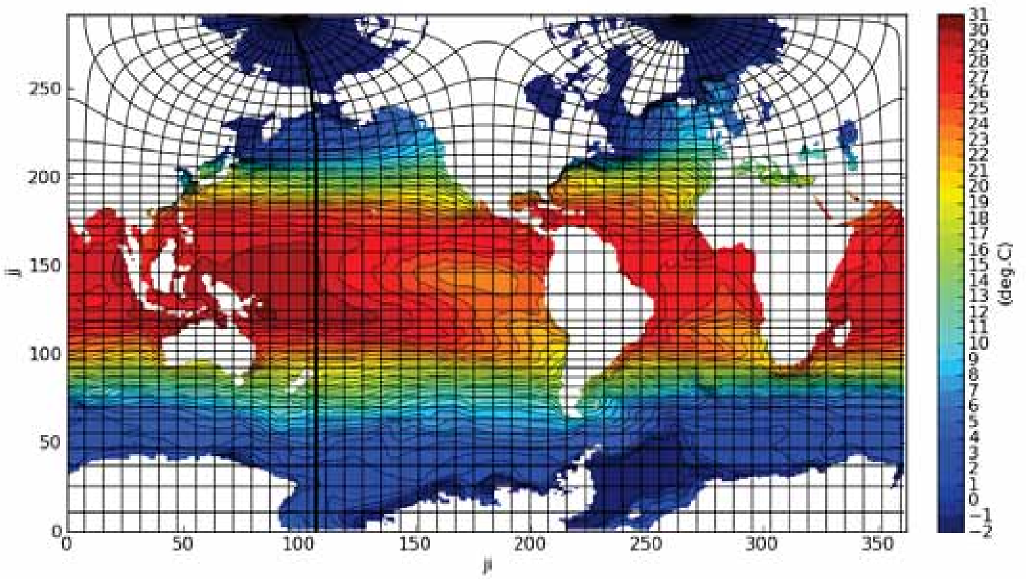
The Ocean:

The “Nucleus for European Modelling of the Ocean” is based on the OPA 9 (Océan Parallélisé) model:

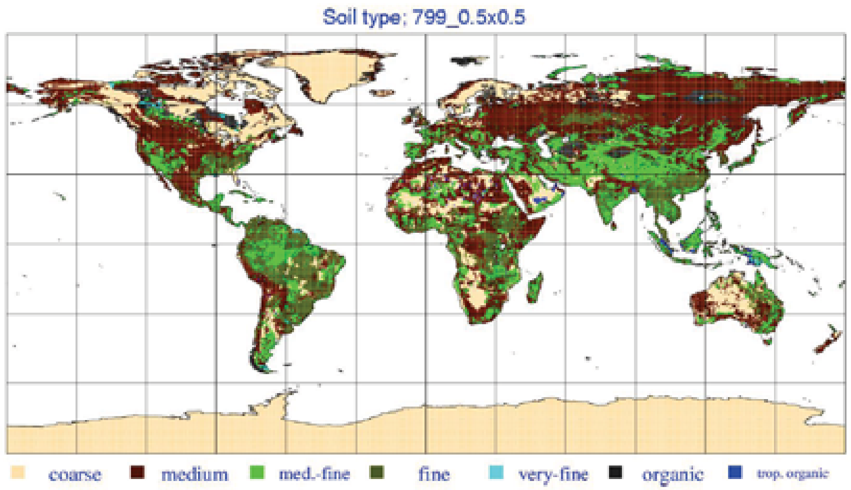
- NEMO2: Primitive equations, free surface, energy and enstrophy conserving momentum advection.
- TVD advection scheme (Zalesak 1979). Free slip lateral BCs.
- Gent and McWilliams (1990) vertical adiabatic mixing scheme for T and S
- Vertical eddy diffusion using TKE scheme (Gaspar et al. 1990).

- ORCA1 grid: Arakawa-C, about 1° resolution (not constant), higher resolution (1/3°) near the equator. Tripolar grid. 42 levels.

- + Louvain La Neuve Ice Model (LIM2) for sea-ice (3-layer thermodynamic model)



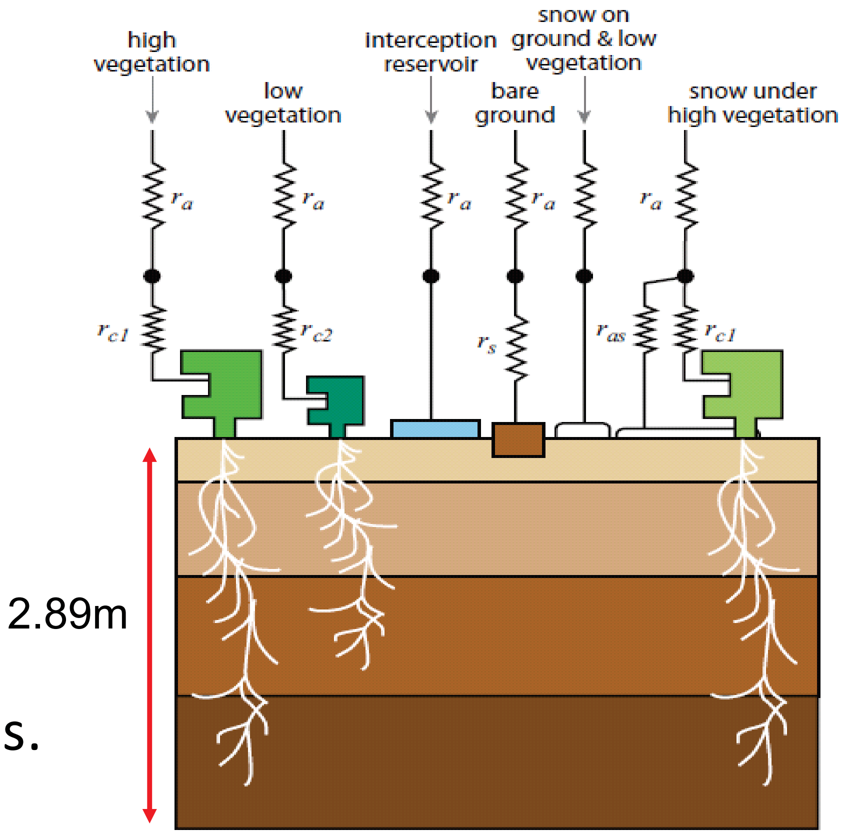
Land Surface: H-TESSEL



- Water + heat exchanges
- 6 land tiles: bare ground, low and high vegetation, intercepted water, shaded and exposed snow

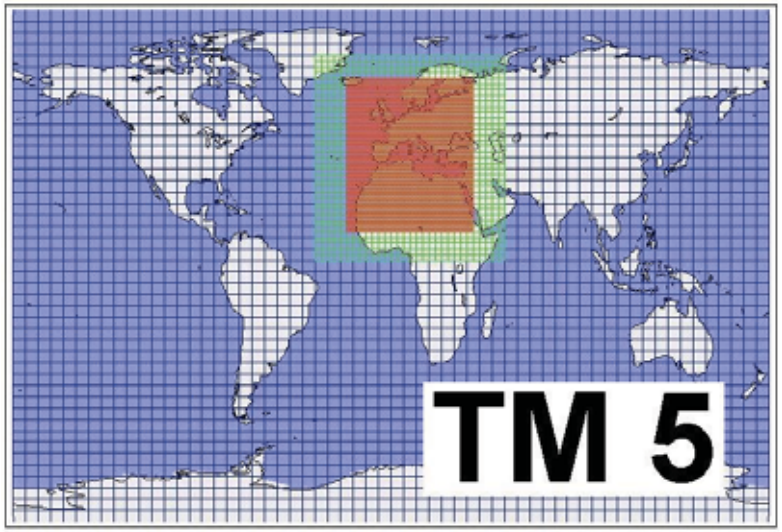
- Energy balance for each tile w/ vegetation evaporation, roughness and snow properties
- Snow albedo and density prognostic
- Parametrization of fast surface runoff
- Spatially varying soil textures + soil hydraulic properties
- Soil water flow: Richard's equation + van Genuchten for conductivity and diffusivity + 4 soil layers
- Instantaneous collection of runoff in river basins.

Schematics of the land surface



Refs:: van den Hurk et al. 2000, ECMWF tech. memo 295 + Balsamo et al. 2009, ECMWF tech. memo 563

To be coupled in the next versions:
Atmospheric chemistry and aerosols: TM5



- Tropospheric chemistry + aerosols
- Direct and indirect radiative forcing computed in IFS
- 3°x2° and 6°x4° resolutions
- Tropospheric photochemistry based on CBM (carbon bond mechanism) IV
- Aerosol mass and number concentration computed with M7 (Vignati et al. 2004)
- Online parametrizations for biogenic emissions.

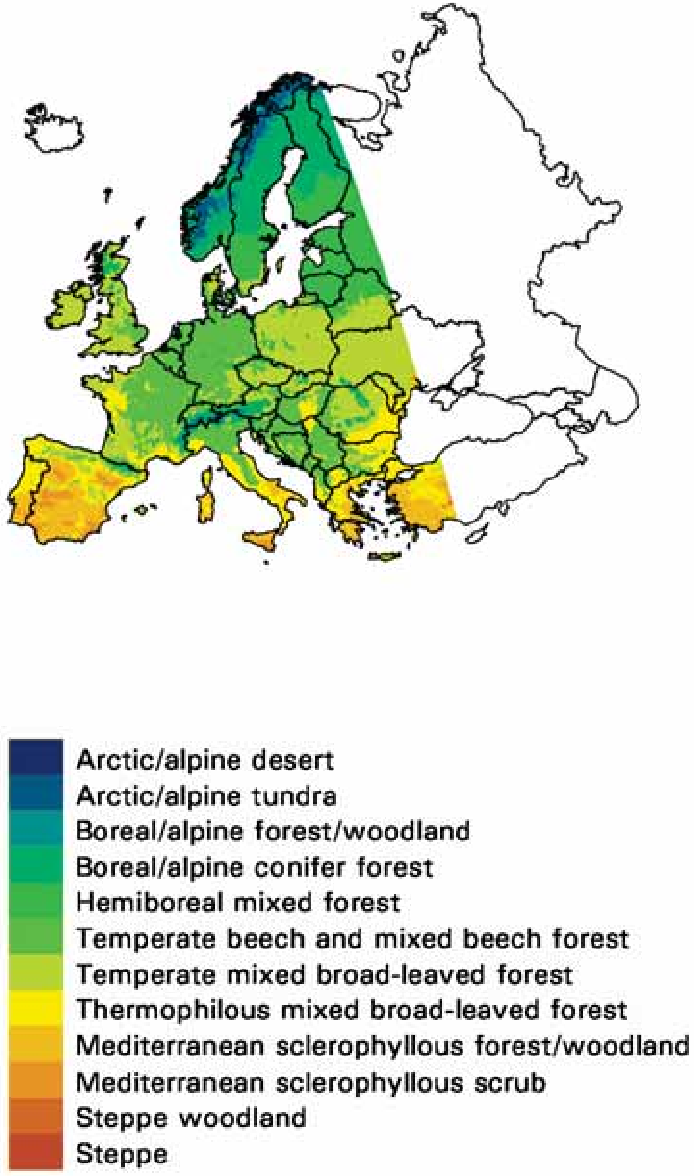
Ref.: Krol et al. 2005 ACP 5, 417-432.

To be coupled in the next versions:

Vegetation and biogeochemistry: LPJ-GUESS

General Ecosystem Simulator (GUESS), +
Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ)

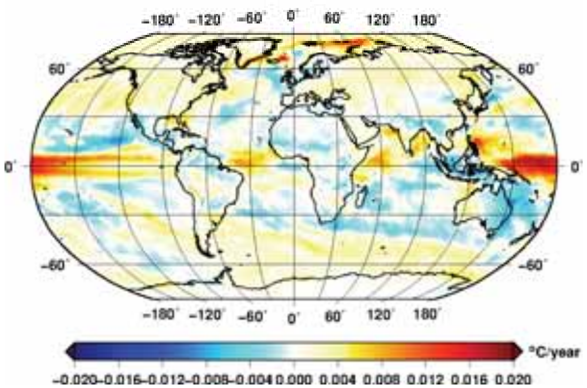
- Plant physiology + ecosystem biogeochemistry
- Functional types, vegetation dynamics + canopy structure
- Stochastic establishment, individual tree mortality and disturbances → successional vegetation dynamics
- Process-based description for the main biogenic volatile organic compounds



Ref.: Smith et al. 2001. Global ecology and biogeography, vol 10 (6).

From large to small scales (and back)

- Climate projections from global climate models are available at coarse resolutions (~100 km)

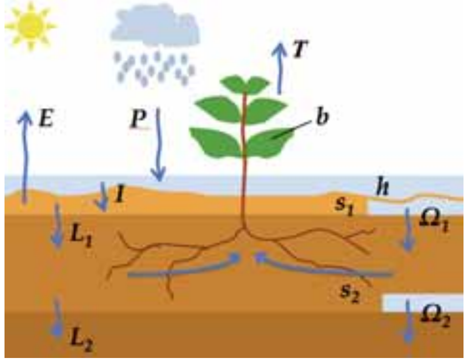

EC–Earth RCP 4.5 – Tot. precipitation trend 2006–2100

- Climate change impacts act mostly at local scales (impacts on ecosystems, hydrology, risks, surface processes)

→ Scale mismatch and need for downscaling

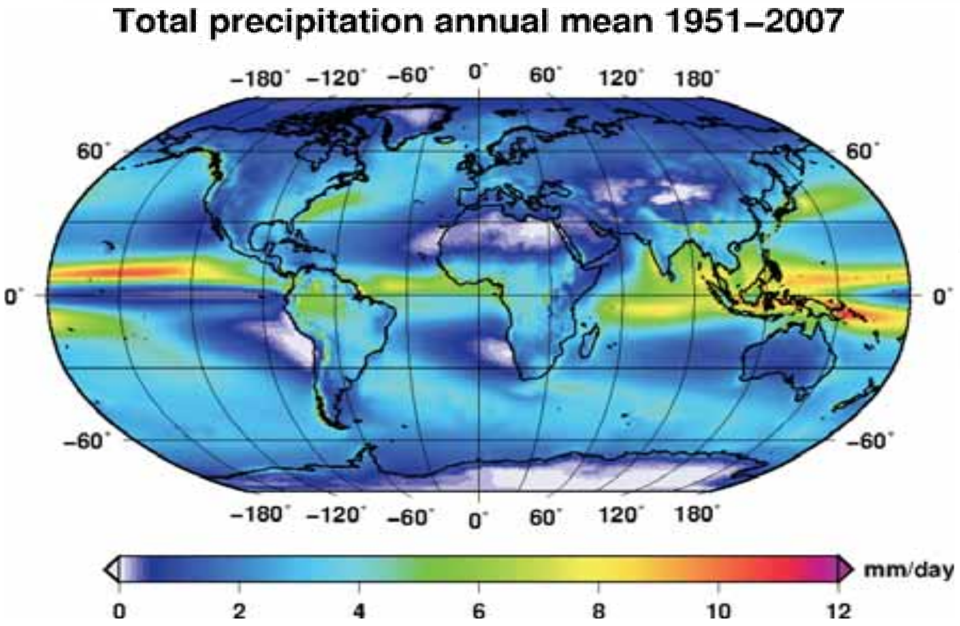
- Local surface processes may feed back on large scales

→ need for upscaling

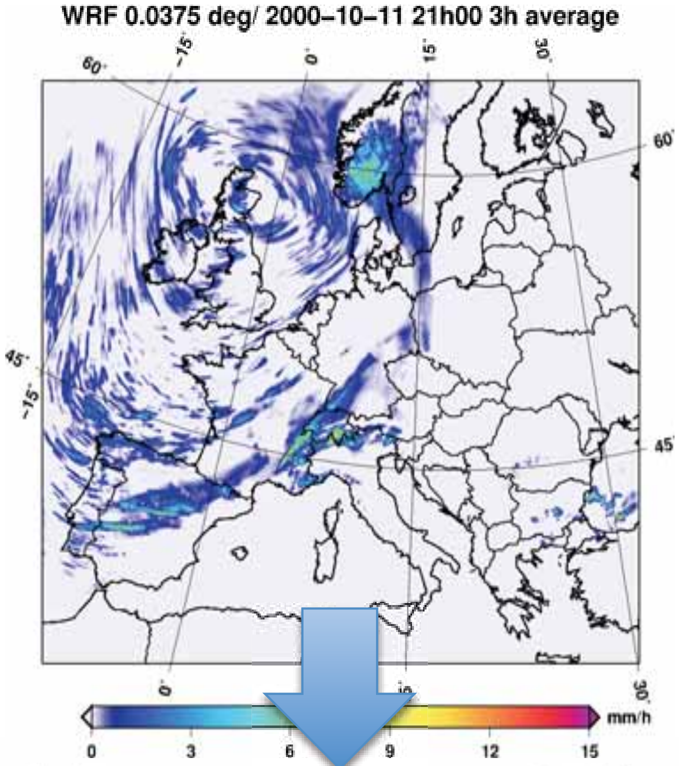


The downscaling modelling chain

Global climate model



Regional climate model



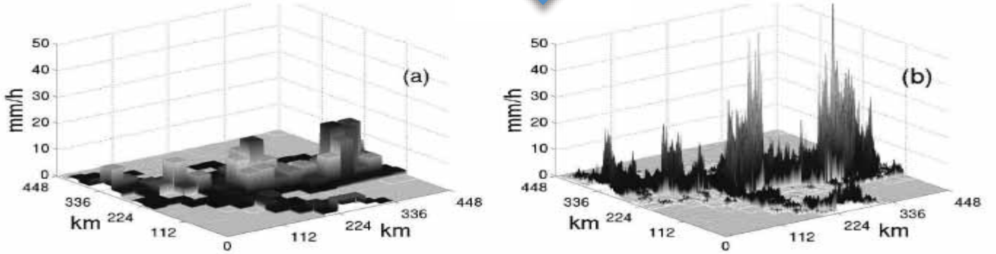


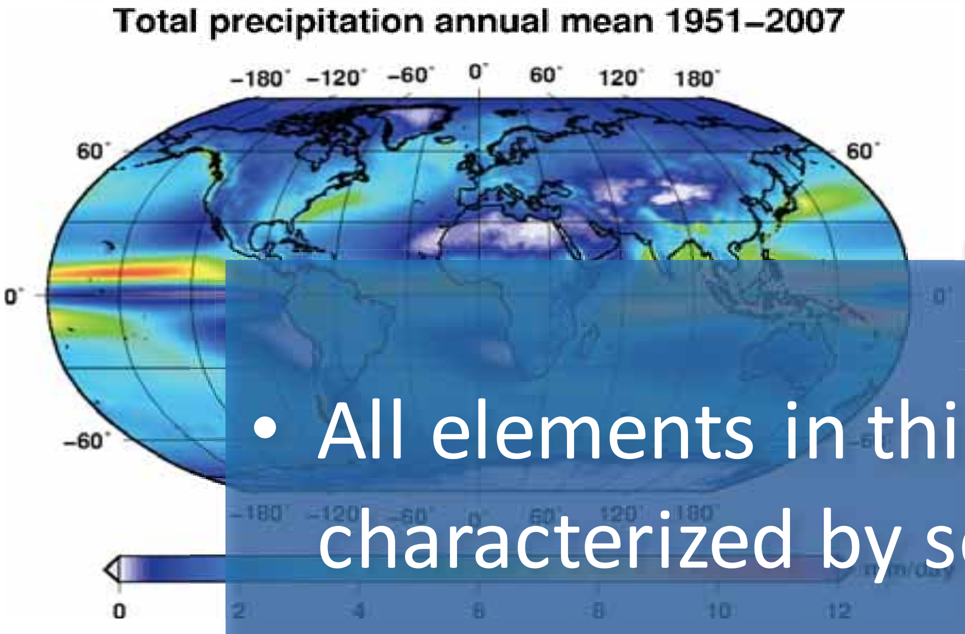
FIG. 10. (a) A snapshot of the forecasted rain field obtained from the LAM forecast and (b) one example of a downscaled field obtained by application of the RainFARM. The vertical scale indicates precipitation intensity (mm h^{-1}) and it is the same for the two fields.

Statistical/stochastic downscaling

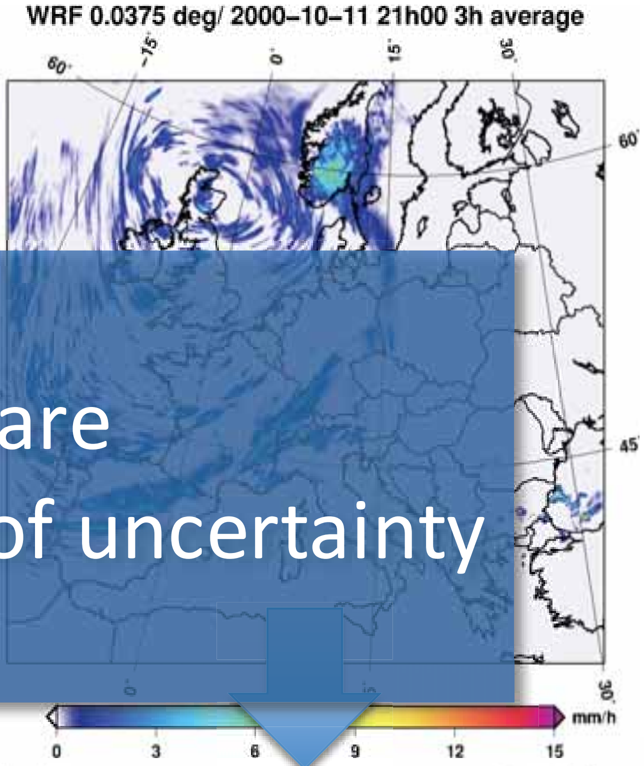
Impact on eco-hydrological processes

The downscaling modelling chain

Global climate model



Regional climate model



- All elements in this chain are characterized by sources of uncertainty

Impact on eco-hydrological processes

Statistical/stochastic downscaling

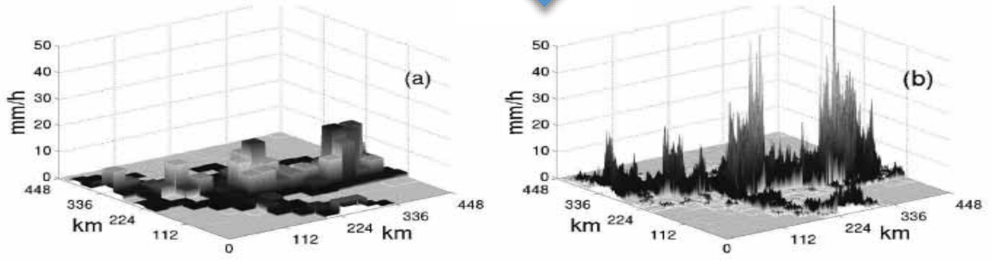
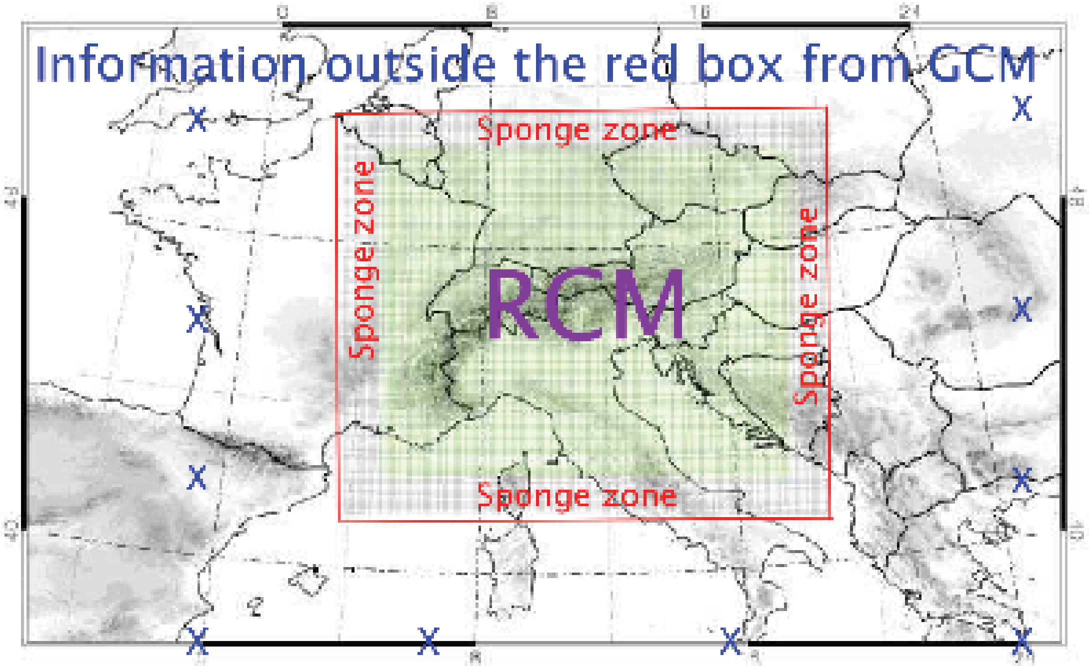


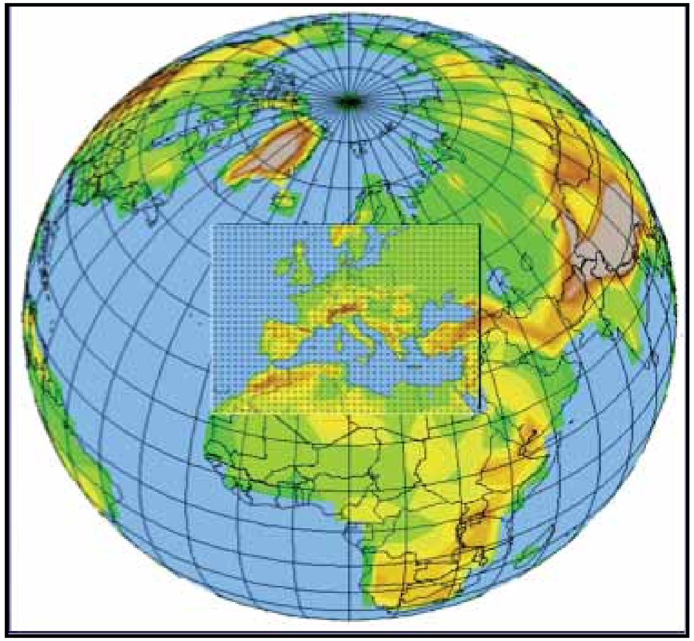
FIG. 10. (a) A snapshot of the forecasted rain field obtained from the LAM forecast and (b) one example of a downscaled field obtained by application of the RainFARM. The vertical scale indicates precipitation intensity (mm h^{-1}) and it is the same for the two fields.

Regional Climate Models

Dynamical downscaling uses a limited-area, high-resolution regional climate model (RCM) driven by boundary conditions from a GCM to derive smaller-scale information. Current RCMs have a resolution of 10 to 50 km

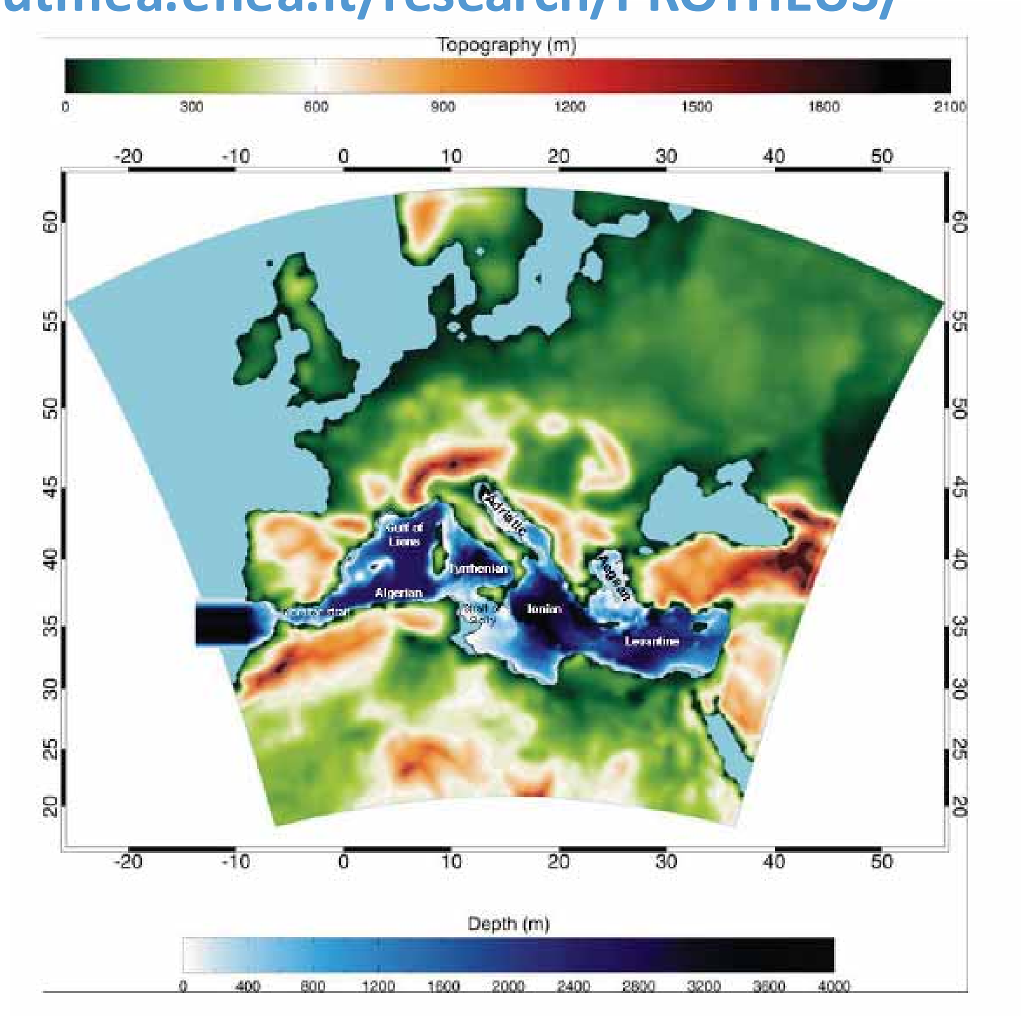
- **RCMs simulate** spatial contrasts at a scale much smaller than that of the driving GCM, in particular where there are significant regional influences arising from **mountains and coastlines**
- The higher resolution of RCMs aims at gaining an **improved representation of climate** variability, precipitation and **localized extreme events.**
- **It allow to resolve explicitly some phenomena (e.g convection) or to use different parameterizations**



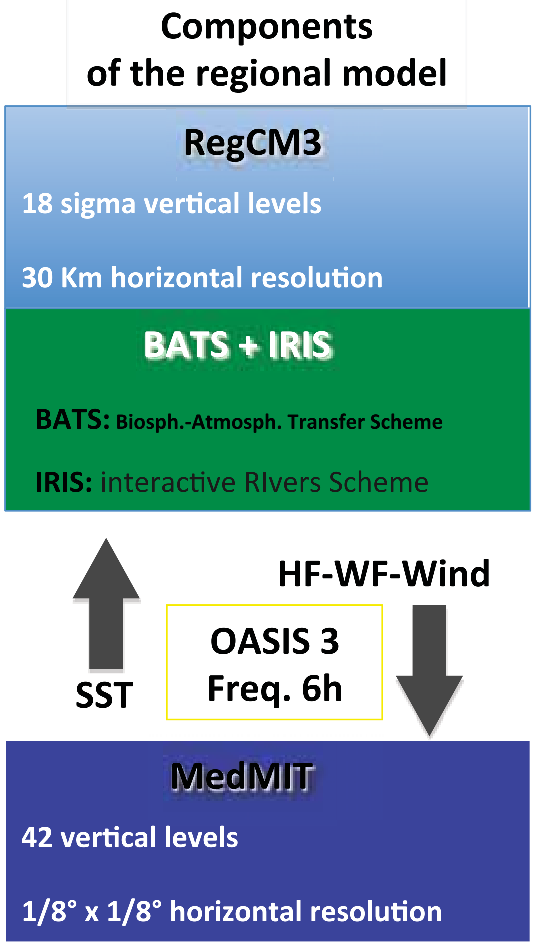


PROTHEUS Regional Climate Model

Atmosphere-ocean RCM for the Mediterranean basin
utmea.enea.it/research/PROTHEUS/



Artale et al., *Climate Research*, 2012



Components of the regional model

RegCM3

18 sigma vertical levels

30 Km horizontal resolution

BATS + IRIS

BATS: Biosph.-Atmosph. Transfer Scheme

IRIS: interactive RIvers Scheme

HF-WF-Wind

SST

OASIS 3
Freq. 6h

MedMIT

42 vertical levels

1/8° x 1/8° horizontal resolution

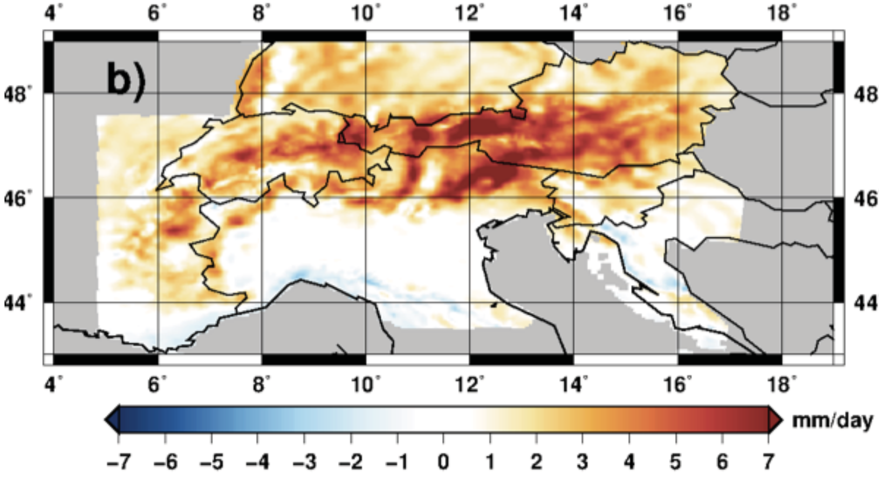
ATMOSPHERIC MODEL
30 km res.

COUPLER

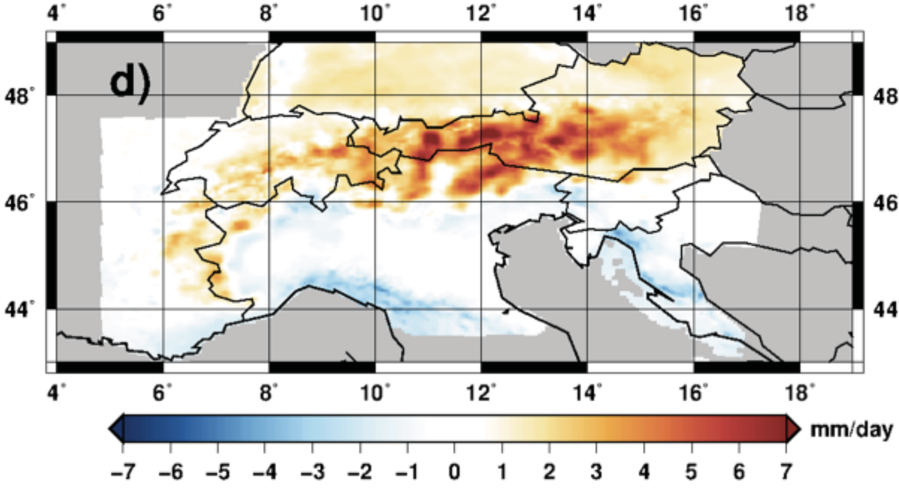
OCEANIC MODEL

Summer precipitation biases in the Alpine Region WRF 0.04°/0.11° vs. EURO4M

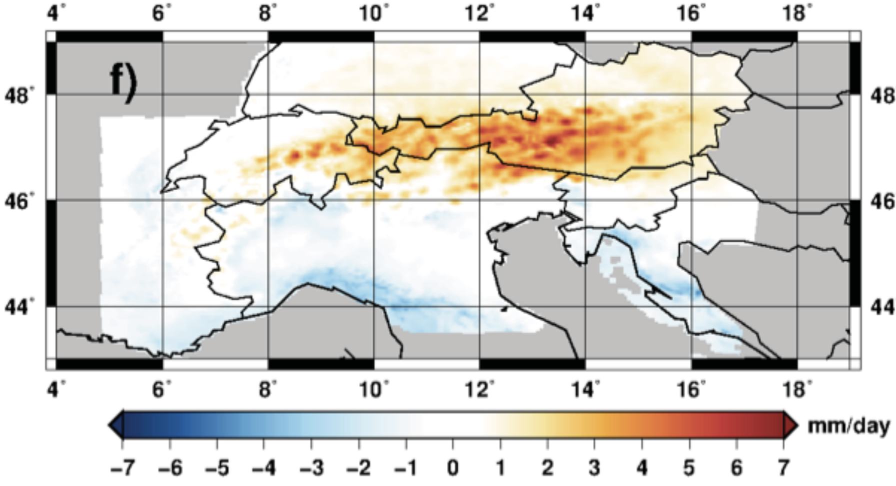
Kain-Fritsch, 0.11°

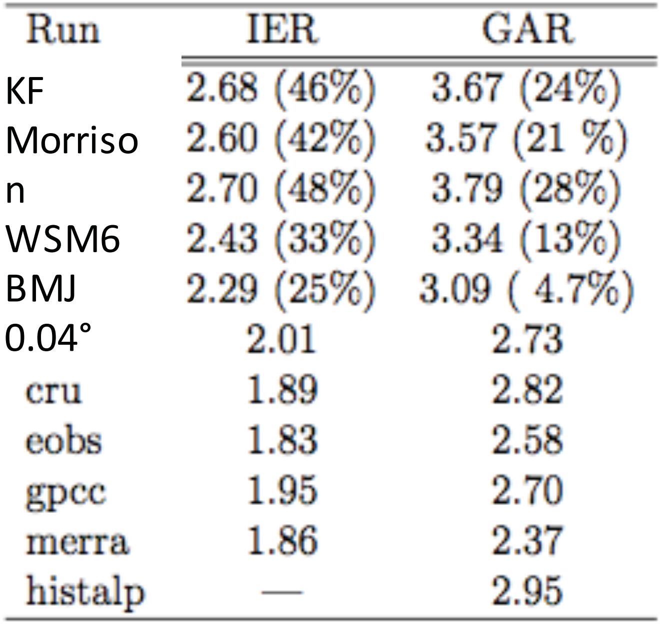


Betts- Miller-Janjic, 0.11°



Explicit convection, 0.04°

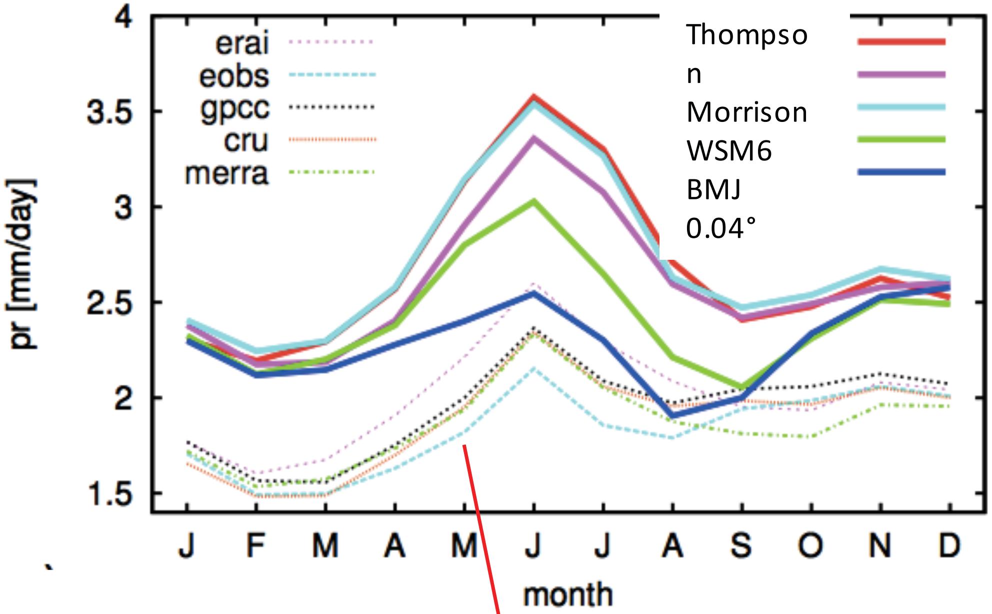




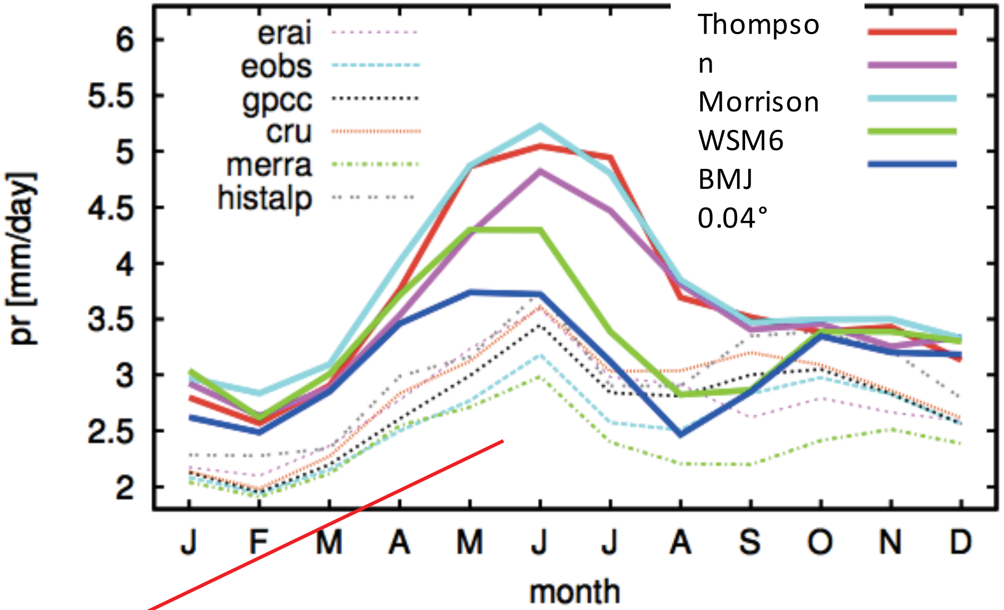
Run	IER	GAR
KF	2.68 (46%)	3.67 (24%)
Morrison	2.60 (42%)	3.57 (21 %)
	2.70 (48%)	3.79 (28%)
WSM6	2.43 (33%)	3.34 (13%)
BMJ	2.29 (25%)	3.09 (4.7%)
0.04°	2.01	2.73
cru	1.89	2.82
eobs	1.83	2.58
gpcc	1.95	2.70
merra	1.86	2.37
histalp	—	2.95

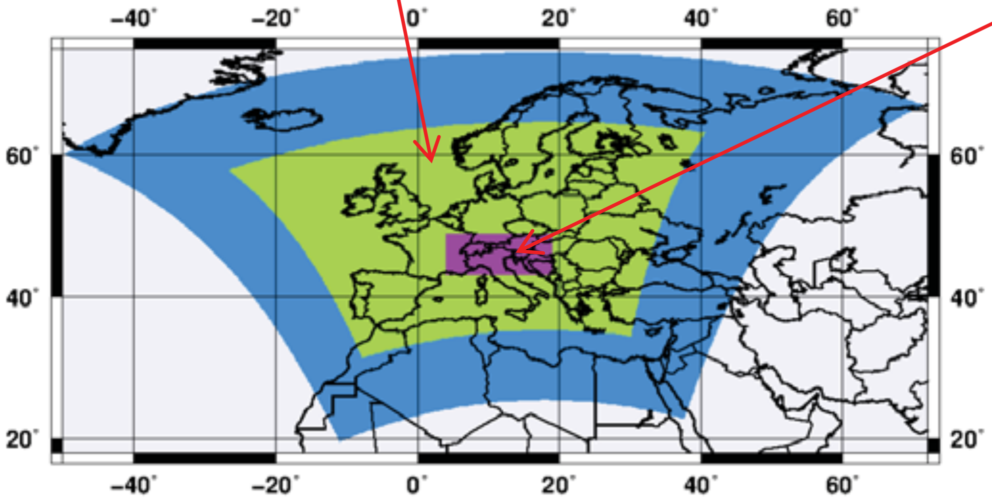
Precipitation seasonal cycle – sensitivity to parameterizations

European domain



Greater Alpine Region

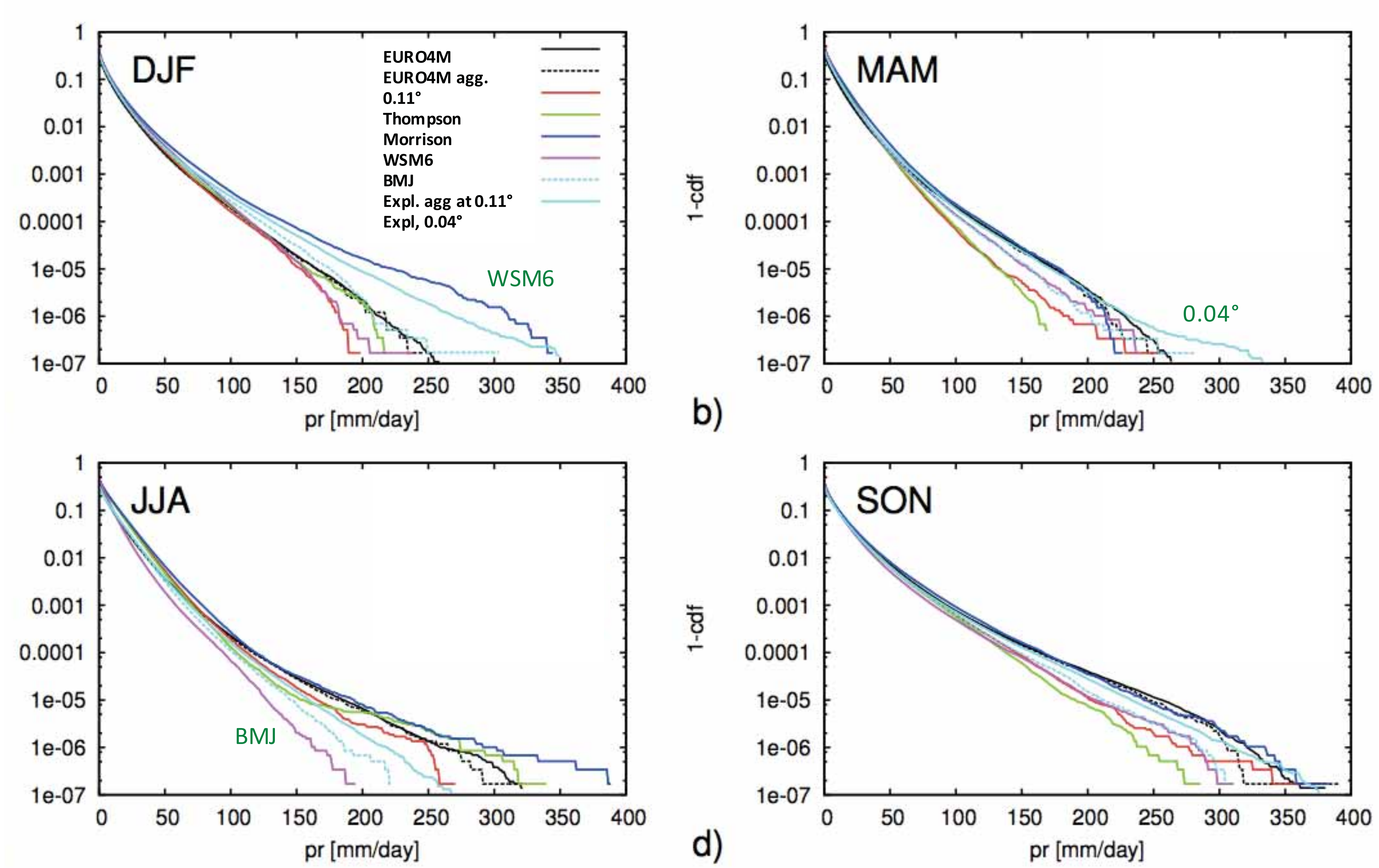




- The 0.04° run with explicit convection manages to reproduce JJA precipitation averages compatible with observed.
- Different microphysics → no improvement in winter, role of humidity transport

** Pieri A., von Hardenberg J., Parodi A., Provenzale A.: Sensitivity of precipitation statistics to resolution, microphysics and convective parameterization: a case study with the high-resolution WRF climate model over Europe, Journal of Hydrometeorology, sub judice.*

Probability of exceedence of precipitation thresholds in the GAR

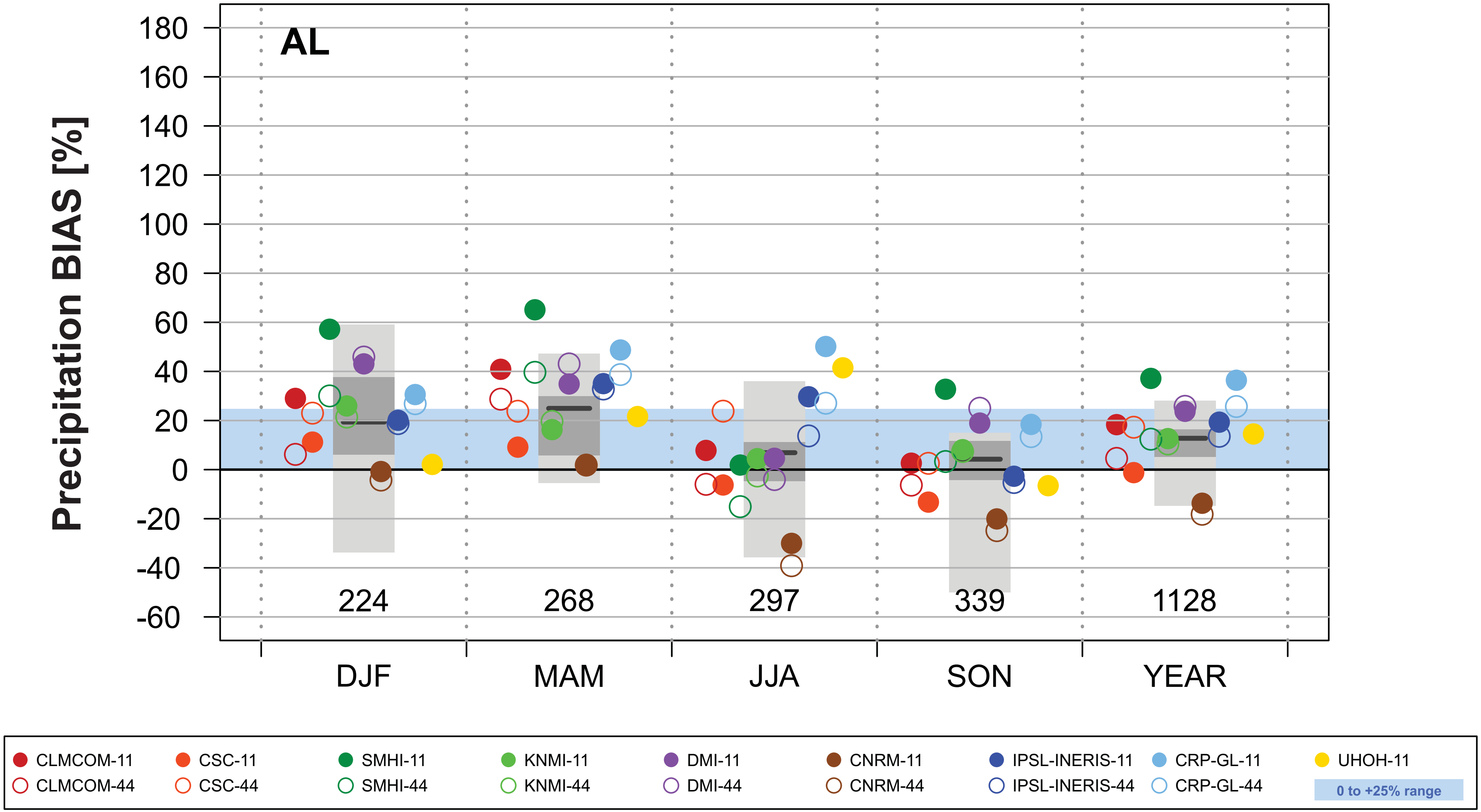


WSM6

0.04°

BMJ

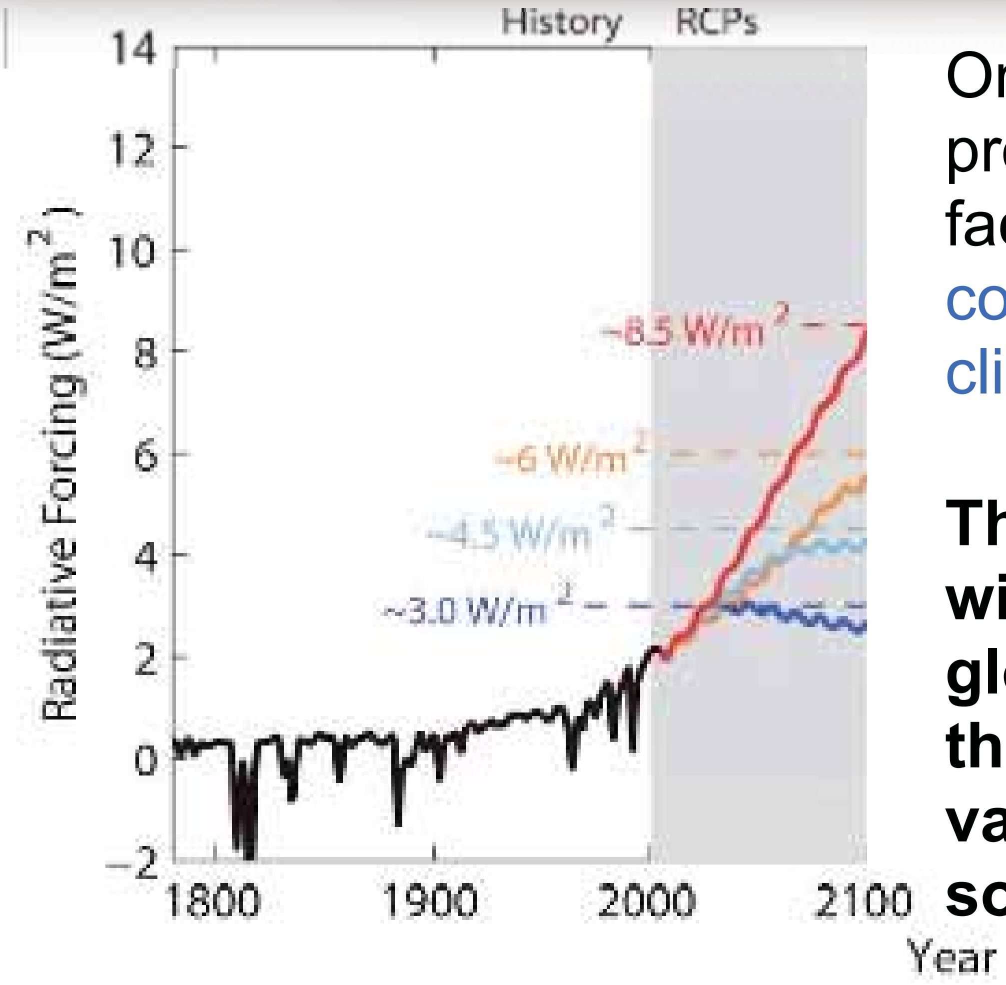
Biases of the Euro-CORDEX ensemble 1989-2008, BIAS wrt EOBS



Ref: S. Kotlarski et al.: Regional climate modeling on European scales, Geosci. Model Dev., 7, 1297–1333, 2014

Global Climate Projections

Scenarios and future projections

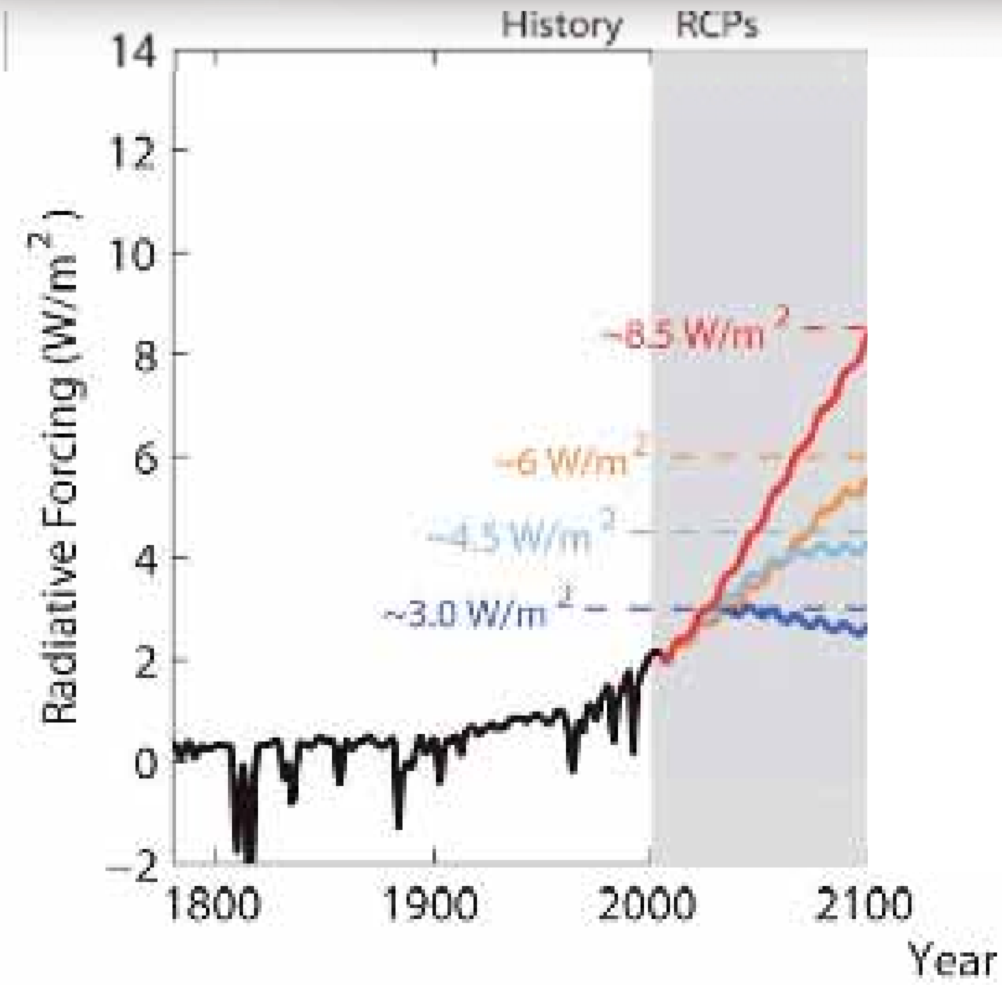


Once a model is validated it is run to produce **projections using**, as forcing factors, possible or expected future conditions of the main drivers of the climate system.

This is the meaning of "scenario": with the model we want to determine global climate conditions in case of the emission of GHG take certain values, in case of land use changes, socio-economic choices, etc.

Representative Concentration Pathways (RCPs), used in the IPCC AR5, encompass a range of plausible futures

Scenarios and future projections



Representative Concentration Pathways (RCPs) SCENARIOS

RCP8.5

One high pathway for which radiative forcing reaches values greater than 8.5 W/m^2 by 2100 and continues to rise for some amount of time

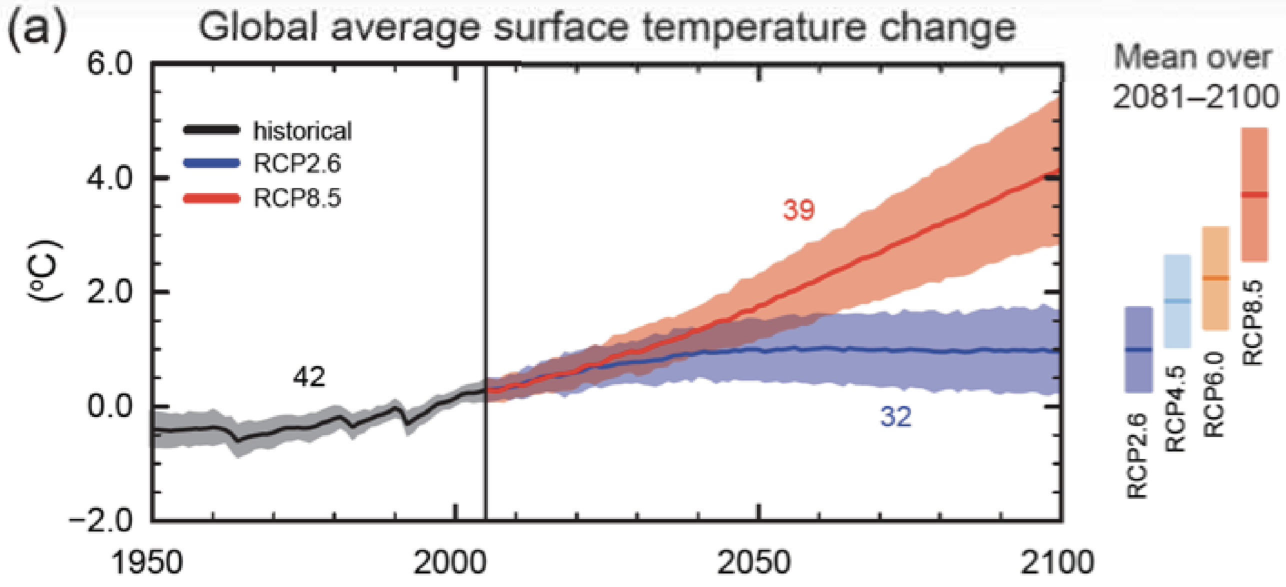
RCP6.0 and **RCP4.5**

Two *stabilization pathways* in which radiative forcing is stabilized at approximately 6 W/m^2 and 4.5 W/m^2 after 2100

RCP2.6

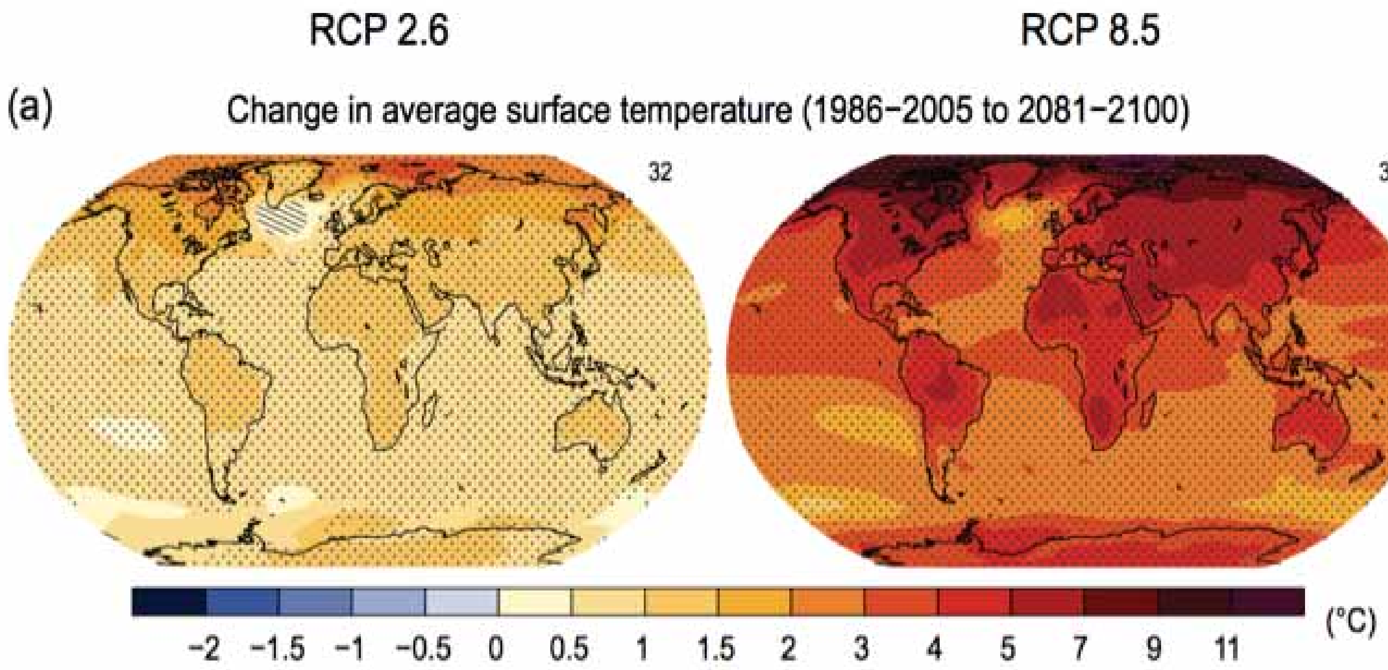
One pathway where radiative forcing peaks at approximately 3 W/m^2 before 2100 and then declines (Mitigation scenario).

Future projections



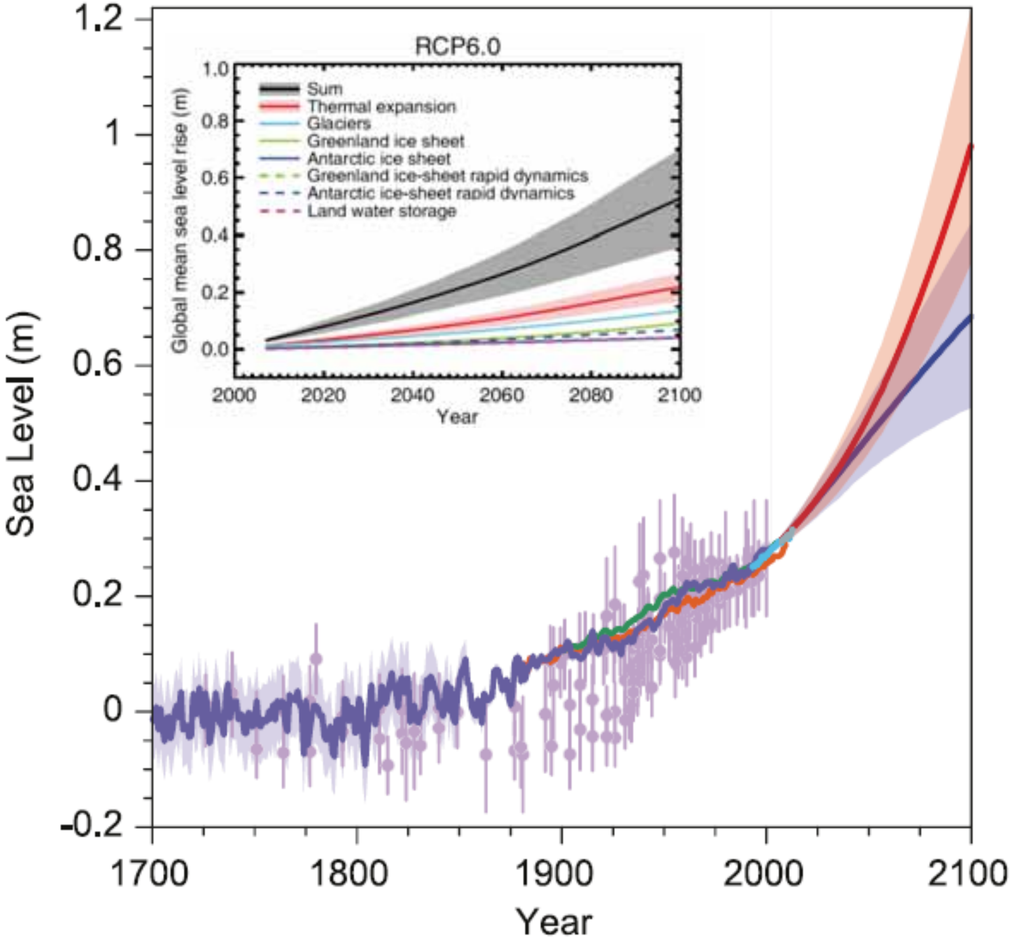
Global temperatures are likely to exceed 1.5°C for all RCPs except RCP 2.6 by the end of the 21st century and likely to exceed 2°C for RCP 6.0 and RCP 8.5

Not a regionally uniform warming: the Arctic region is expected to continue to warm more than the global average and warming over land regions will be larger than over oceans



Future projections

Past and future sea-level rise



For the past, proxy data are shown in light purple and tide gauge data in blue. For the future, the IPCC projections for very high emissions (red, RCP8.5 scenario) and very low emissions (blue, RCP2.6 scenario) are shown.
Source: IPCC AR5 Fig. 13.27.

SEA LEVEL RISE

(1) Global sea level is rising
(2) The rise has accelerated since pre-industrial times
(3) The rise will accelerate further in this century.

For high emissions IPCC now predicts a global rise by **45-82 cm** by the year 2100, which would **threaten the survival of coastal cities and entire island nations**.

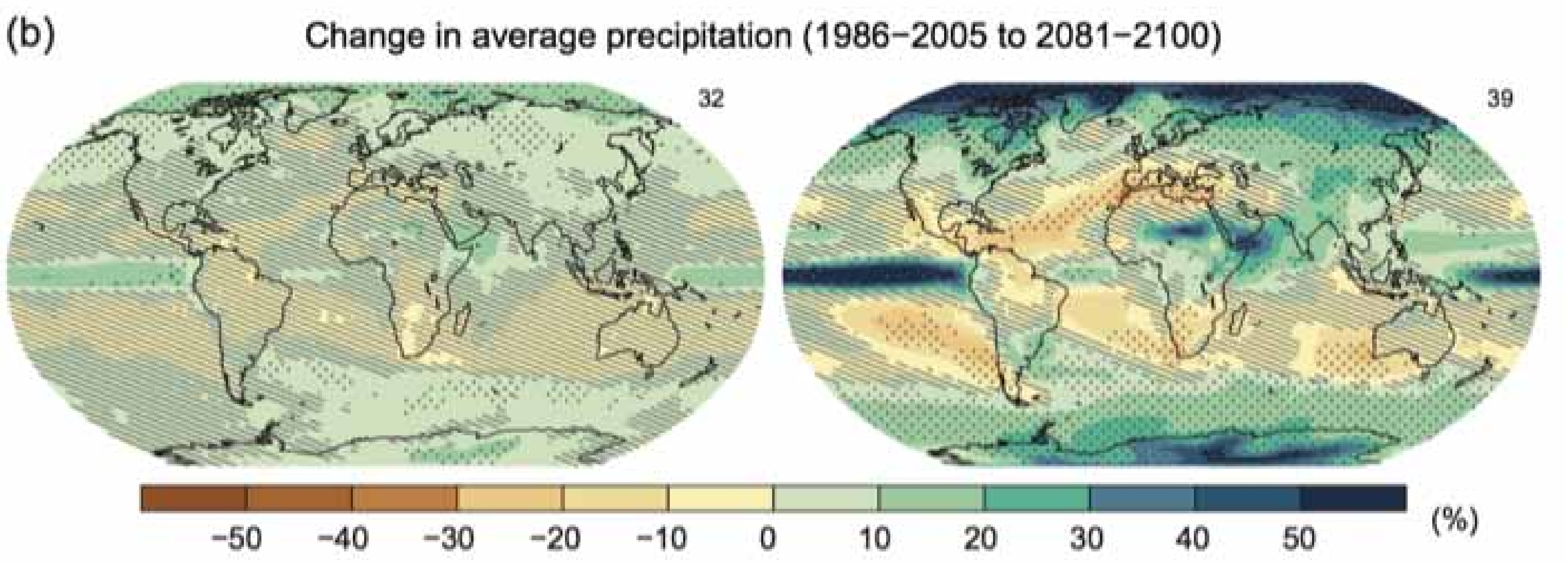
Even under a highly optimistic scenario, a rise by **26-55 cm** is predicted, with serious potential **impacts on many coastal areas, including coastal erosion and a greatly increased risk of flooding.**

Future projections

PRECIPITATION

The contrast between wet and dry regions and wet and dry seasons is expected to increase (with some regional exceptions)

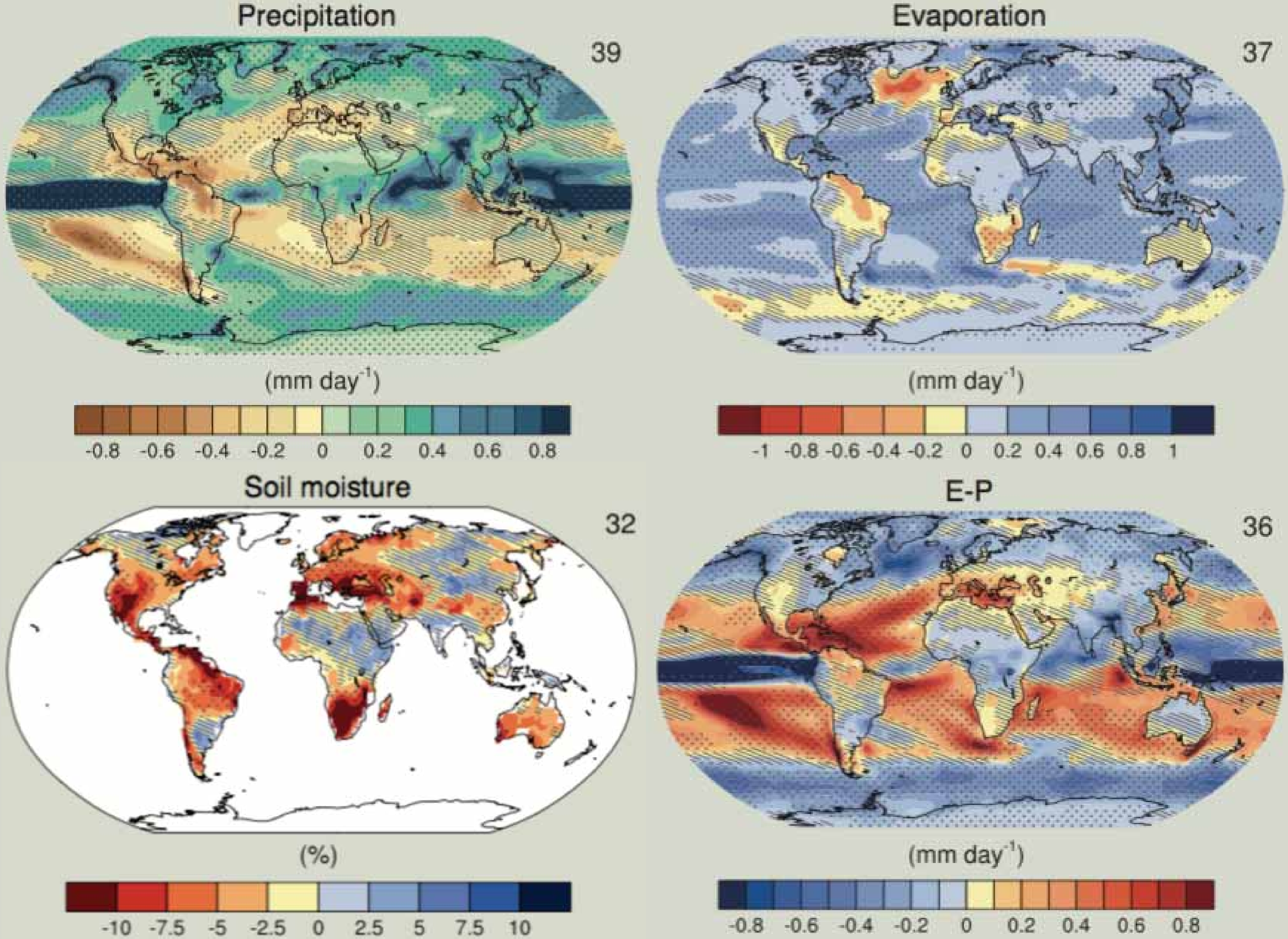
RCP 2.6 **RCP 8.5**



Regions between 15°-40° drier

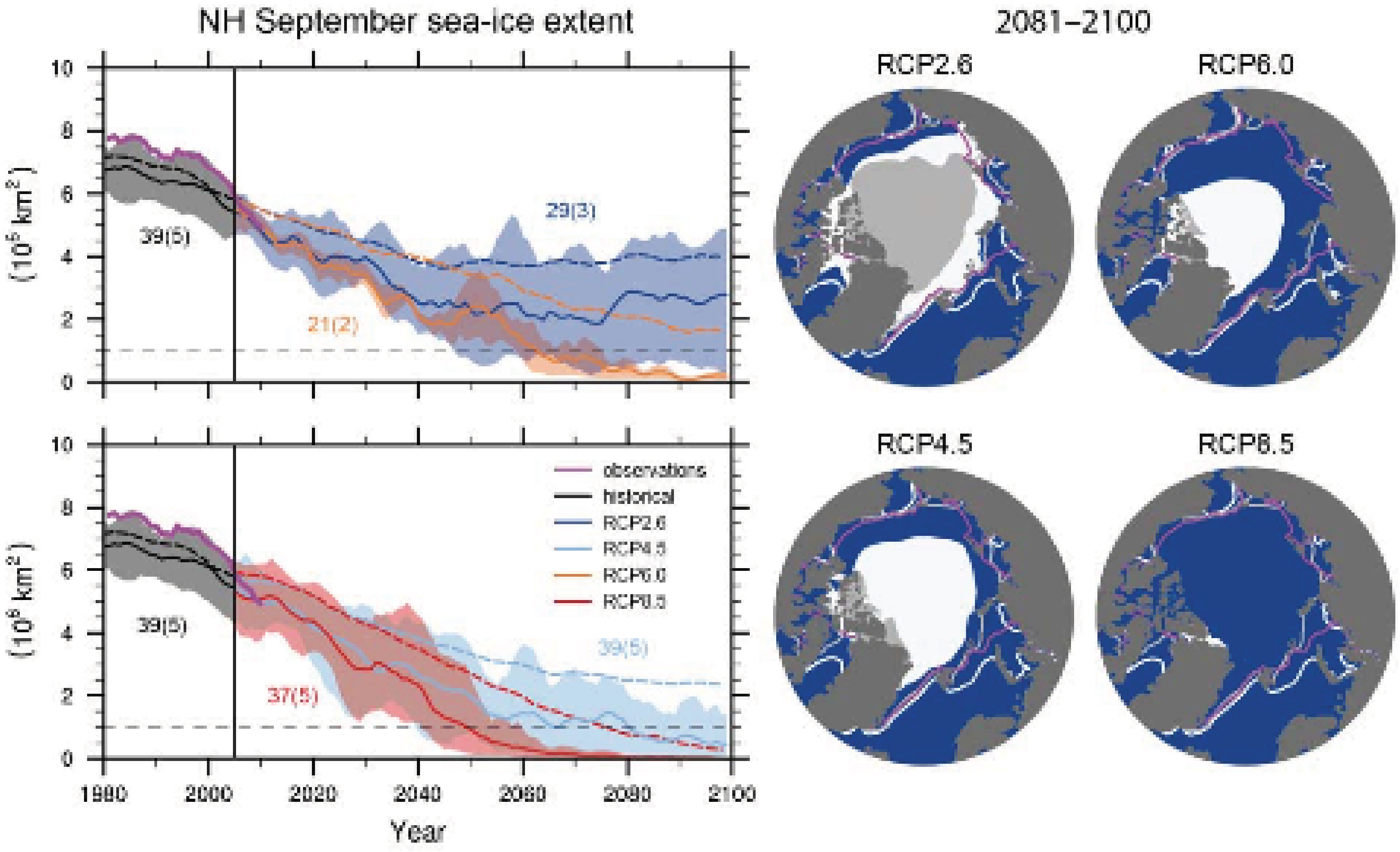
Higher precipitations at high latitudes

Annual mean hydrological cycle change (RCP8.5: 2081-2100)



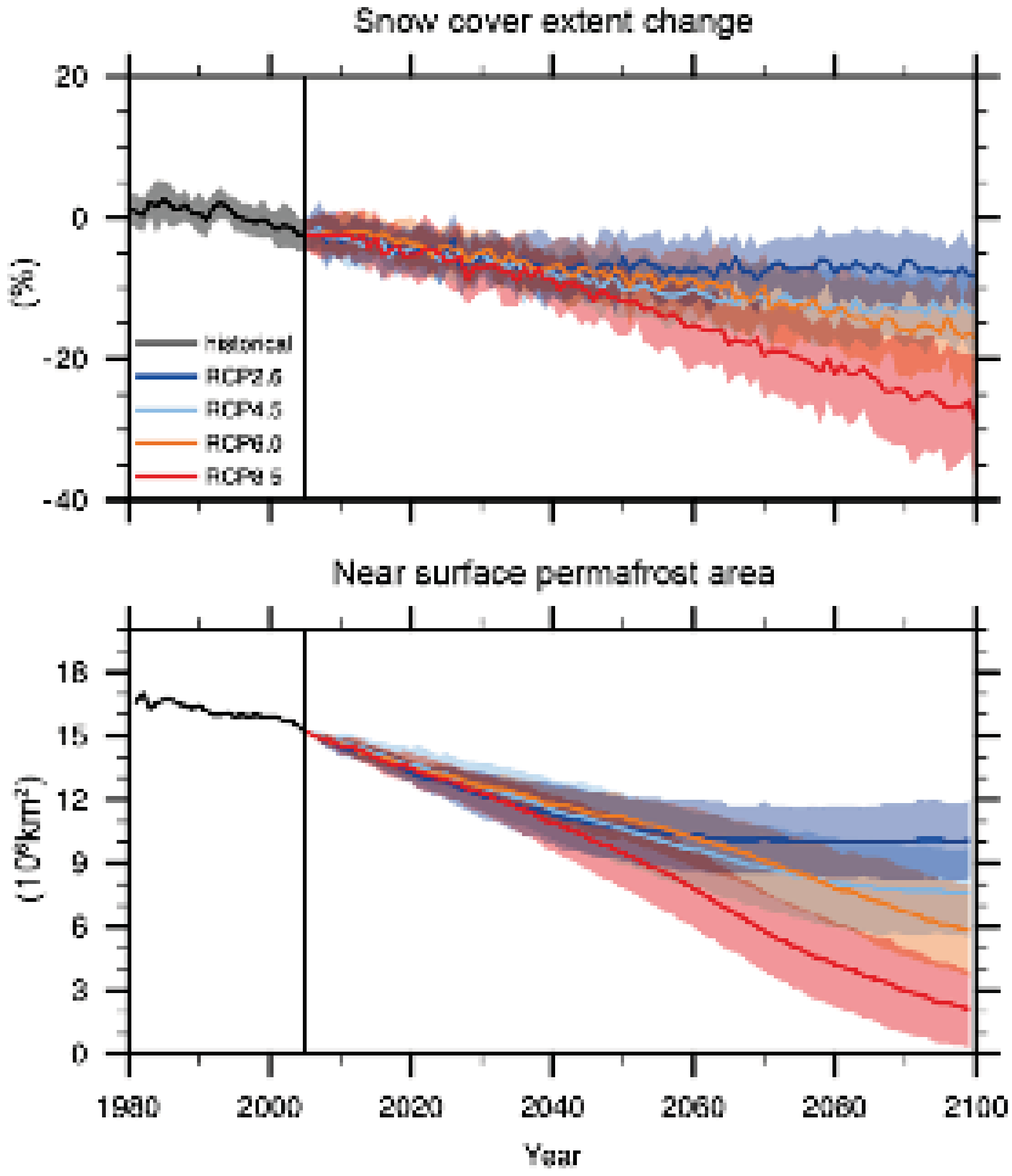
Future projections

SEA ICE EXTENT

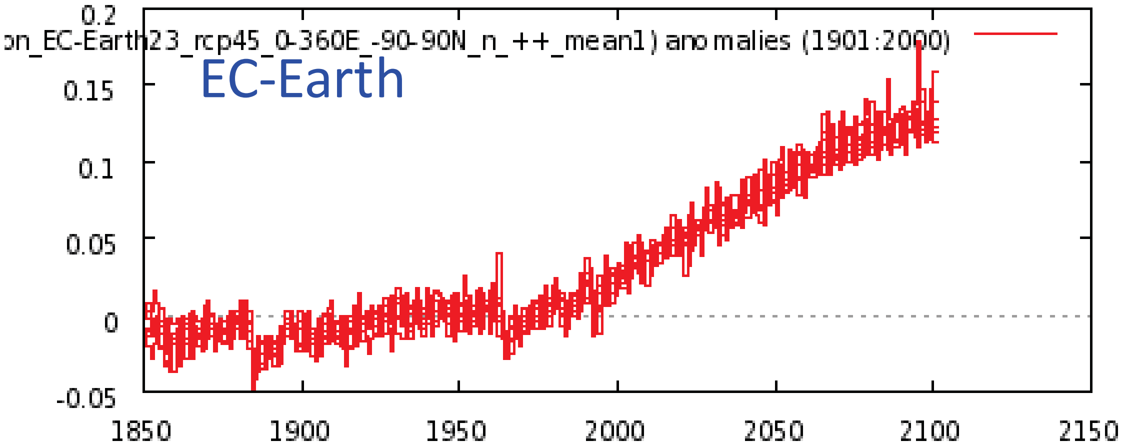


Future projections

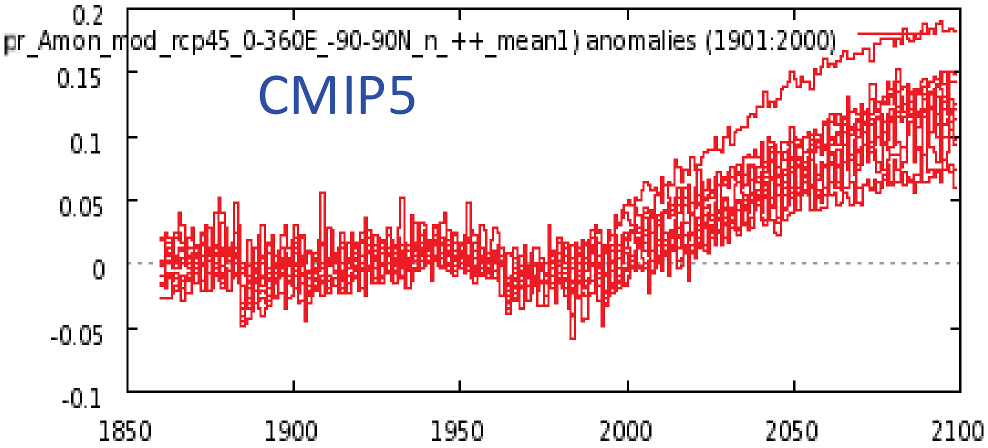
SNOW COVER EXTENT



Global Precipitation (RCP 4.5)

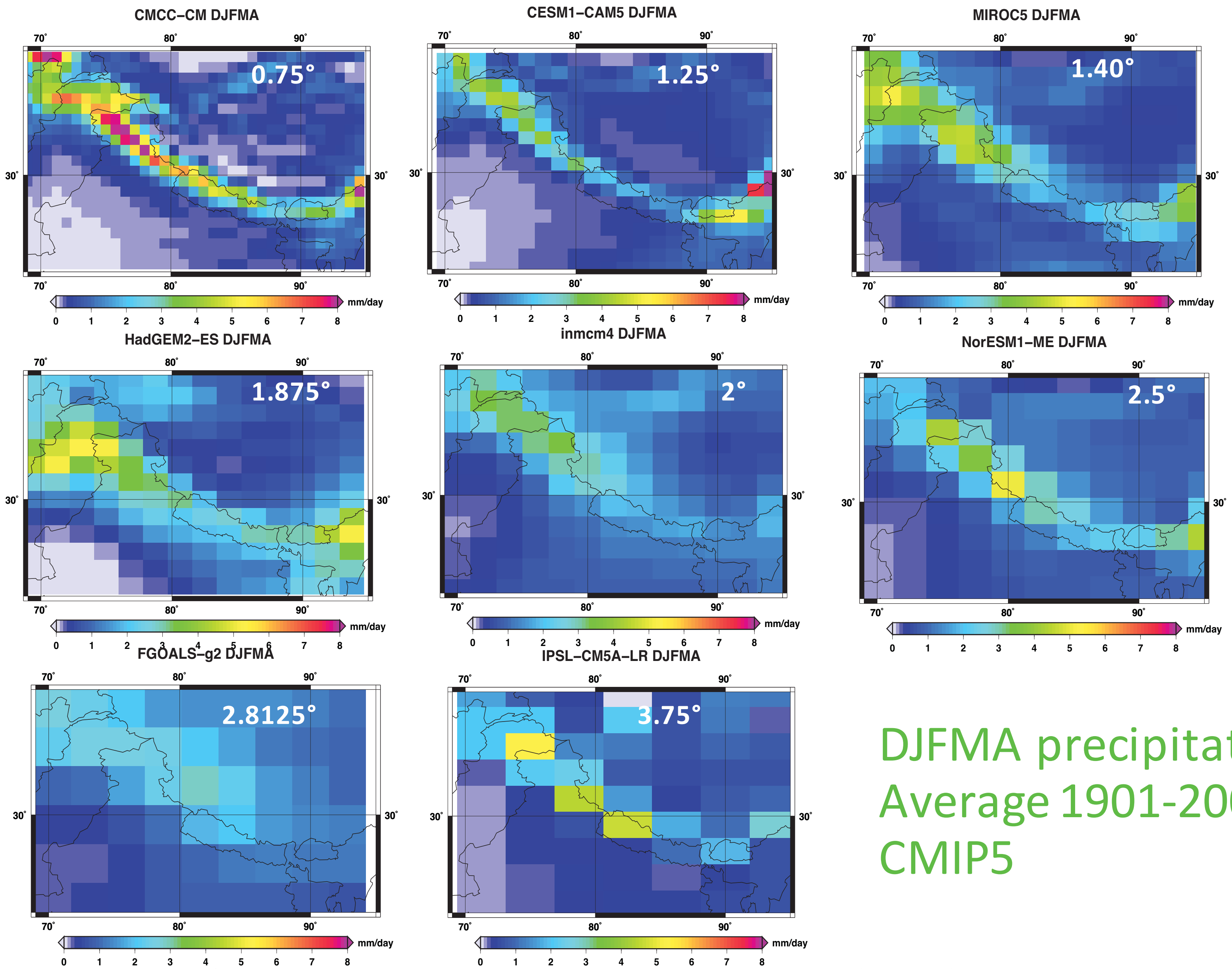


Natural/internal variability



Model uncertainty

Spread between CMIP5 models

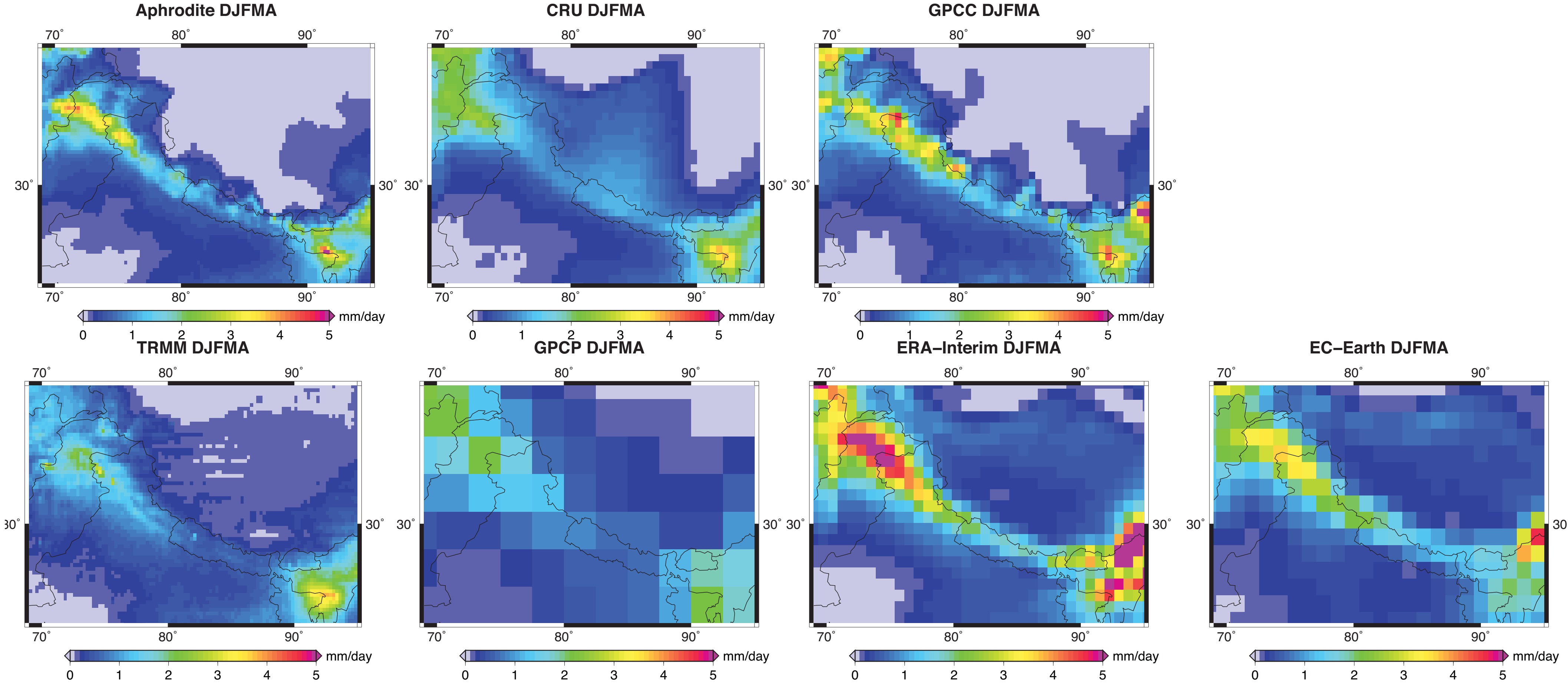


DJFMA precipitation
Average 1901-2005
CMIP5

* *Palazzi E., J. von Hardenberg, S. Terzago, A. Provenzale. 2014. Precipitation in the Karakoram-Himalaya: A CMIP5 view, Climate Dynamics, doi: 10.1007/s00382-014-2341-z*

Uncertainties in observational data

Winter precipitation (DJFMA), Multiannual average 1998-2007

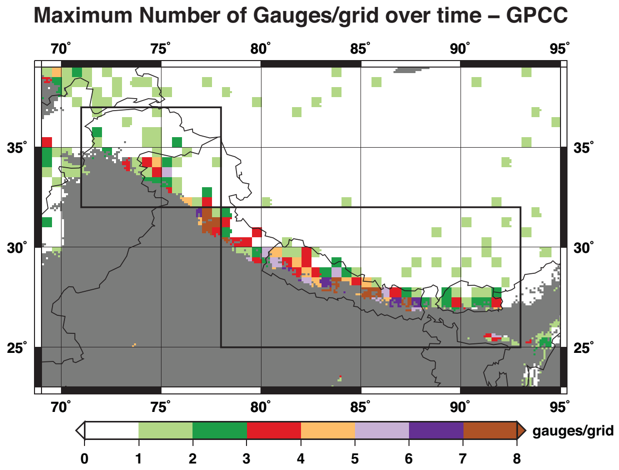


** Palazzi, E., J. von Hardenberg, and A. Provenzale. 2013. Precipitation in the Hindu-Kush Karakoram Himalaya: Observations and future scenarios, J. Geophys. Res. Atmos., 118, 85–100*

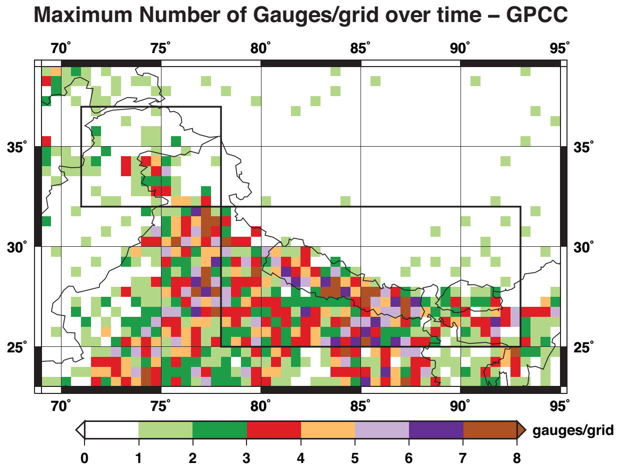
** Filippi, L., Palazzi, E., von Hardenberg, J. & Provenzale, A. 2014. Multidecadal Variations in the Relationship between the NAO and Winter Precipitation in the Hindu-Kush Karakoram. Journal of Climate (2014). doi:10.1175/JCLI-D-14-00286.1,*

Precipitation datasets & issues

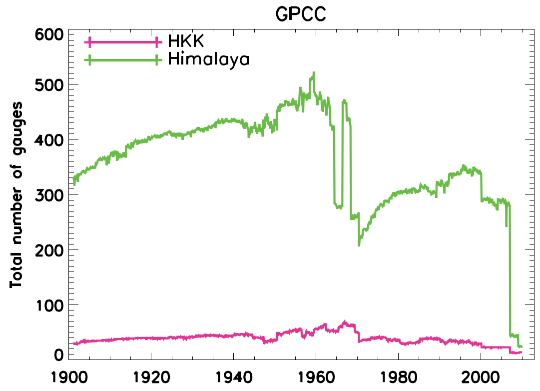
Maximum number of gauges/pixel (1901-2013). Elevation > 1000 m a.s.l.


Maximum Number of Gauges/grid over time – GPCC

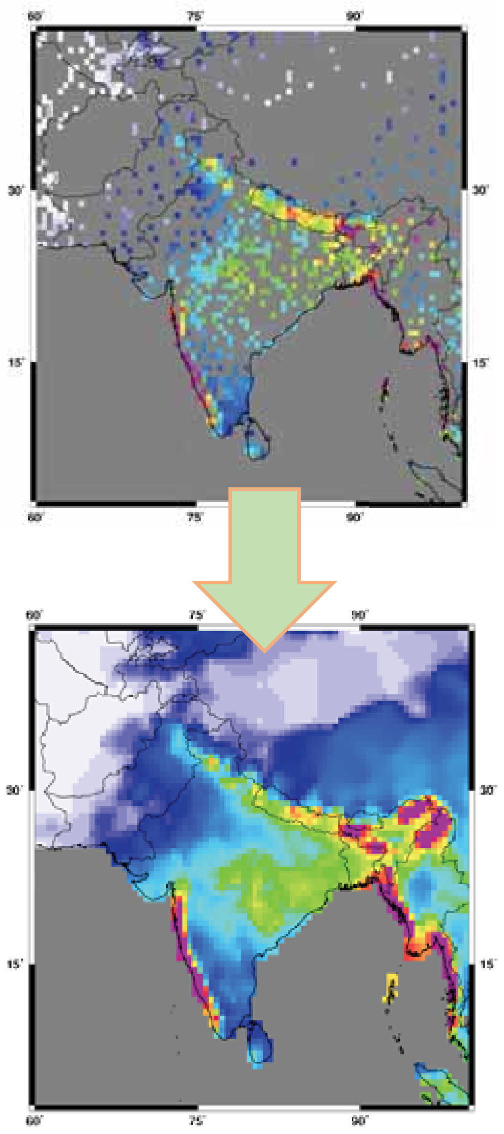
Maximum number of gauges/pixel (1901-2013).


Maximum Number of Gauges/grid over time – GPCC

Time series of the total number of gauges in the HKK and Himalaya


GPCC

GPCC raw

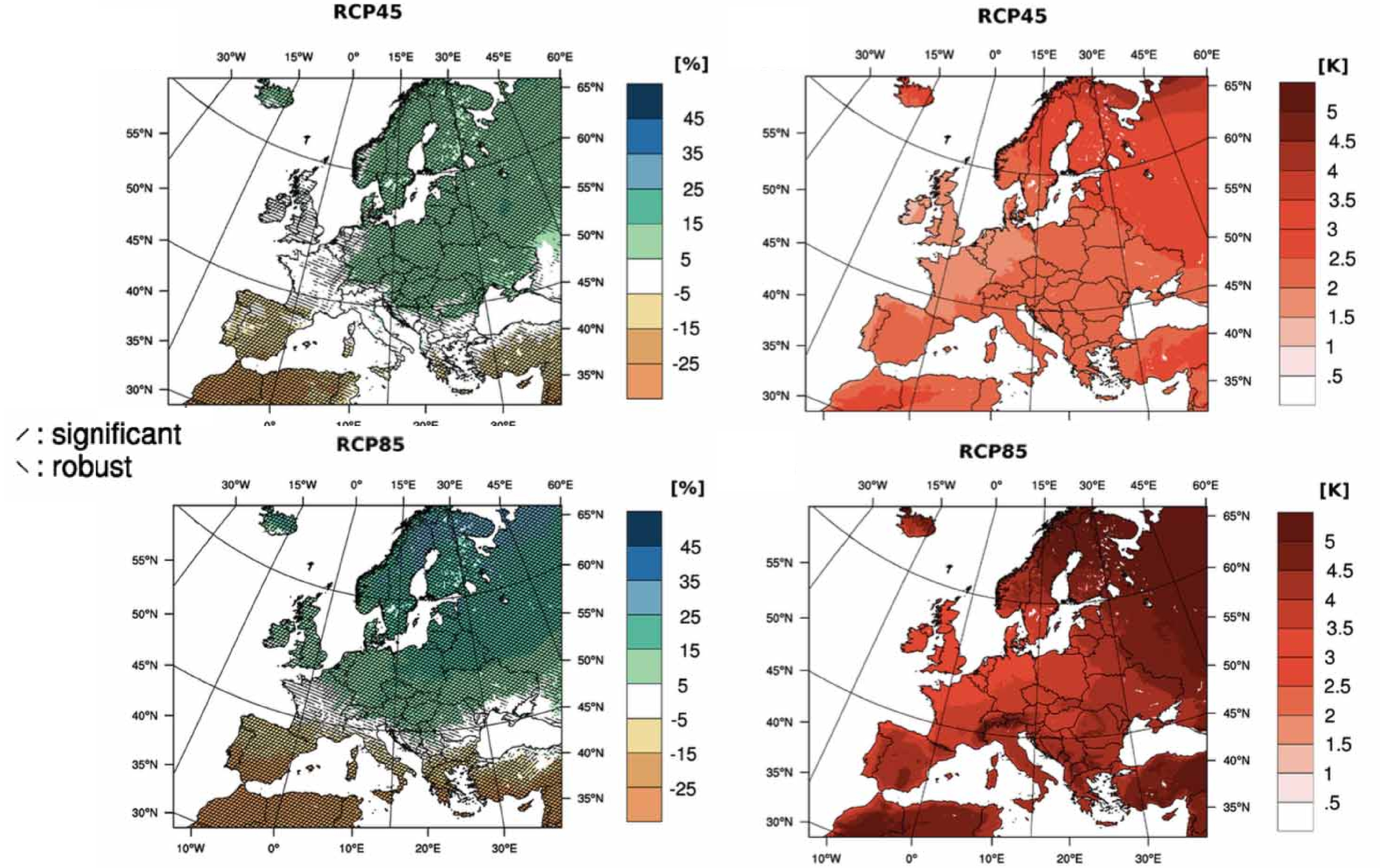


GPCC interpolated

GPCC Gridded dataset

Regional Climate Projections

Projected changes from the EURO-CORDEX ensemble (2071-2100 vs. 1971-2000)



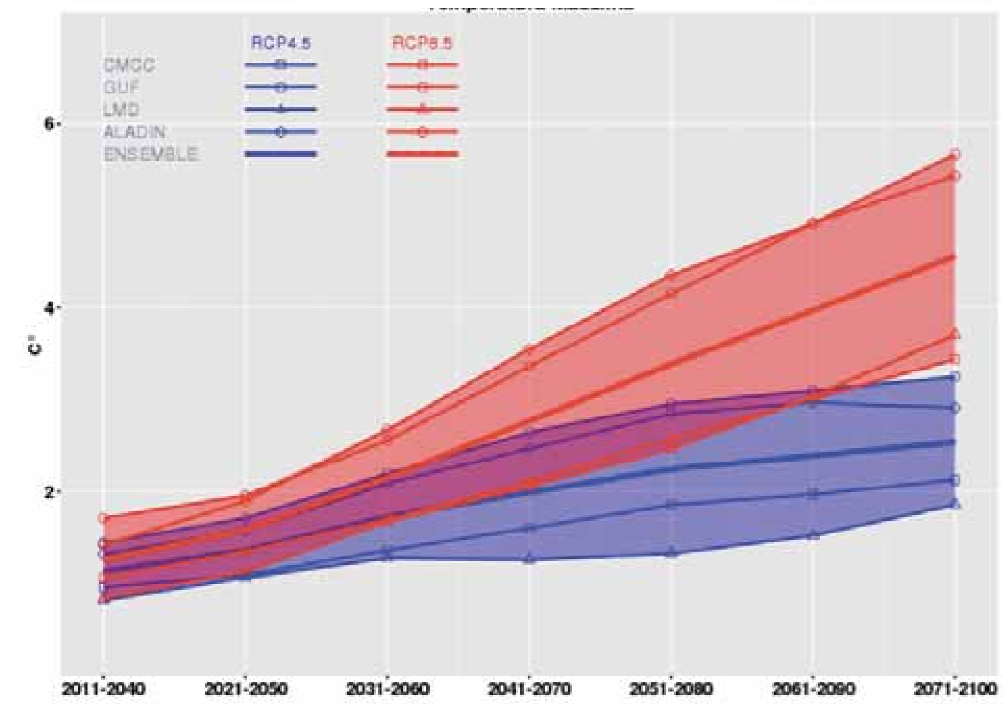
Precipitation

Surface temperature

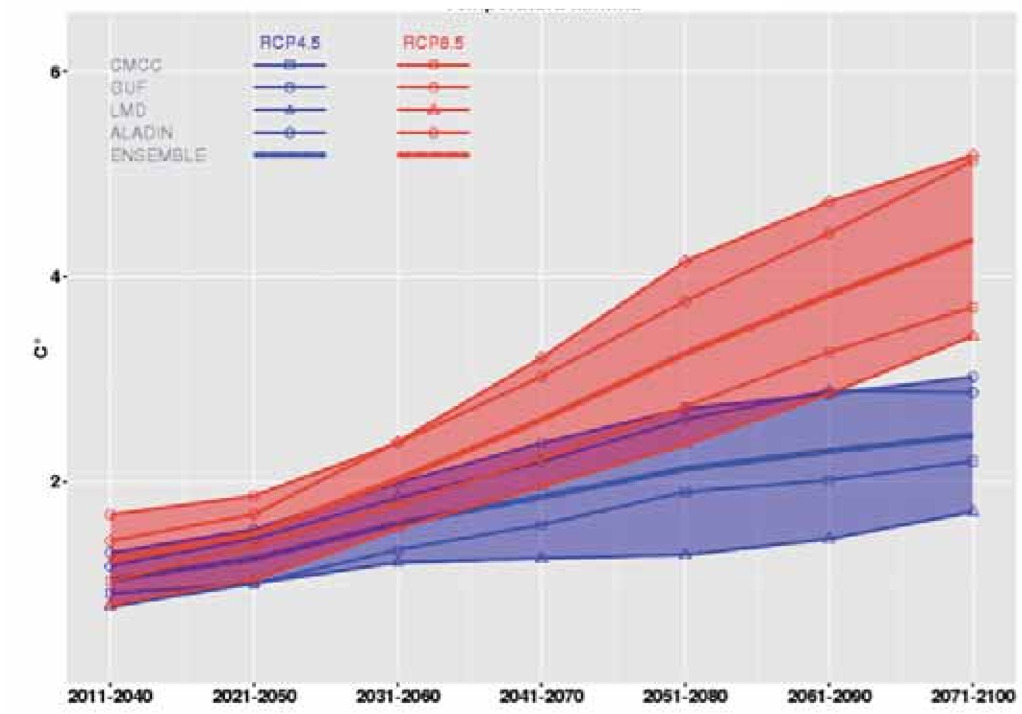
From: Jacob et al. Reg Environ Change (2014) 14:563–578

Temperature changes in Italy, 4 MED-Cordex models, wrt 1970-2000

Max temperature

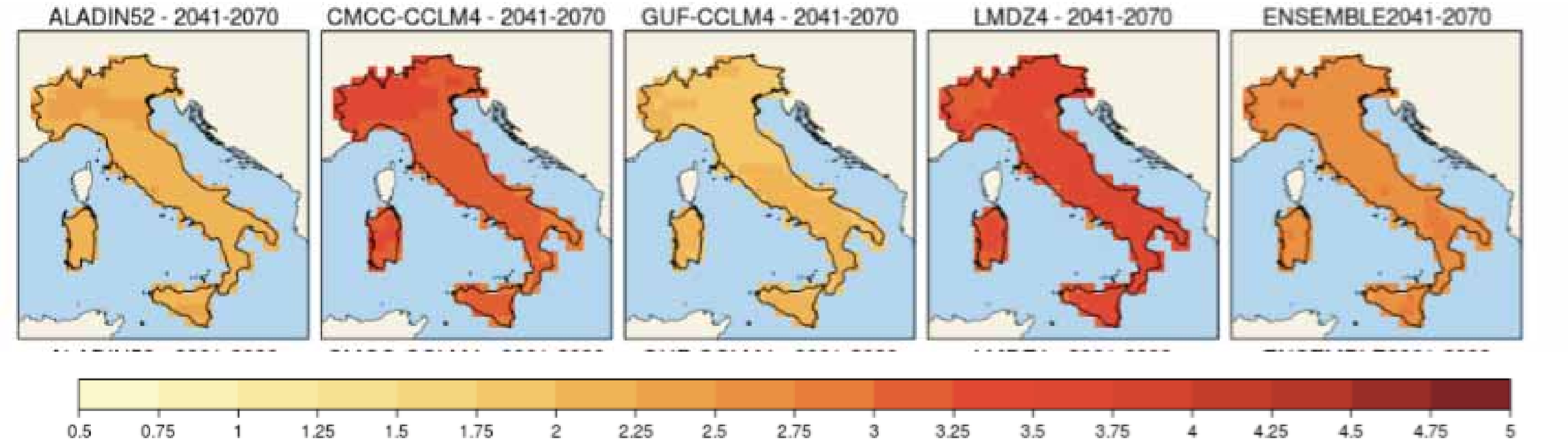


Min temperature

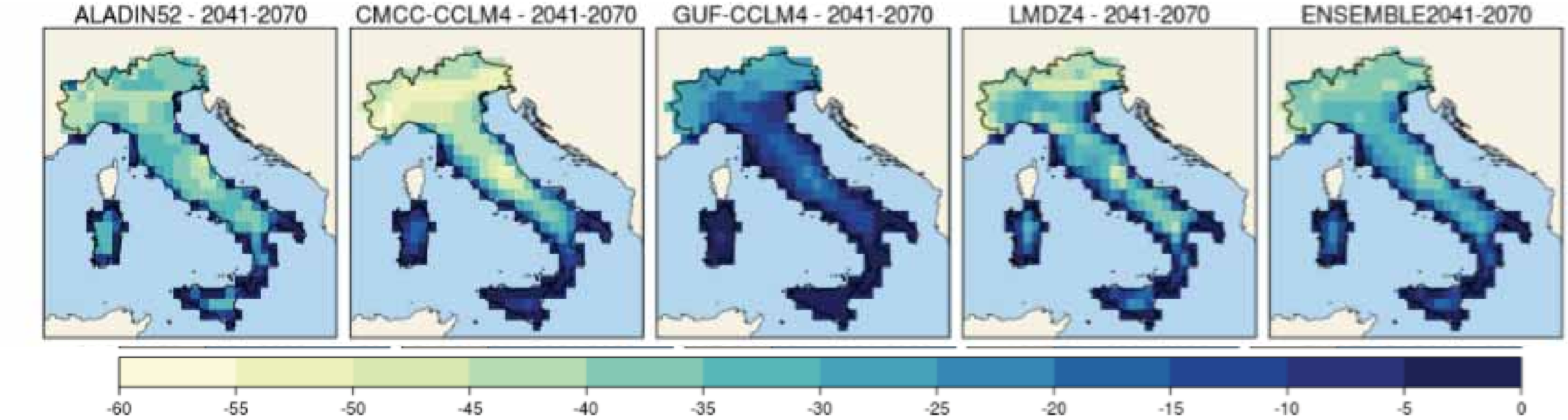


Projected changes (2041-2070) in Italy from 4 MED-Cordex models

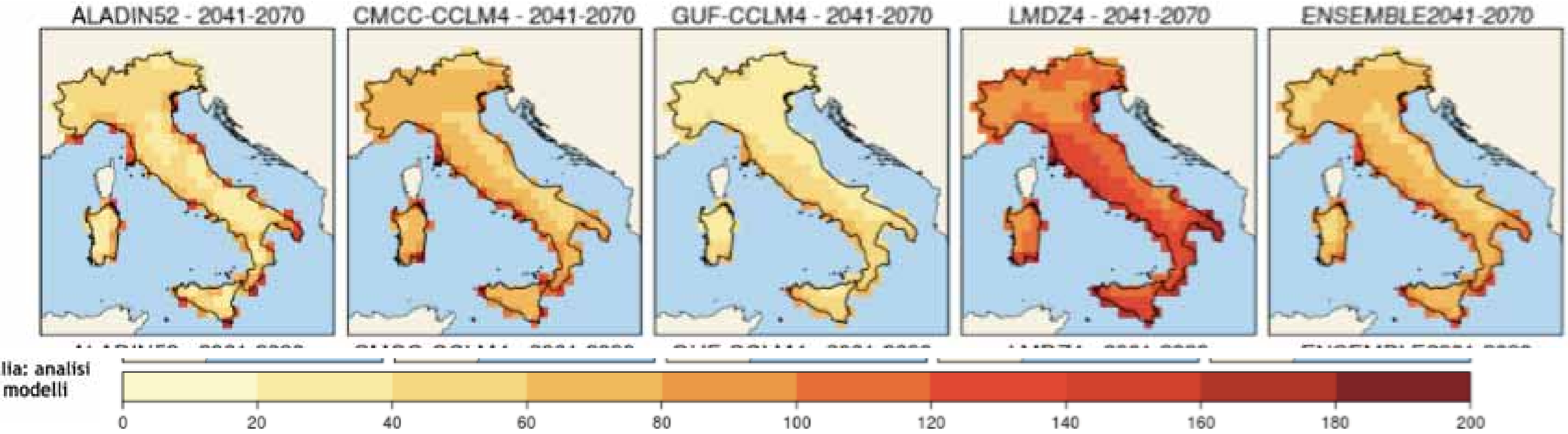
Surface temperature change (°C)



Freeze days change (% FD0)



Heat waves (days, WSDI)

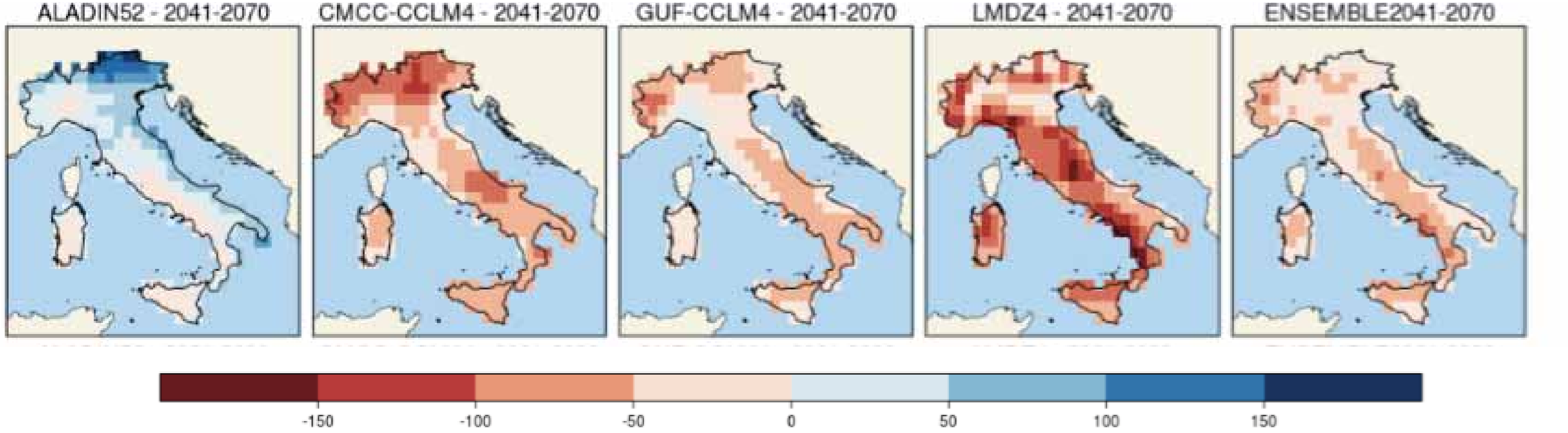


ISPRA Istituto Superiore per la Protezione e la Ricerca Ambientale

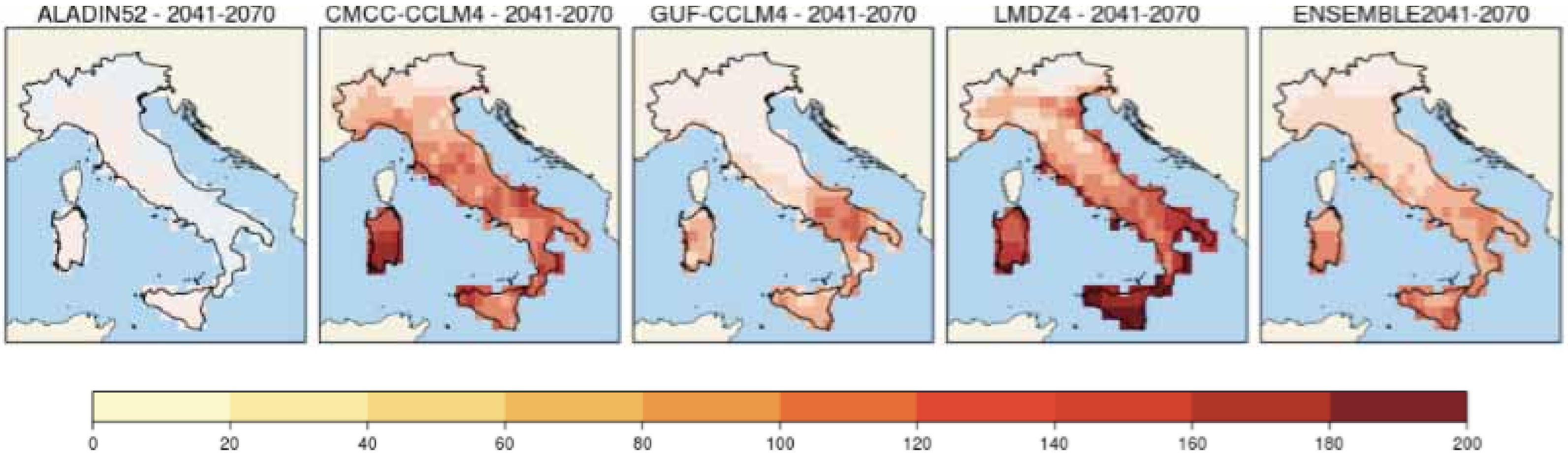
Il clima futuro in Italia: analisi delle proiezioni dei modelli regionali

Projected changes (2041-2070) in Italy from 4 MED-Cordex models

Precipitation (mm)



Max number of days
with no rain
per year (days)



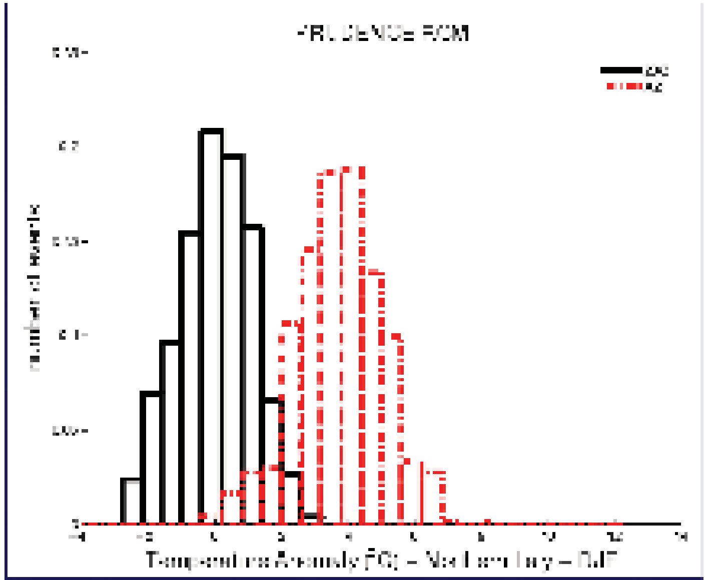
Il clima futuro in Italia: analisi
delle proiezioni dei modelli
regionali

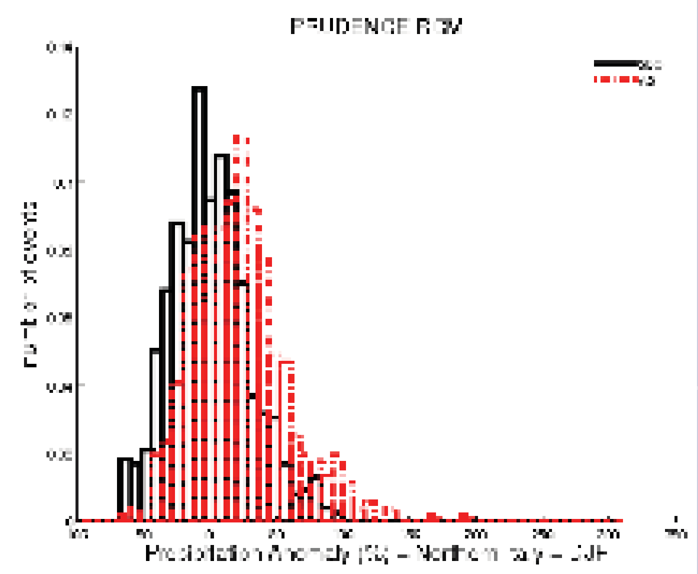
Distribution of seasonal anomalies over Northern Italy (10 PRUDENCE models, Scenario A2, 2070-2100)

Temperature

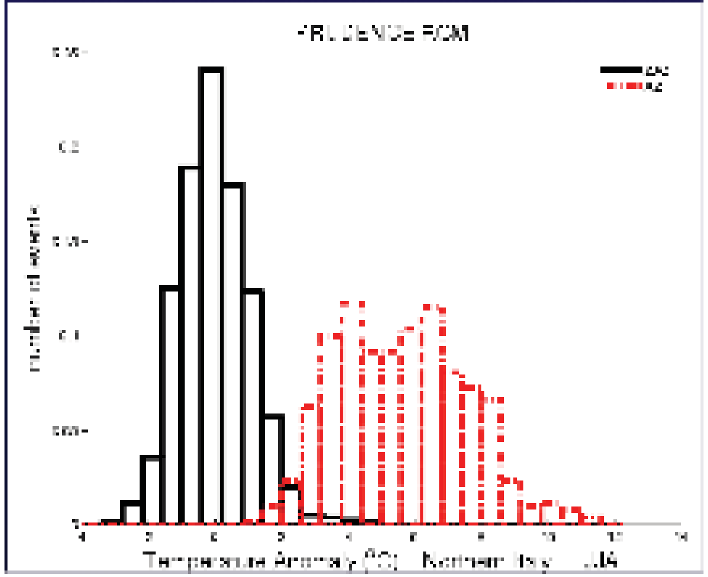
Precipitation

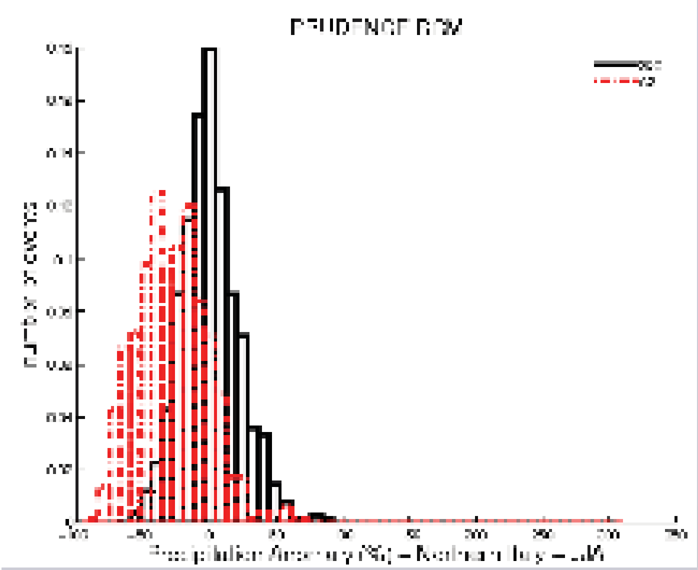
Winter





Summer

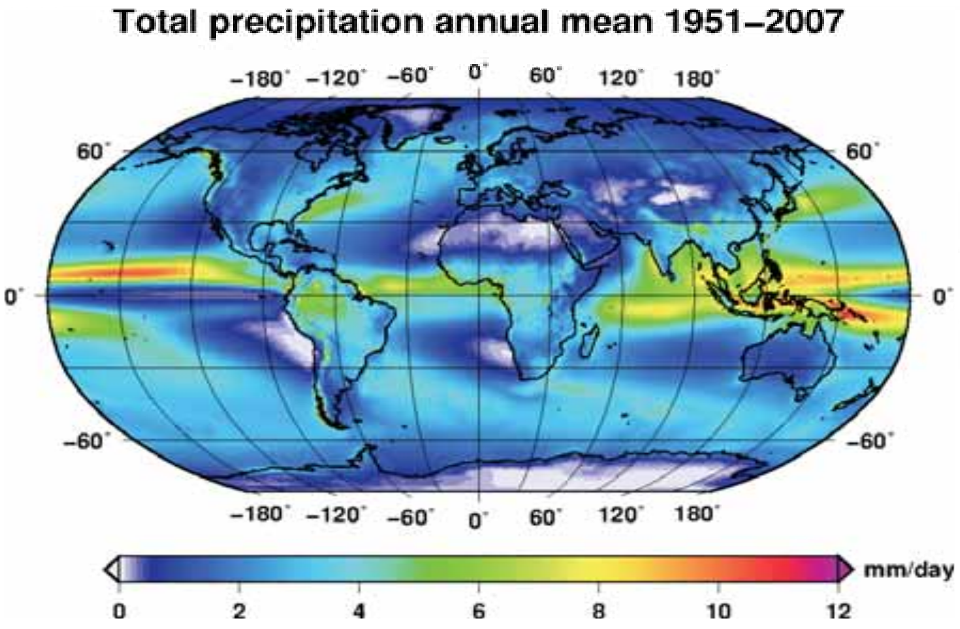




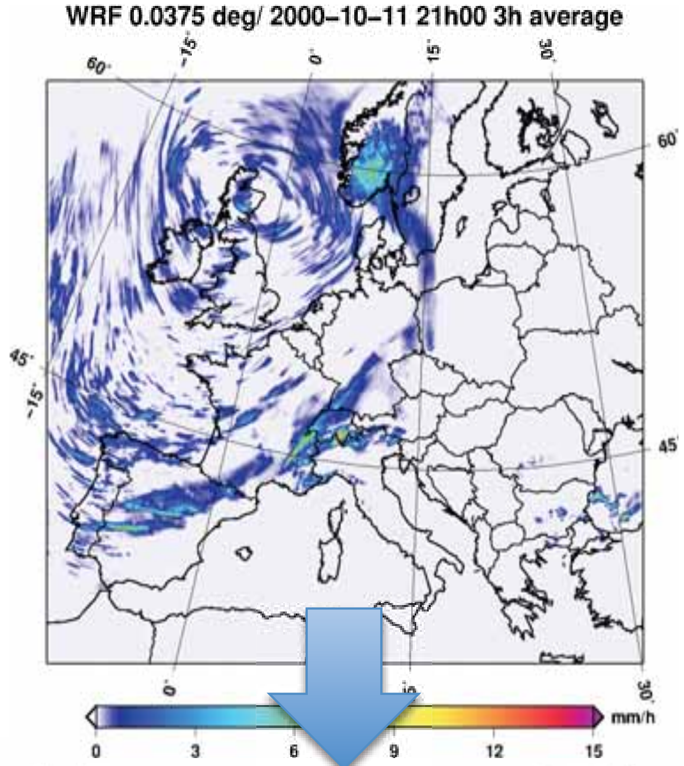
Stochastic Downscaling

The downscaling modelling chain

Global climate model



Regional climate model



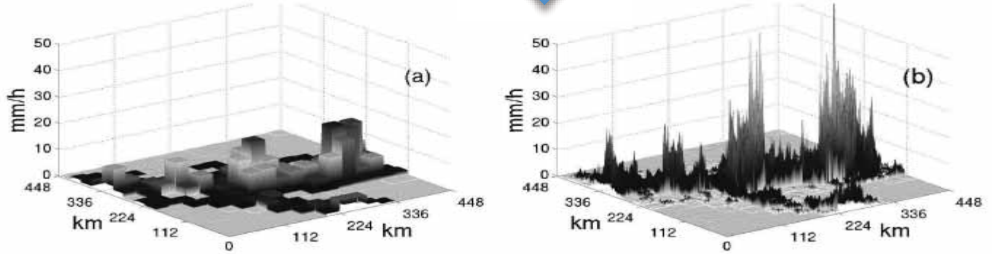
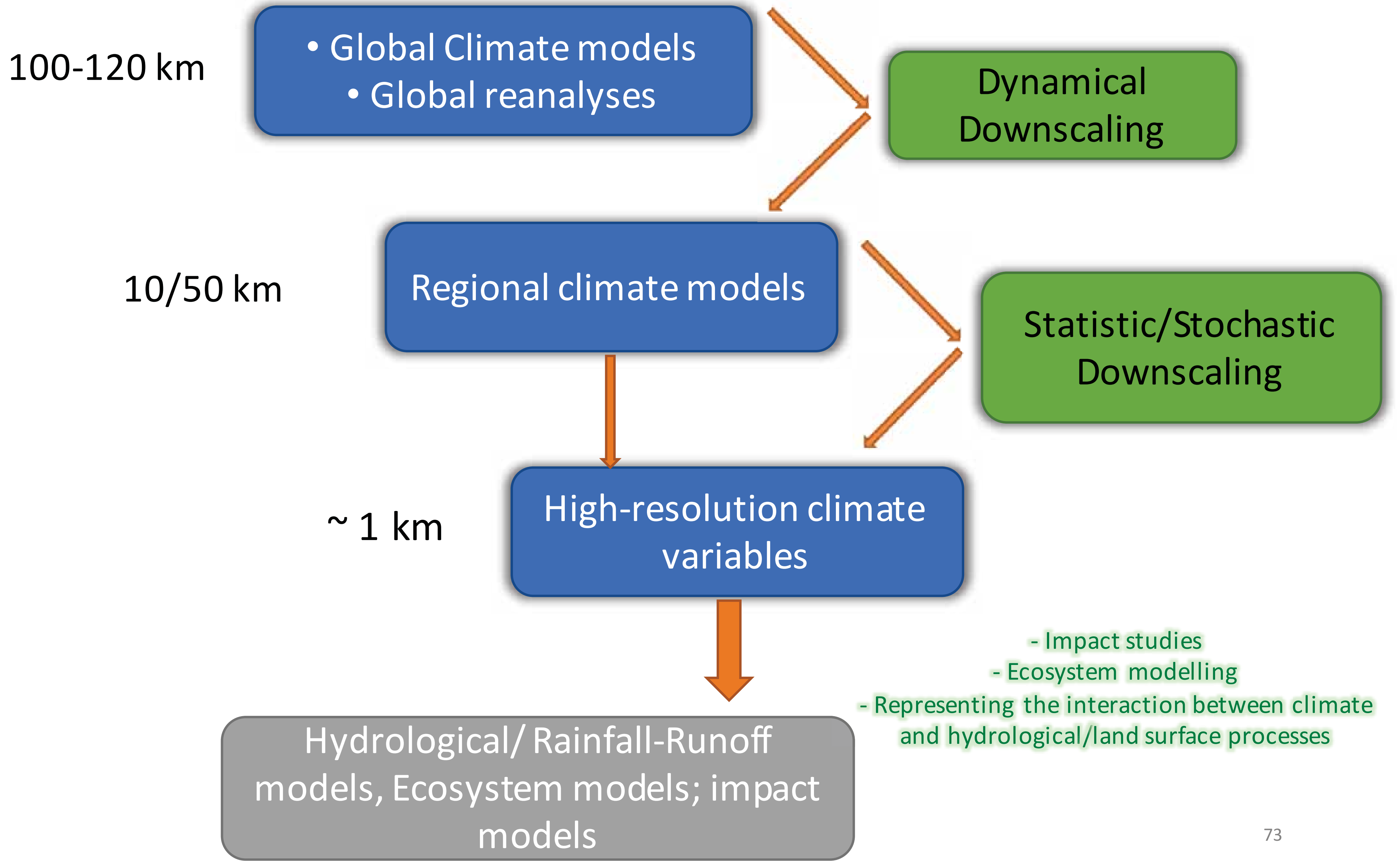


FIG. 10. (a) A snapshot of the forecasted rain field obtained from the LAM forecast and (b) one example of a downscaled field obtained by application of the RainFARM. The vertical scale indicates precipitation intensity (mm h^{-1}) and it is the same for the two fields.

Statistical/stochastic downscaling

Impact on eco-hydrological processes

Modeling chain: bridging the gap



100-120 km

- Global Climate models
- Global reanalyses

Dynamical Downscaling

10/50 km

Regional climate models

Statistic/Stochastic Downscaling

~ 1 km

High-resolution climate variables

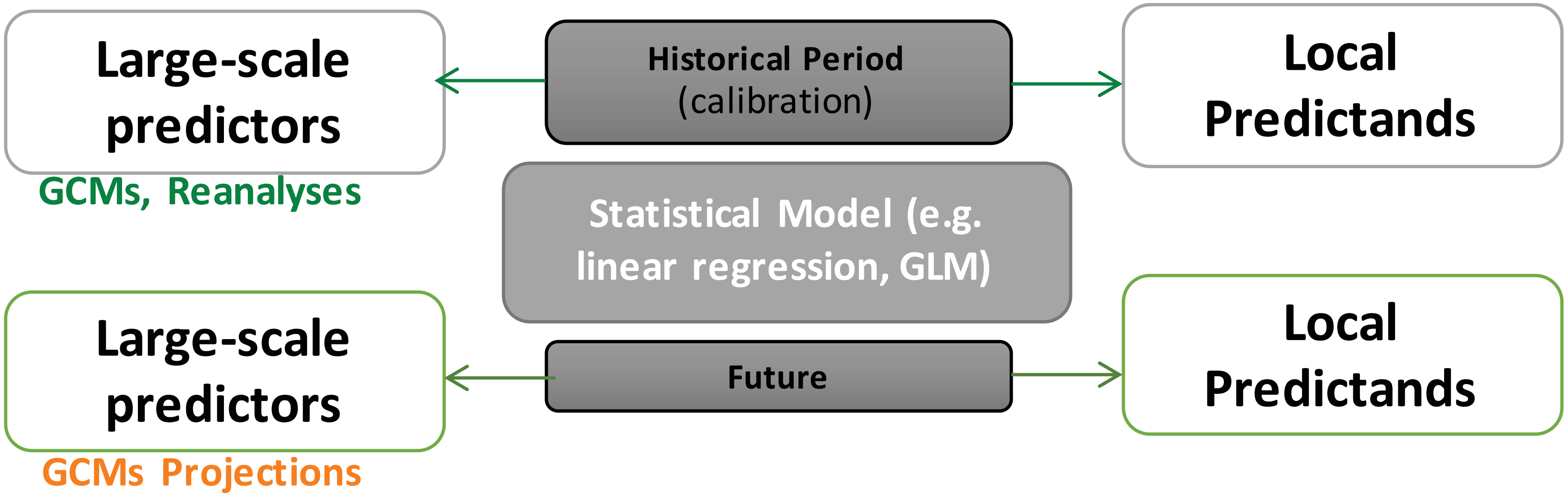
Hydrological/ Rainfall-Runoff models, Ecosystem models; impact models

- Impact studies
- Ecosystem modelling
- Representing the interaction between climate and hydrological/land surface processes

Statistical downscaling

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

1. Find large-scale predictors
2. Determine their statistical relation with a predictand
3. Use the projected values of the predictors to estimate the future values and variability of the predictand (assuming statistical stationarity)



Large-scale predictors

GCMs, Reanalyses

Historical Period (calibration)

Local Predictands

Statistical Model (e.g. linear regression, GLM)

Large-scale predictors

GCMs Projections

Future

Local Predictands

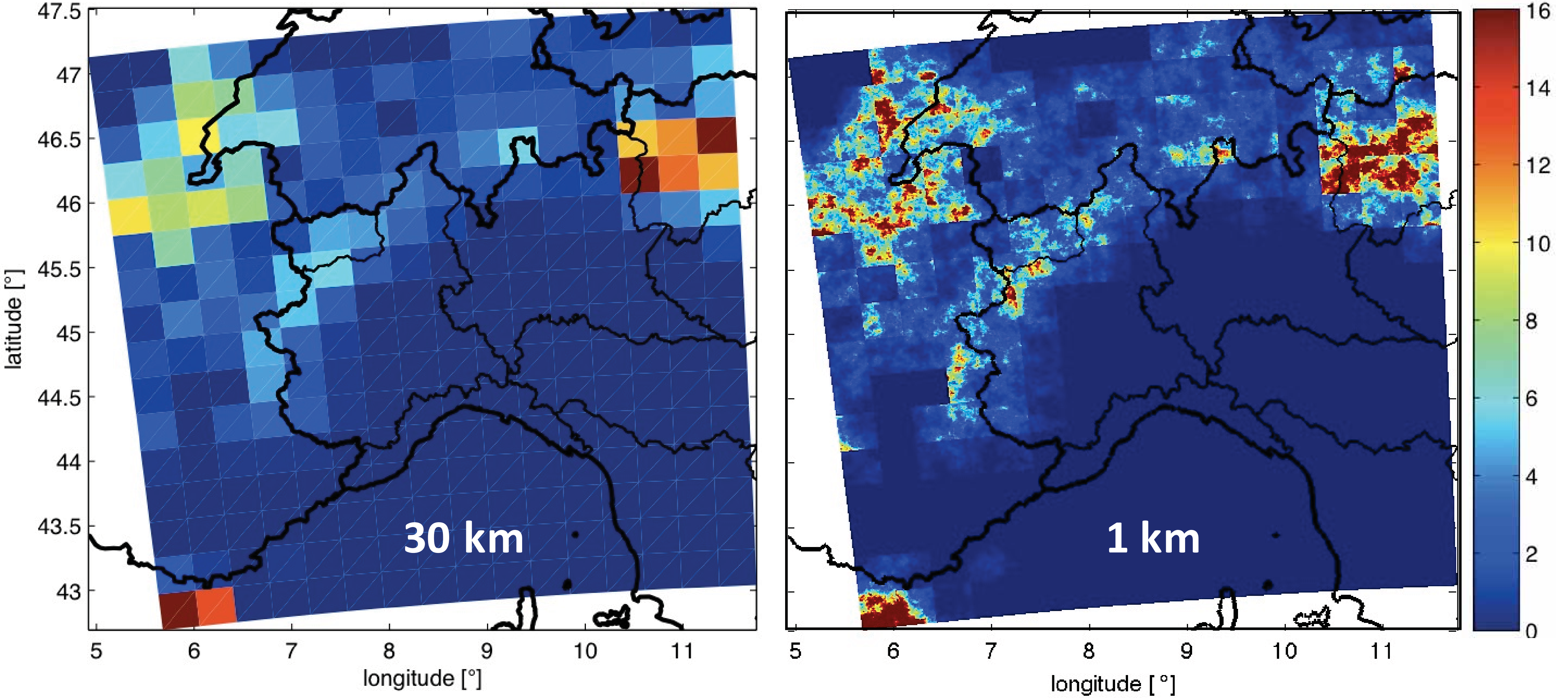
Stochastic Downscaling

Generates **stochastic ensembles of small-scale predictions from the output of atmospheric models or from a measured field with a coarse spatial or temporal resolution**, using different approaches, e.g.:
- Random distribution of rain cells
- Multifractal cascades → based on the theory of scaling in rainfall
- **Nonlinearly transformed spectral models**

Suitable for precipitation
The precipitation fields generated by stochastic procedures are consistent with the large-scale features imposed by meteorological forecast, as the total rainfall volume, and with the known statistical properties of precipitation at multiple scales.

Stochastic downscaling: example

Example SON 1958



Precipitation field from PROTHEUS

Stochastic realization of the PROTHEUS downscaled field, obtained with RainFARM

Stochastic downscaling: the RainFARM downscaling procedure

RAINFarm: Rainfall Filtered Auto Regressive Model

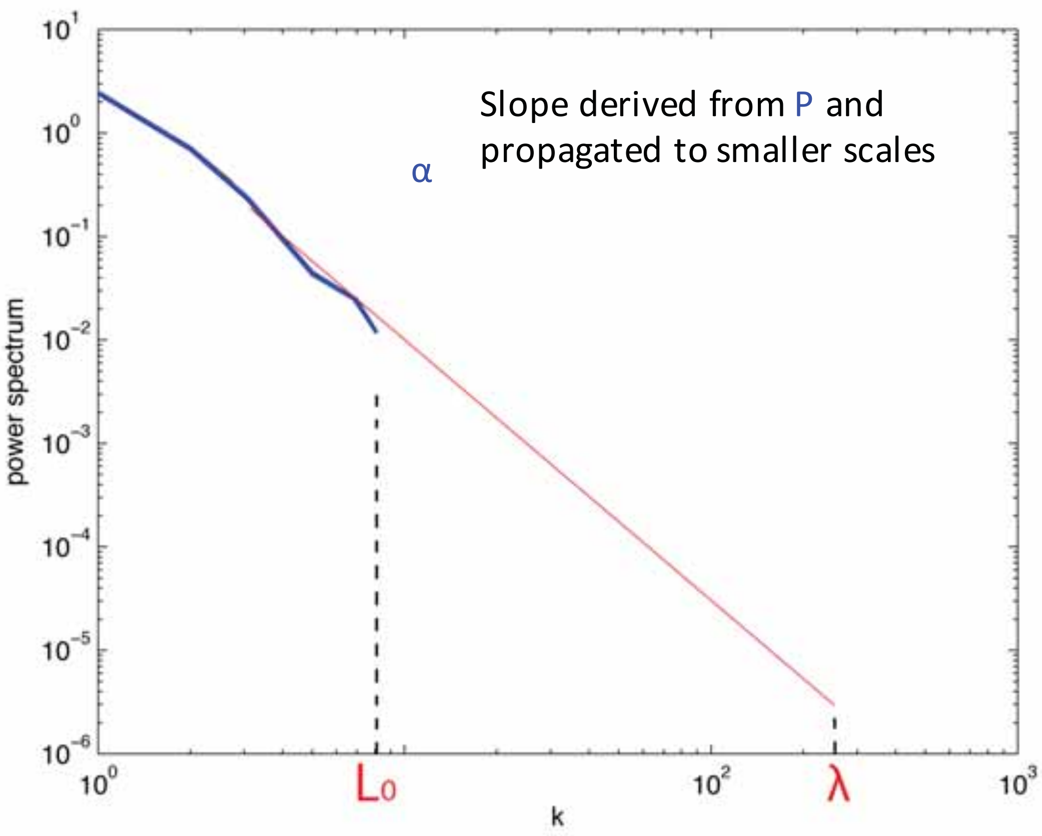
P(X, Y, T), input field, reliability scales L_0, T_0

r(x,y,t), output field, resolution λ, τ

- Belongs to the family of “Metagaussian models”, based on the nonlinear transformation of a linearly correlated process

- Uses simple statistical properties of large-scale meteorological predictions (shape of the power spectrum) and generates small-scale rainfall fields propagating this information to smaller scale, provided that the input field shows a (approximate) scaling behavior

SPATIAL Power spectrum of rainfall field



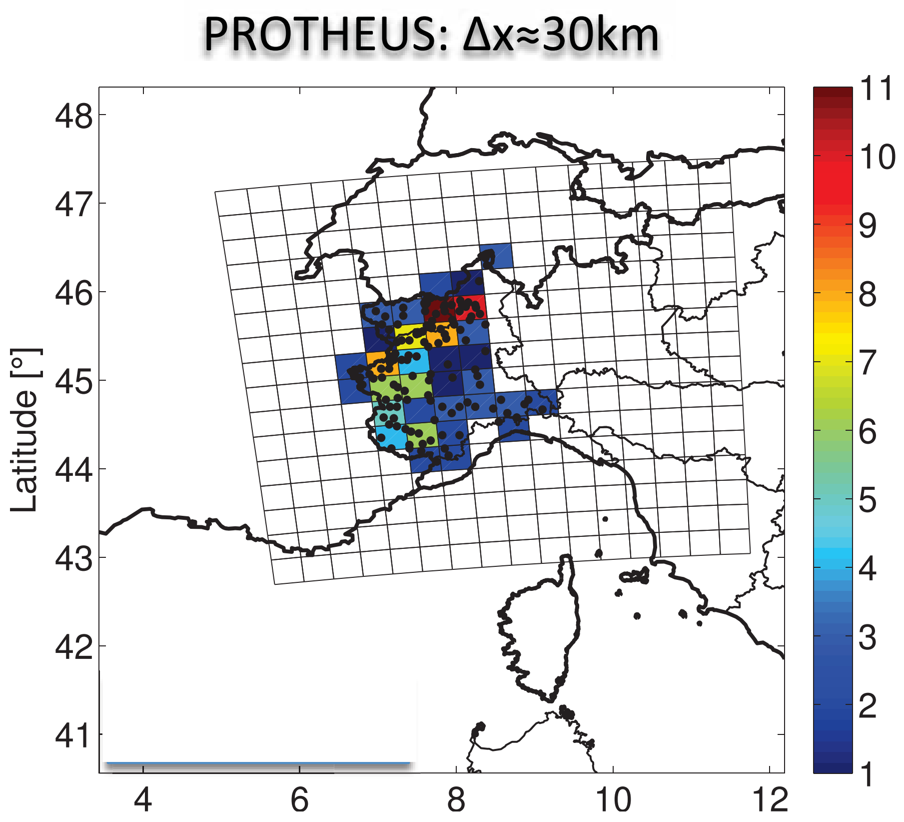
Slope derived from P and propagated to smaller scales

* N. Rebora, L. Ferraris, J. von Hardenberg, A. Provenzale , 2006; *RainFARM: Rainfall Downscaling by a Filtered Autoregressive Model*. J. Hydrometeorology, 7, 724-738

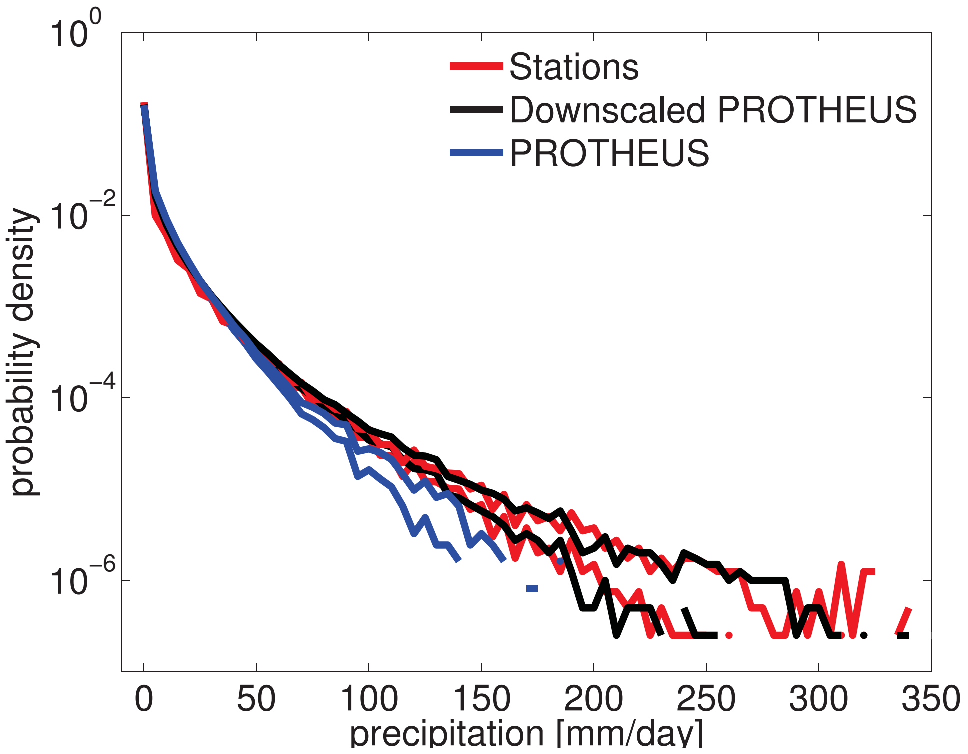
Stochastic downscaling

RainFARM (Rainfall Filtered Auto Regressive Model)

- 122 rain gauges
- 1958-2001
- Daily resolution
- Altitude max: 2526 m
- Altitude min: 127 m



PROTHEUS: Δx≈30km

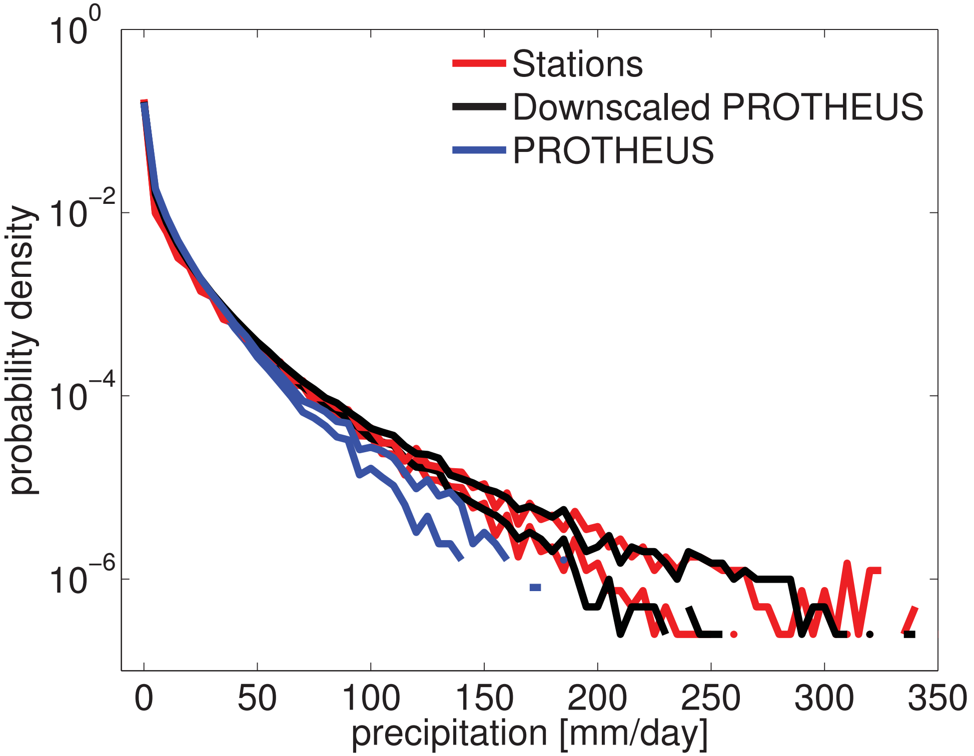


* *D'Onofrio, D.; Palazzi, E.; von Hardenberg, J., Provenzale A., Calmanti S.; Stochastic Rainfall Downscaling of Climate Models. J of Hydrometeorology 15 (2), 830-843 (2014)*

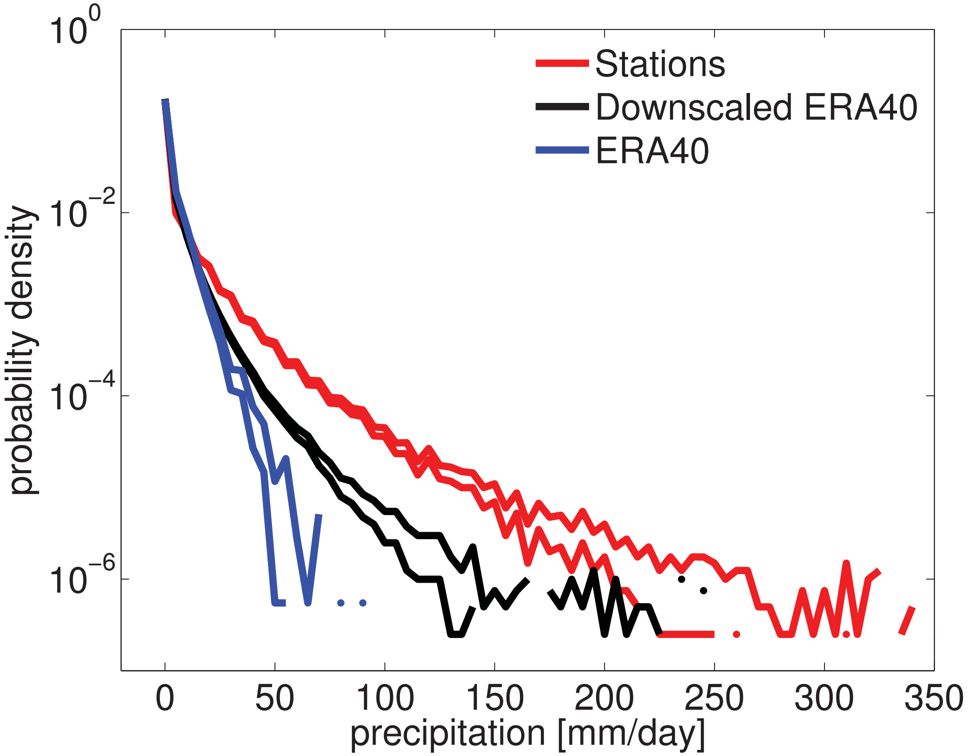
Downscaling: downscaled PROTHEUS/ERA40 and PROTHEUS/ERA40 vs individual raingauge data

PDFs of total daily precipitation

PROTHEUS



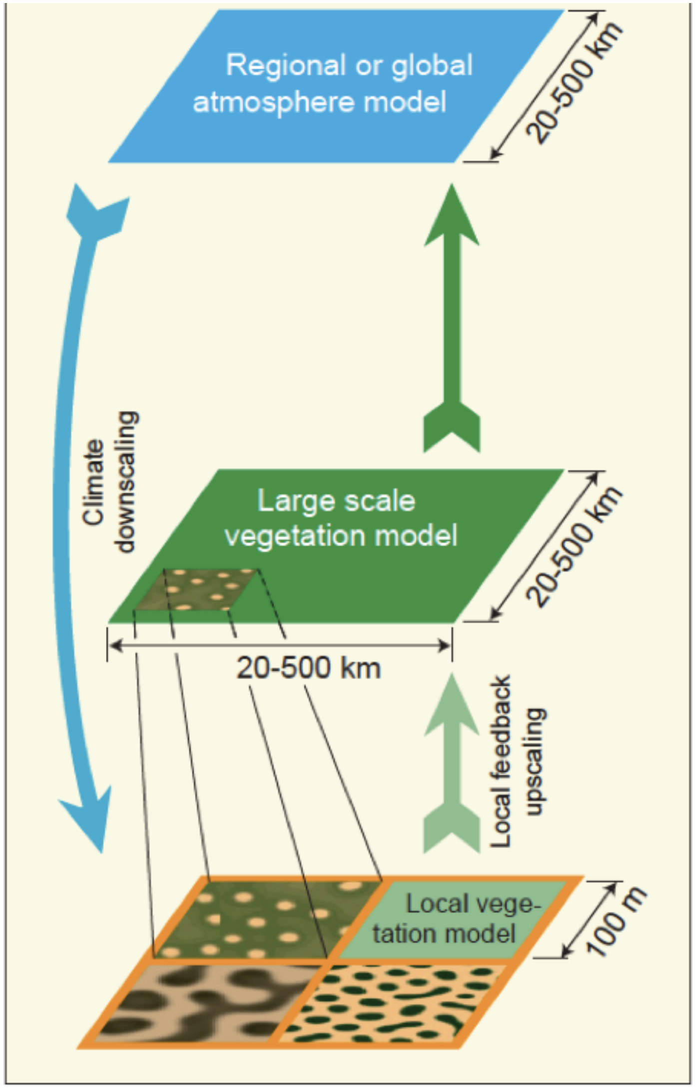
ERA40



The agreement between the downscaled PROTHEUS pdfs and the observations is excellent.
The distribution of downscaled ERA40 fields is wider than the original one, but still underestimates the probability of occurrence of intense rainfall events at all amplitudes

Open questions and perspectives

- **Coupling of feedback at multiple scales** in climate models (including local feedbacks) is an essential step to better understand and predict global climate changes
- Need for **multi-scale models to adequately address feedbacks at disparate scales** → modelling chain from GCMs to models representing local-vegetation feedbacks through downscaling
- Can we develop vegetation/land-surface models properly parameterizing small-scale processes such as multiple steady states of vegetation ?



Rietkerk, M. et al. (2011)
Ecological Complexity 8 (3):223-228

Final remarks

- Numerical climate models provide useful tools to investigate climate processes and to understand the mechanisms driving the current and future changes.
- They also can be (and are) used as tools to provide projections of future changes. Several sources of uncertainty affect these projections at different scales
- Local impact studies (such as local/regional ecosystem modelling) need projections at a regional scale, but in some areas great uncertainties affect in particular the projections for some variables, such as precipitation.
- We can use downscaling chains/methods to provide projections at resolutions needed by local impact studies but these methods cannot correct for large-scale biases in the driving models.
- Downscaling methods which take into account complex orography need further development.