Regional Climate Modelling:

motivations, techniques, illustrations, climate change scenario and uncertainties

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Framework and content of the talk

Numerical Modelling

Regional climate processes

Temporal and spatial scales

Past climate, future scenarios

1. **Regional Climate Modelling: What / Why / How**
   - Motivations for using Regional Climate Models (RCM)
   - What are RCM ?
   - The RCM added-values
   - Some drawbacks of RCM and how to fix it
   - Performing regional climate change scenarios with RCM
2. **Illustrations using RCM: Mediterranean and French examples**
   - Temperature and precipitation changes
   - Changes in extreme indices
3. **Uncertainty in regional climate change scenarios**
   - Source of uncertainty
   - Large coordinated programmes: ENSEMBLES, CORDEX
   - Illustrations
4. **Concluding remarks and perspectives**

Motivations for using Regional Climate Model

<u>The dynamical downscaling concept:</u>

- RCM: (1) high-resolution version of a GCM (2) limited to a given area and (3) cheaper than a GCM at the same resolution
- RCM: (4) can be driven by various driving models (reanalysis, GCM, other RCM)
- Mostly used for model evaluation, model development, understanding of regional climate processes, study of regional climate past variability, sensitivity studies of regional climate, regional climate change scenarios, as inputs for impact studies

<u>For who ?</u>

- *Climate researchers (see above)*
- *The research community of the other components of the climate system (RCMs as an input): regional or coastal oceanography, snow and glaciers, land-surface, hydrology*
- *The research "impact" community (impact of climate change): health, biodiversity, economy, tourism, energy*
- *The climate service community : support for decision, adaptation*

What are Regional Climate Models (RCM) ?

Definition of RCM:

"Climate model for regional purposes"

Main characteristics

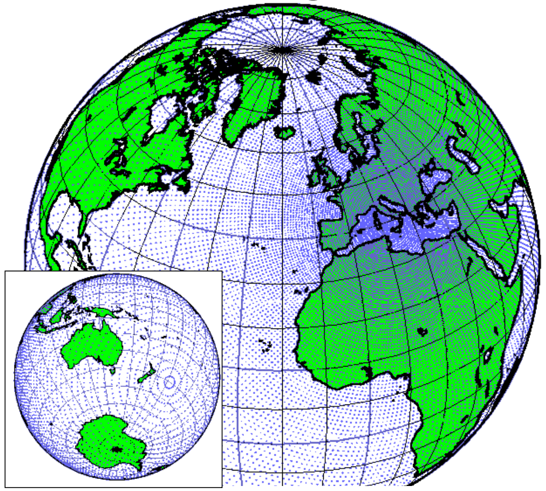
- High-resolution GCM, Stretched or zoom GCM, Limited-area model
- RCM (LAM) = nested/driven climate model by Surface and Lateral Boundary Conditions (SBC, LBC)
- RCM (LAM): one-way nesting
- Components: Atmosphere+Land mostly but sometimes vegetation, snow, glaciers, hydrology, ocean, sea-ice, chemistry, aerosols, lake, human activities (pollution, city, dam, irrigation)

Added-values and drawbacks:

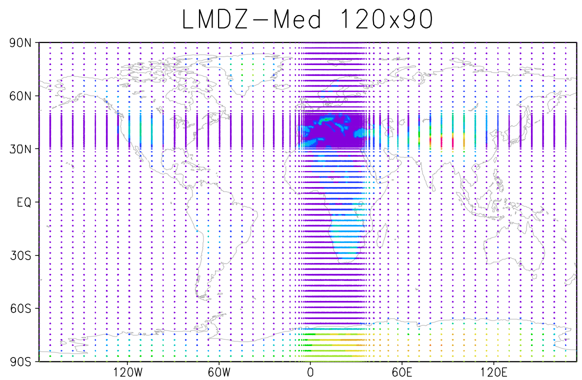
- RCMs bring added-values wrt GCM or reanalyses
- BUT RCM can also come with drawbacks or retained-value wrt their driving model
- This depends on the model, the configuration and the use…

What are Regional Climate Models (RCM) ?

Stretched-grid GCM

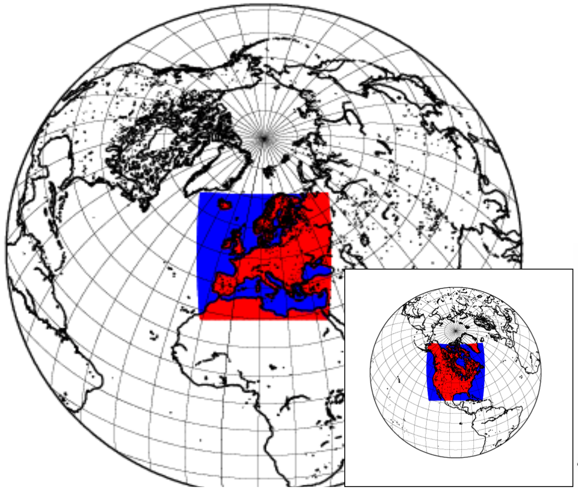


ARPEGE-Climate



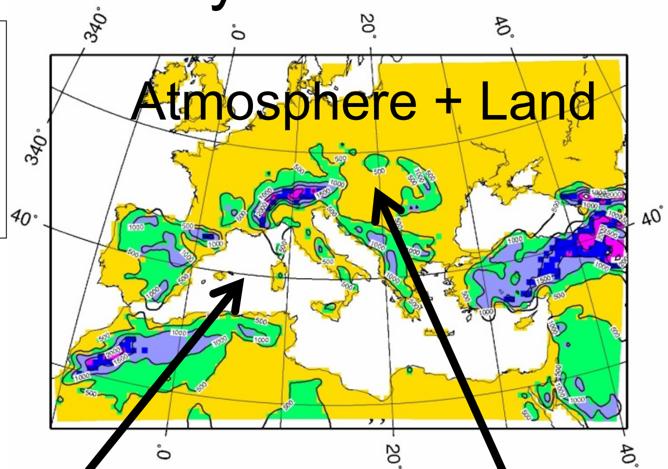
LMDZ

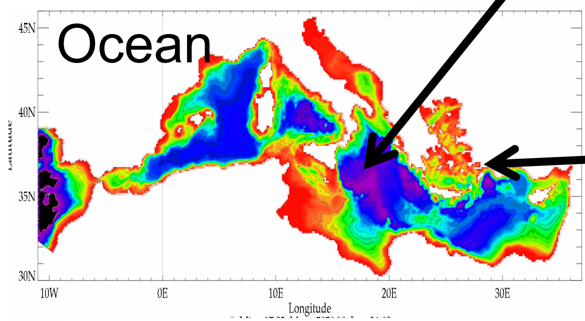
Limited-Area Model

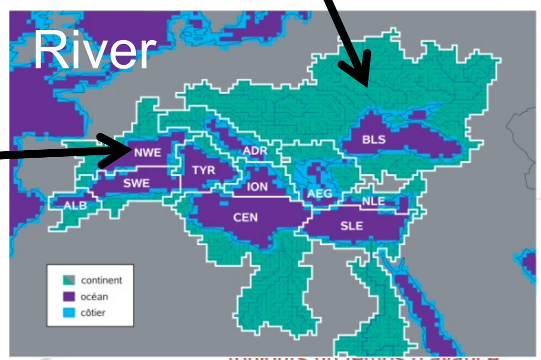


ALADIN-Climate

Regional Climate System Model



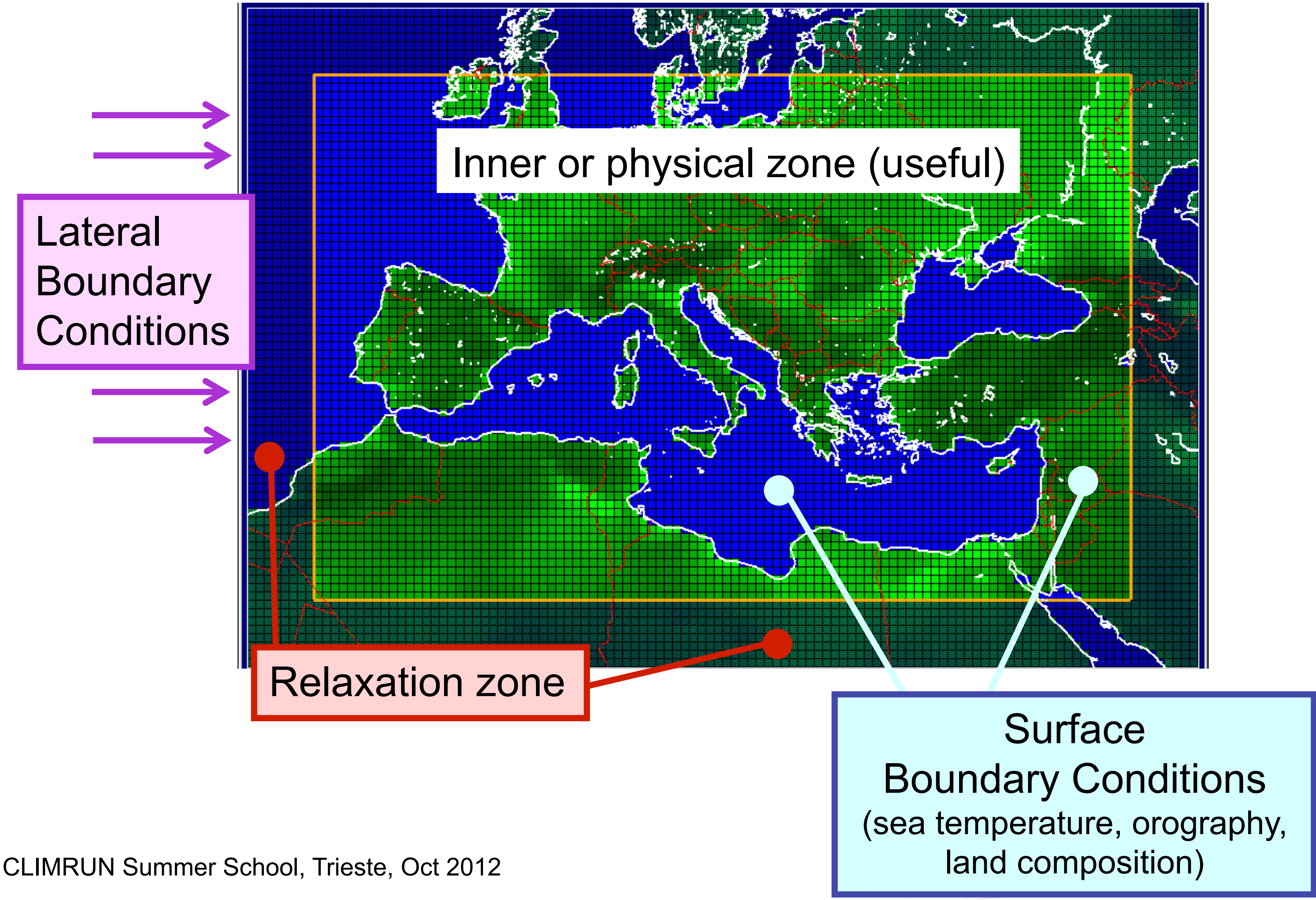




CNRM-RCSM

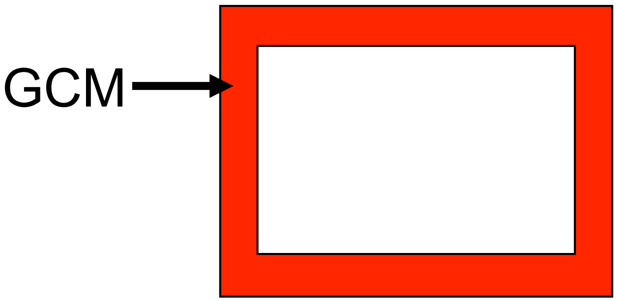
Source: Météo-France

What are Regional Climate Models (RCM) ?

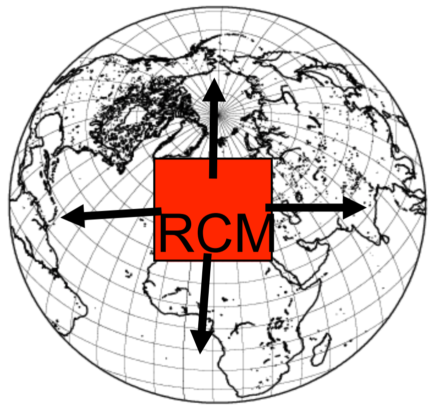


How to drive a RCM ?

One-way nesting
Lateral forcing

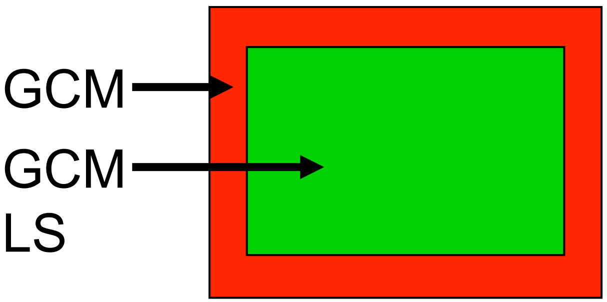


Two way-nesting



$$\frac{dT}{dt} = dynamics + physics + \frac{T - T_{GCM}}{\tau} + \frac{T_{LS} - T_{LS-GCM}}{\tau_1}$$

Spectral nudging



Lateral nudging all scales but only in the relaxation layer

Spectral nudging inside the domain but only for the large-scales

Nudging coef.

Where does the added-value come from ?

<u>Several potential sources of RCM added-value wrt the driver:</u>

- Cheaper in terms of computational resources at the same resolution

- Higher-resolution
  - Turbulence (small scale atmospheric features, mesoscale cyclones)
  - Higher-resolution of the model forcings: orography, islands, land-sea contrast, sea surface temperature, aerosols climatology, land-use, sea-ice coverage
  - Non-hydrostatic model at 2-km resolution with explicit convection scheme

- Regional adaptation of the RCM
  - better evaluation using regional observations
  - more complex physical parameterizations
  - regional tuning of the physics

- More components of the regional climate system
  - Ocean, glaciers, sea-ice, flooded area, irrigation, dam, lake, city, …

Turbulence

GCM at a 450-km resolution | RCM at a 45-km resolution

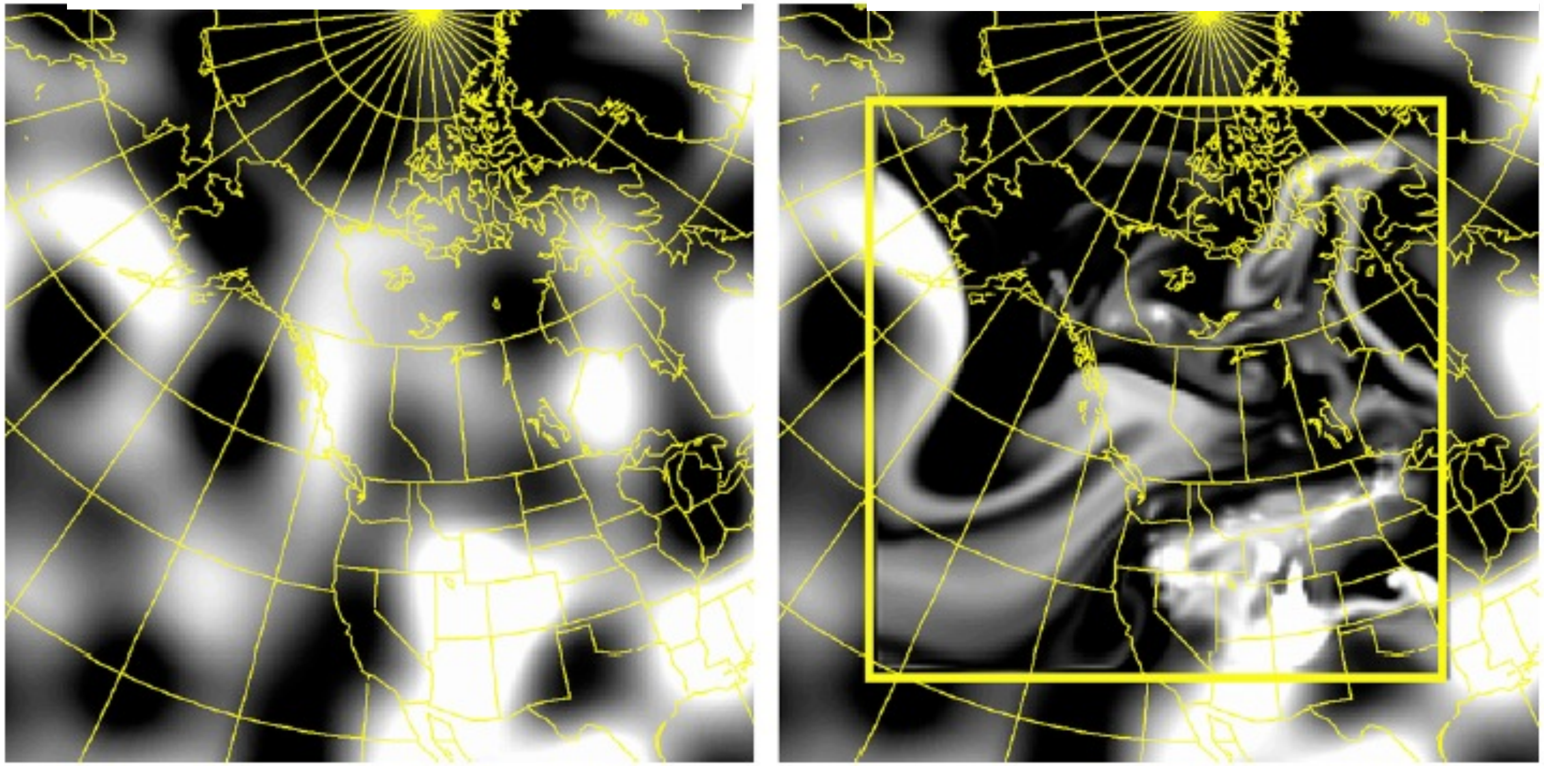
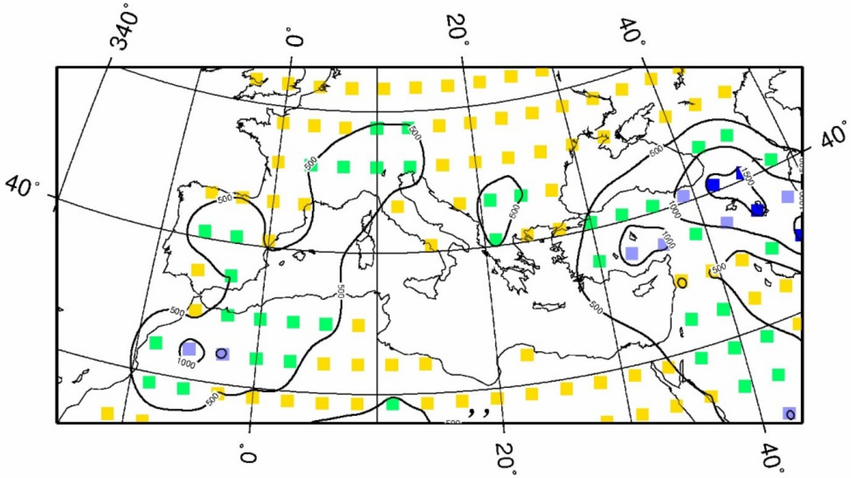


Fig. 5. Instantaneous field of clouds simulated by CGCM2 with equivalent grid mesh of 450 km (left panel) and CRCM with grid mesh of 45 km (right panel) (superimposed on the GCM-simulated field, showing the frame of the RCM domain) (figures kindly provided by Dr. Daniel Caya, Chief, Climate Simulation Team, Ouranos Consortium).

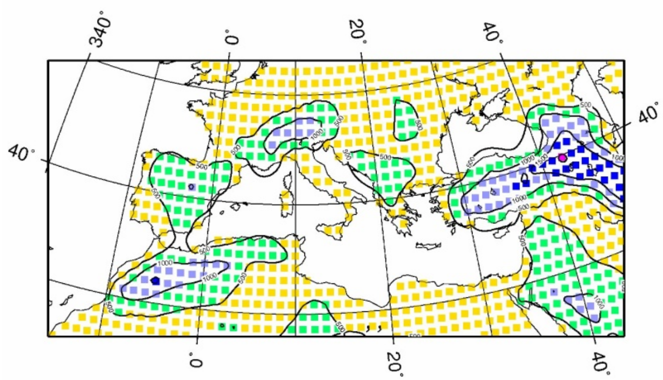
Laprise et al. 2008

Resolution, orography and land-sea contrast

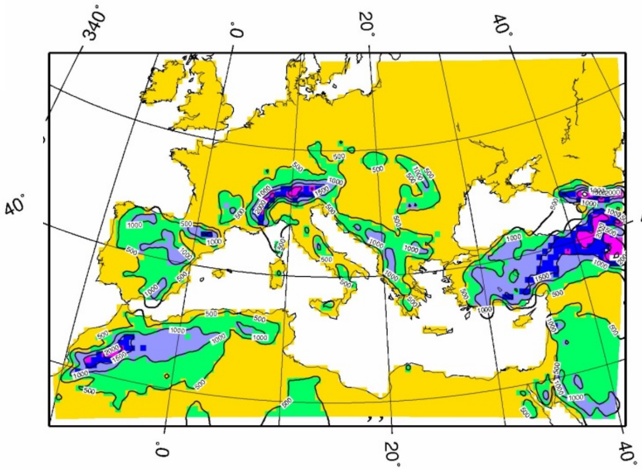
CNRM-CM3 (CMIP3, IPCC-AR4) 250 km



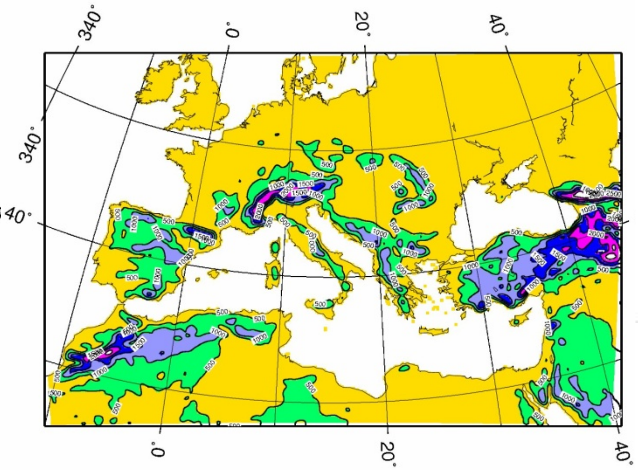
ERA40 – 125 km



RCM 50km



RCM 12km



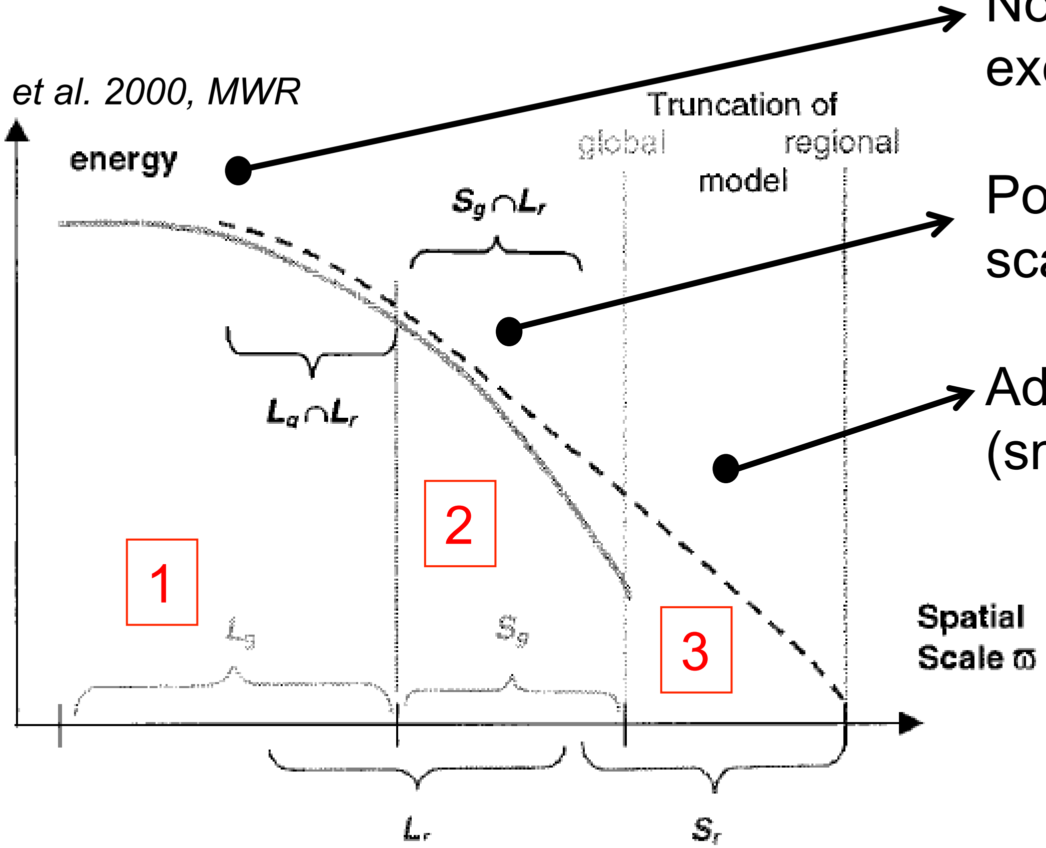
Source: Météo-France

The added-value: question of scales

<u>What are the relative scales of GCM and RCM ?</u>

- in time: RCM can add value at daily and sub-daily time scales
- in space:

VonStorch et al. 2000, MWR



No added-value possible except for two-way nesting

Possible added-value (up-scaling effect)

Added-value of the RCMs (small scales)

The spatial scale separation depends of the driver resolution:
CMIP3, NCEP: 250km
CMIP5: 150km
ERA40: 125 km
ERA-Interim: 80 km

Geography of the RCM added-value

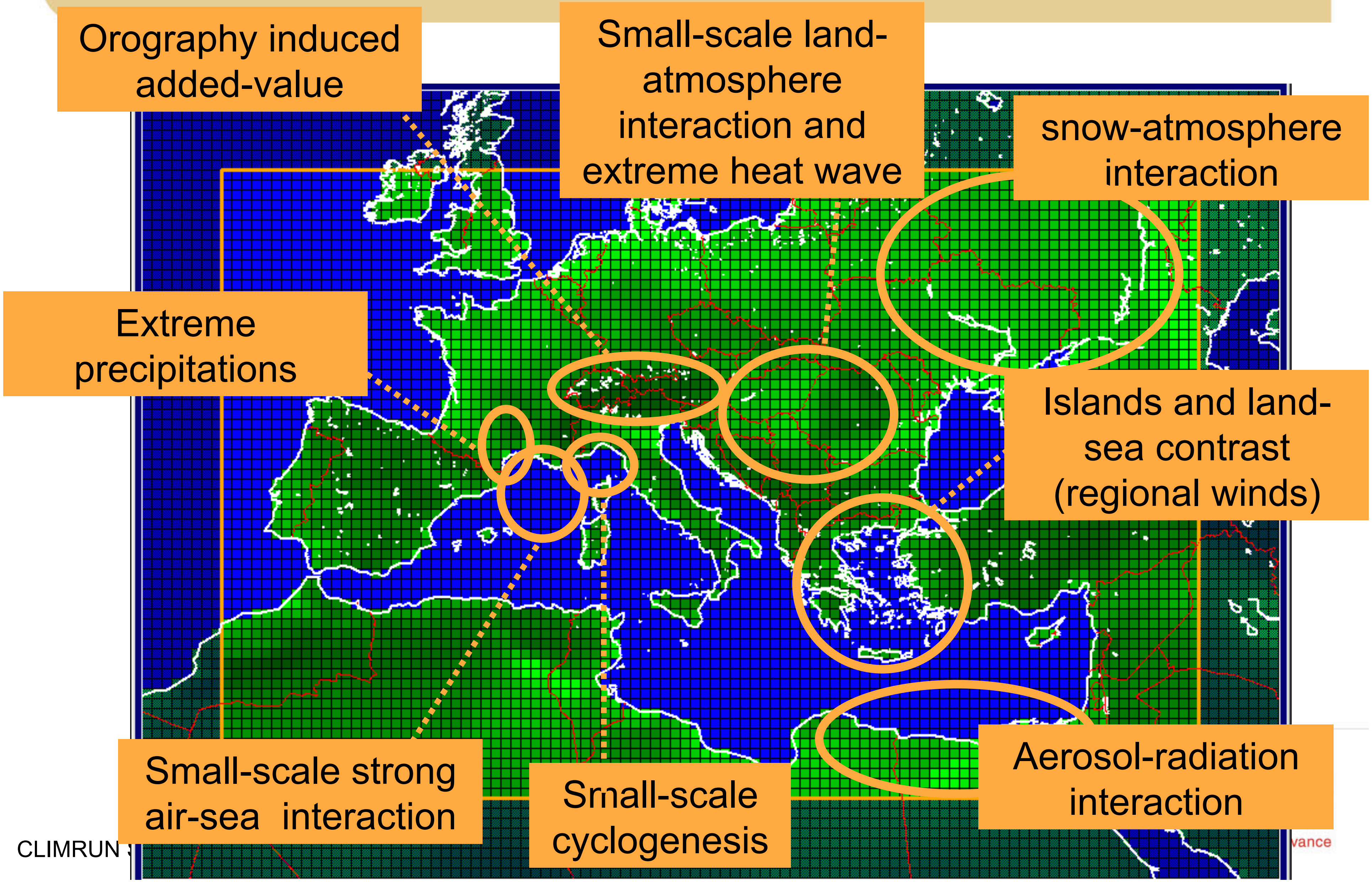


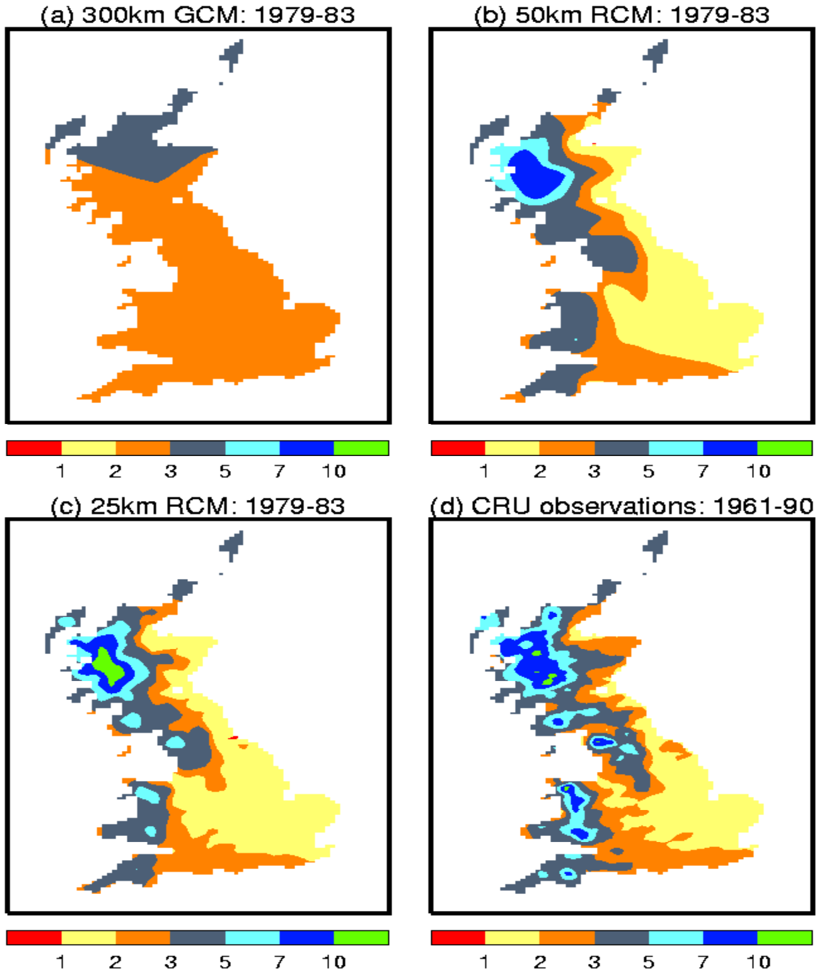
Illustration of the RCM added-value

Added-value in mean precipitation spatial pattern

300km GCM

50km RCM

25km RCM



Observations precipitation in Winter

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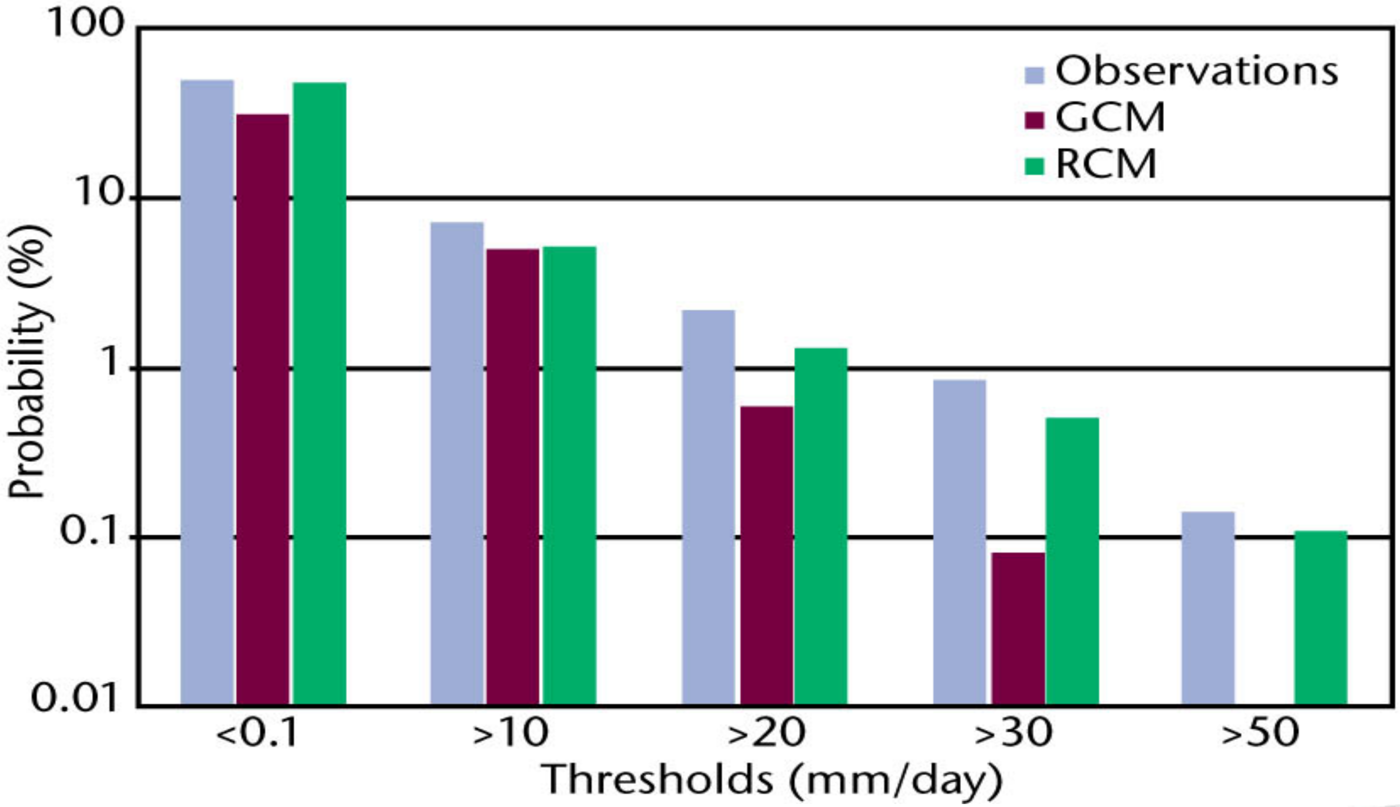
Illustration of the RCM added-value

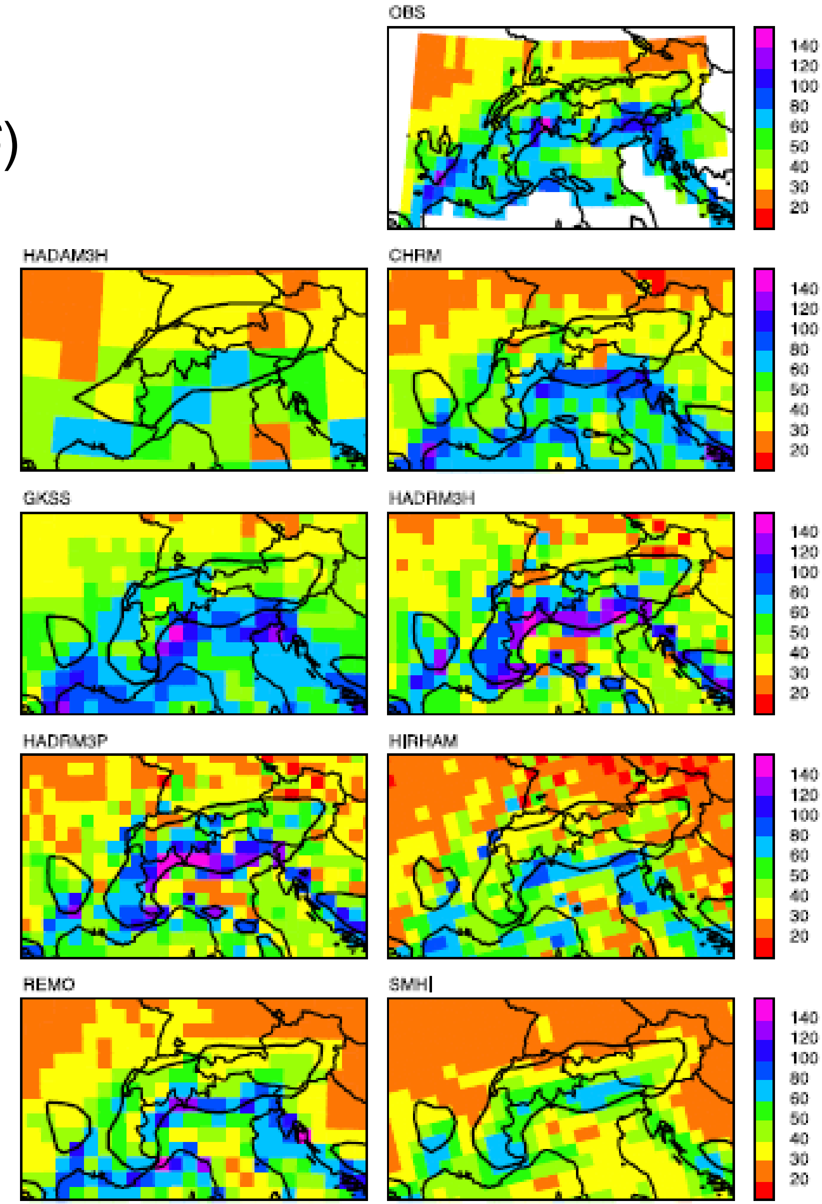
Added-value in extreme precipitations



Daily precipitation distribution over the Alps

Examples: Precipitations and extremes

Model choice uncertainty for extreme precipitation in the Alps (*Frei et al. 2006*)



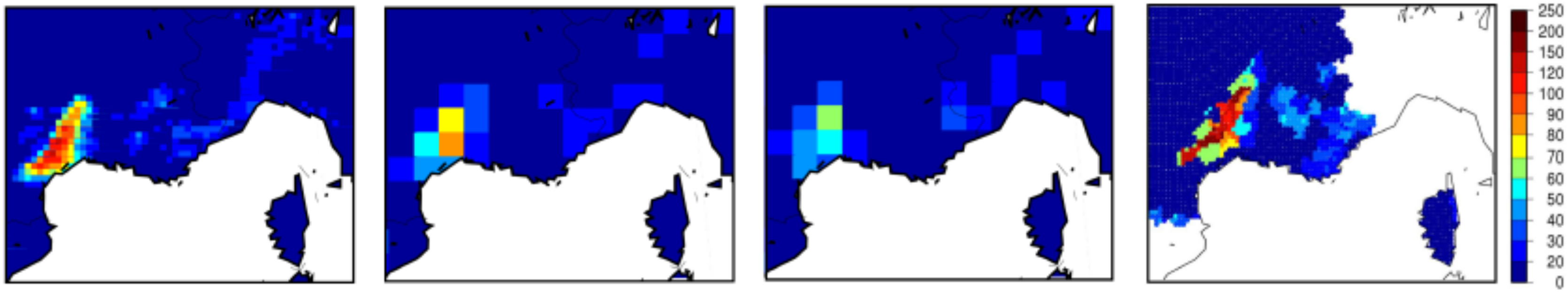
5-year return value for daily precipitation in Autumn (SON)
OBS (1971-1990)
GCM (1961-1990)
RCM (1961-1990)

Illustration of the RCM added-value

Extreme precipitation in France *(Colin, PhD, 2011)*

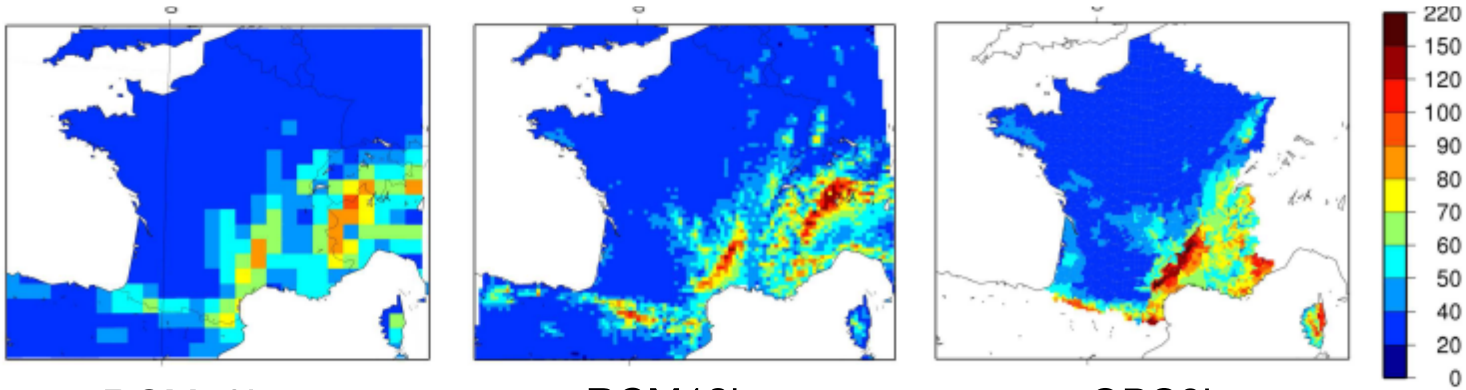
ALADIN RCM (1958-2001, ERA40): 50 km vs 12 km

Accumulated precipitation (mm) for the case study (December, 17th, 1997)



RCM12km RCM12km (50km grid) RCM50km OBS8km

Quantile 99.8 of daily precipitation (mm/d) for the Autumn season (SOND)



RCM50km RCM12km OBS8km

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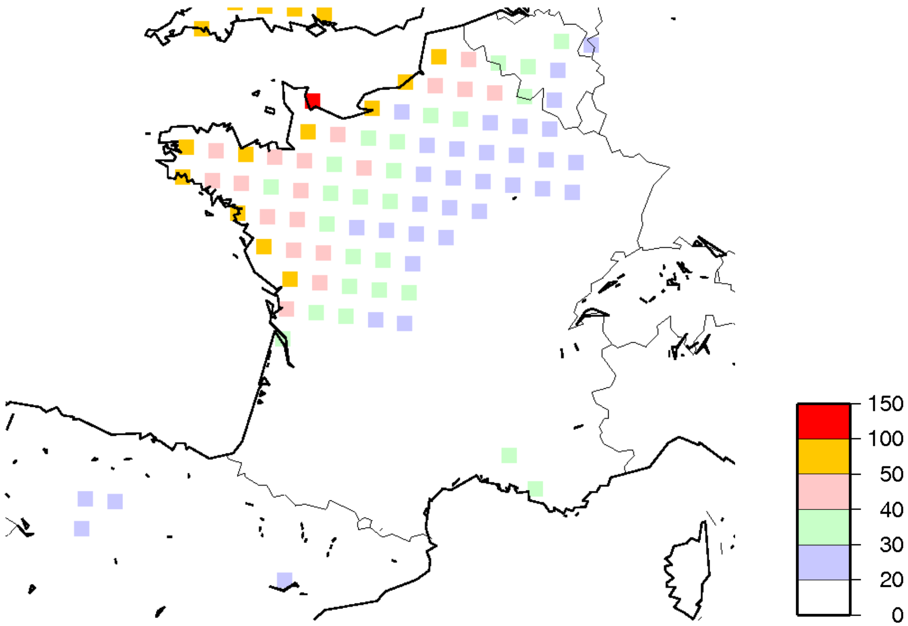
Illustration of the RCM added-value

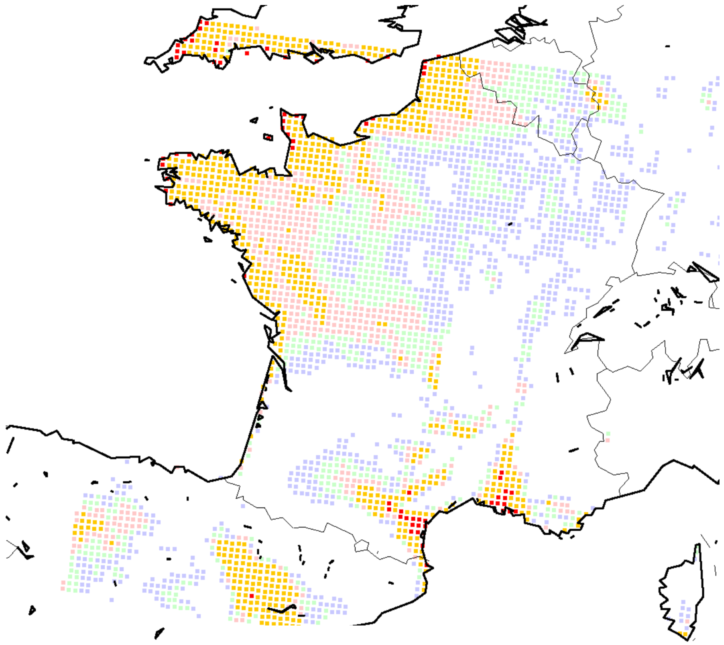
Extreme wind speed in France *(M. Déqué, pers. comm.)*

ALADIN RCM (1958-2001, ERA40): 50 km vs 12 km

Number of days with wind spead over 60 km/h



RCM 50km



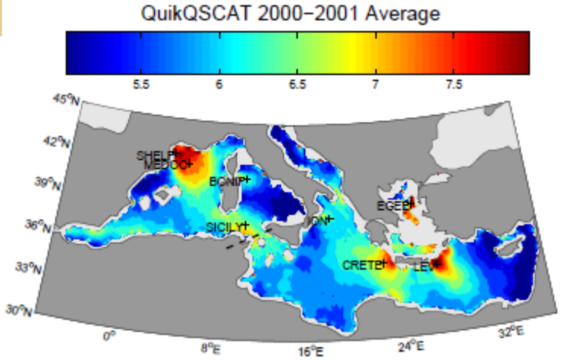
RCM 12km

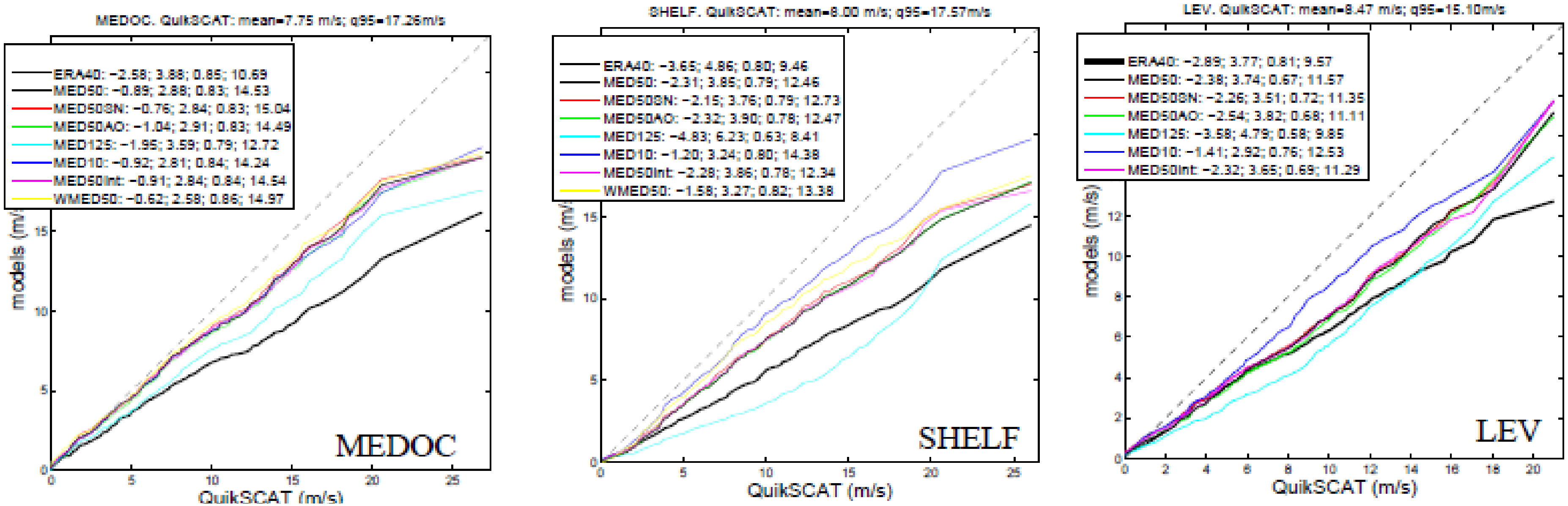
Source: Deque, ANR-SCAMPEI

Illustration of the RCM added-value

Distribution and extreme of the sea wind speed

Quantile-quantile plots for daily wind speed (m/s, 2000-2001) over the sea (*Herrmann et al., 2011*)





ERA40 underestimates the wind speed because of the low-resolution
RCM (50km) has a clear added-value
RCM (12km) has an added-value close to the coast only
Using Spectral Nudging or ERA-Int LBC improves the temporal chronology

The main RCM drawbacks

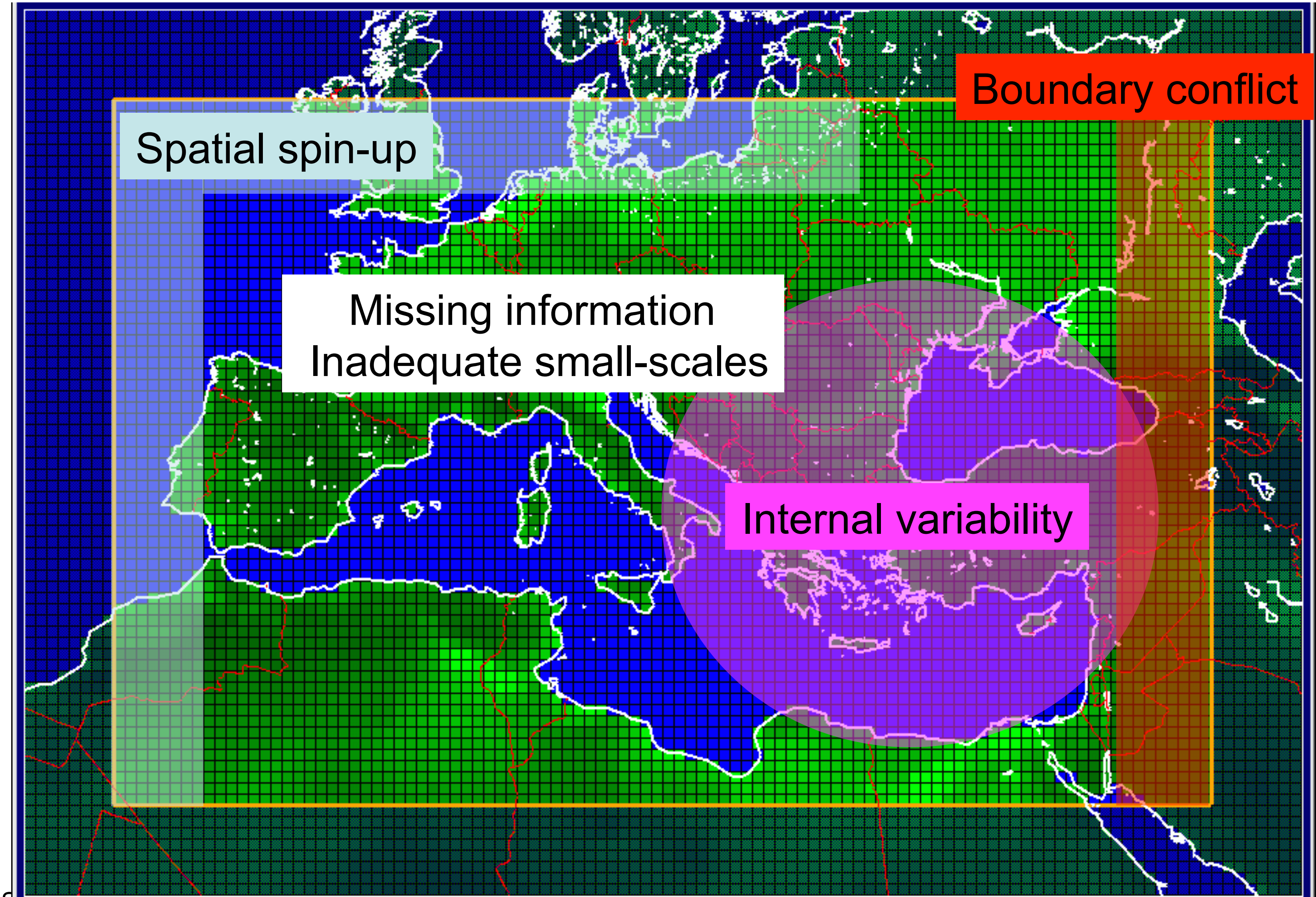
<u>The RCM drawbacks:</u>

- Retained value: the RCM is worse than the driver at a given scale (RCM can in particular degrade the large-scales)
- The additional small scales produced by the RCM are not adequate: noise instead of signal

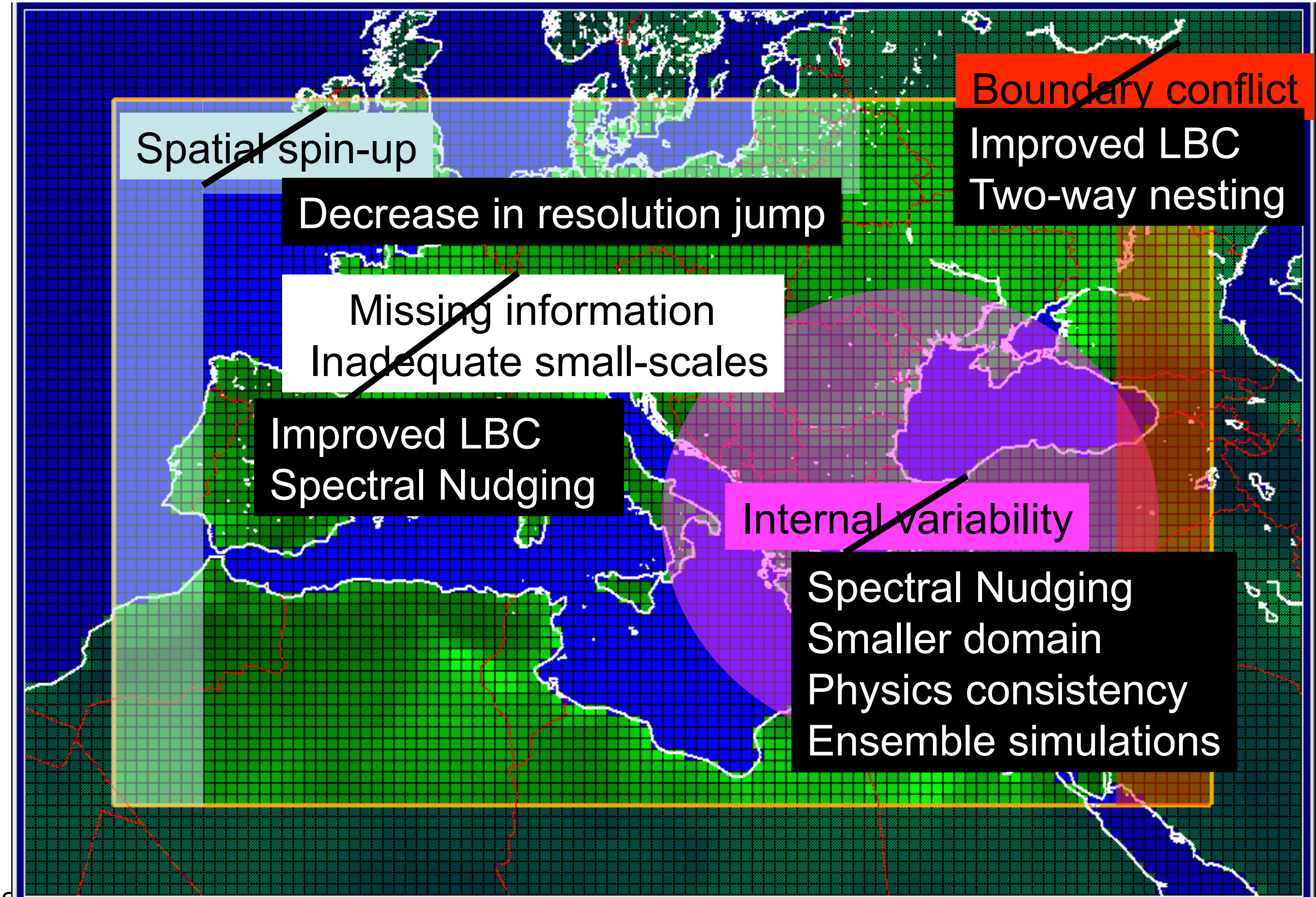
<u>Main causes:</u>

- The use of a particular RCM adds a source of uncertainty (physics, components, design)
- The boundary conditions is often considered as an ill-posed problem (small coupling zone, impact of the domain position, 6h-frequency coupling, spatial spin-up, one-way nesting, mismatch at the outflow)
- RCM internal variability, divergence from driving model
- Inconsistent physics between GCM and RCM

Where are the RCM drawbacks ?



How to fix the RCM drawbacks ?



Performing a regional climate change scenario

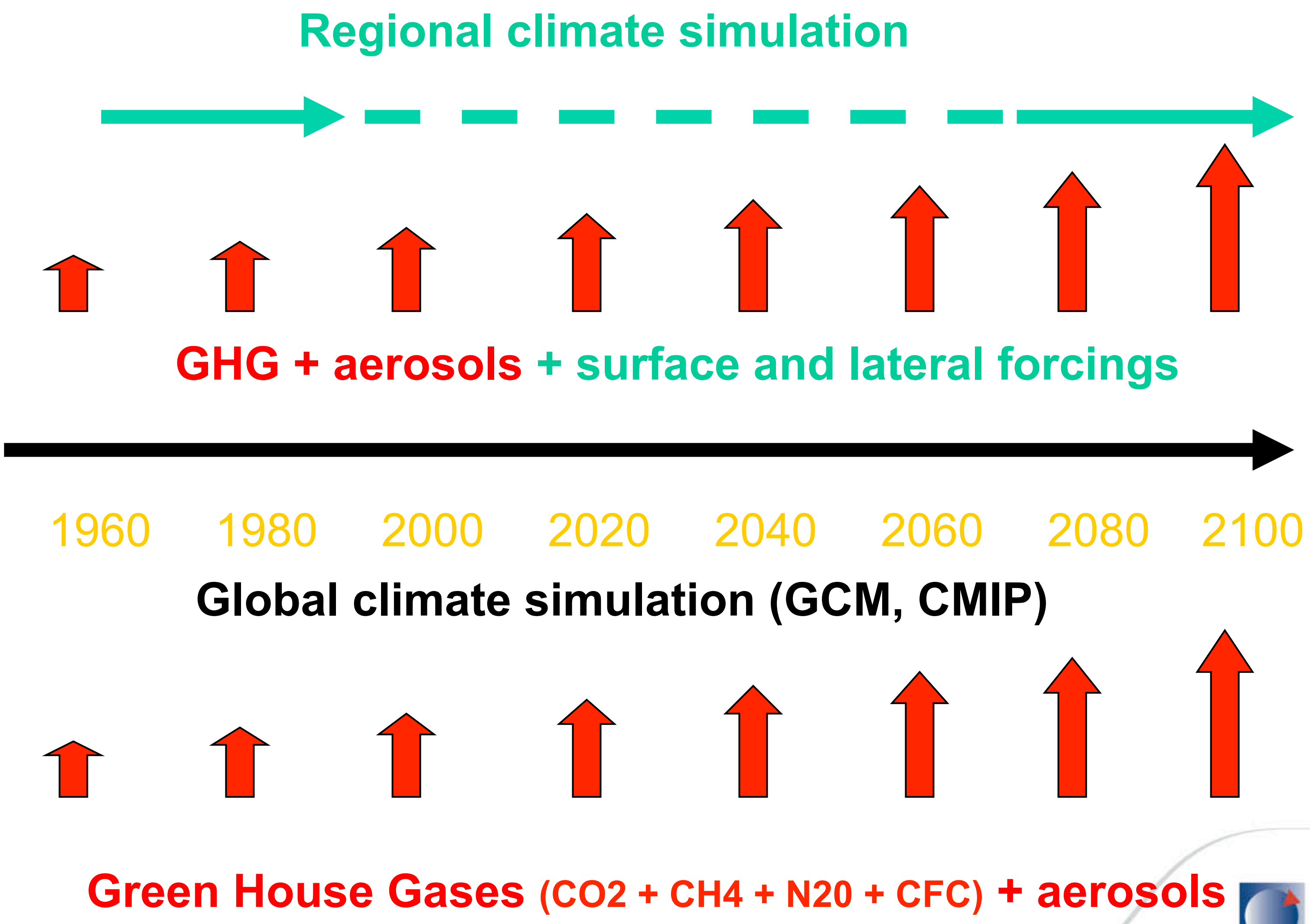
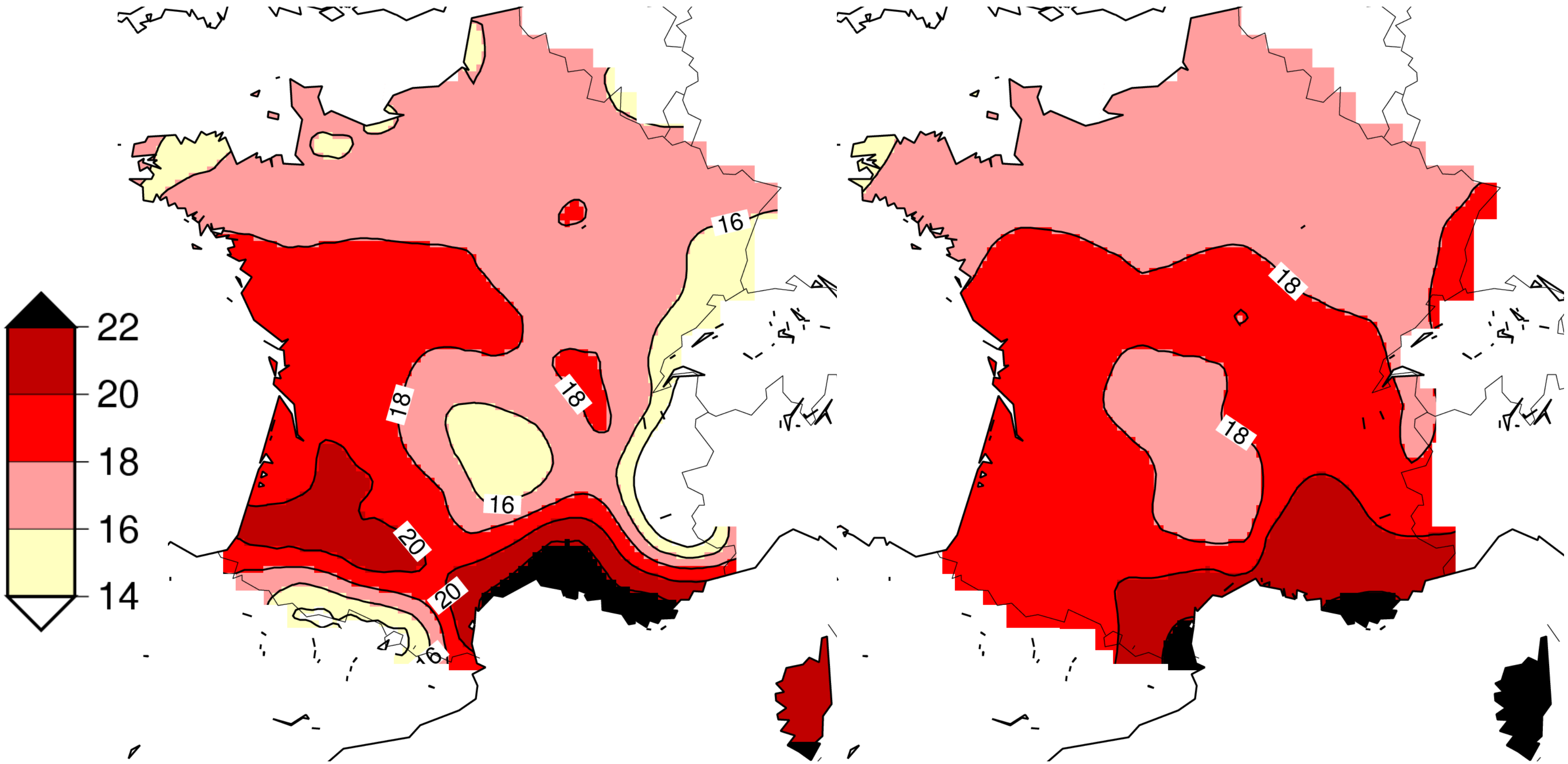


Illustration of RCM evaluation

Model | Observation



Temperature (°C) in Summer (JJA)
ARPEGE-Climat RCM, 50 km (1961-1990)

Source: Météo-France

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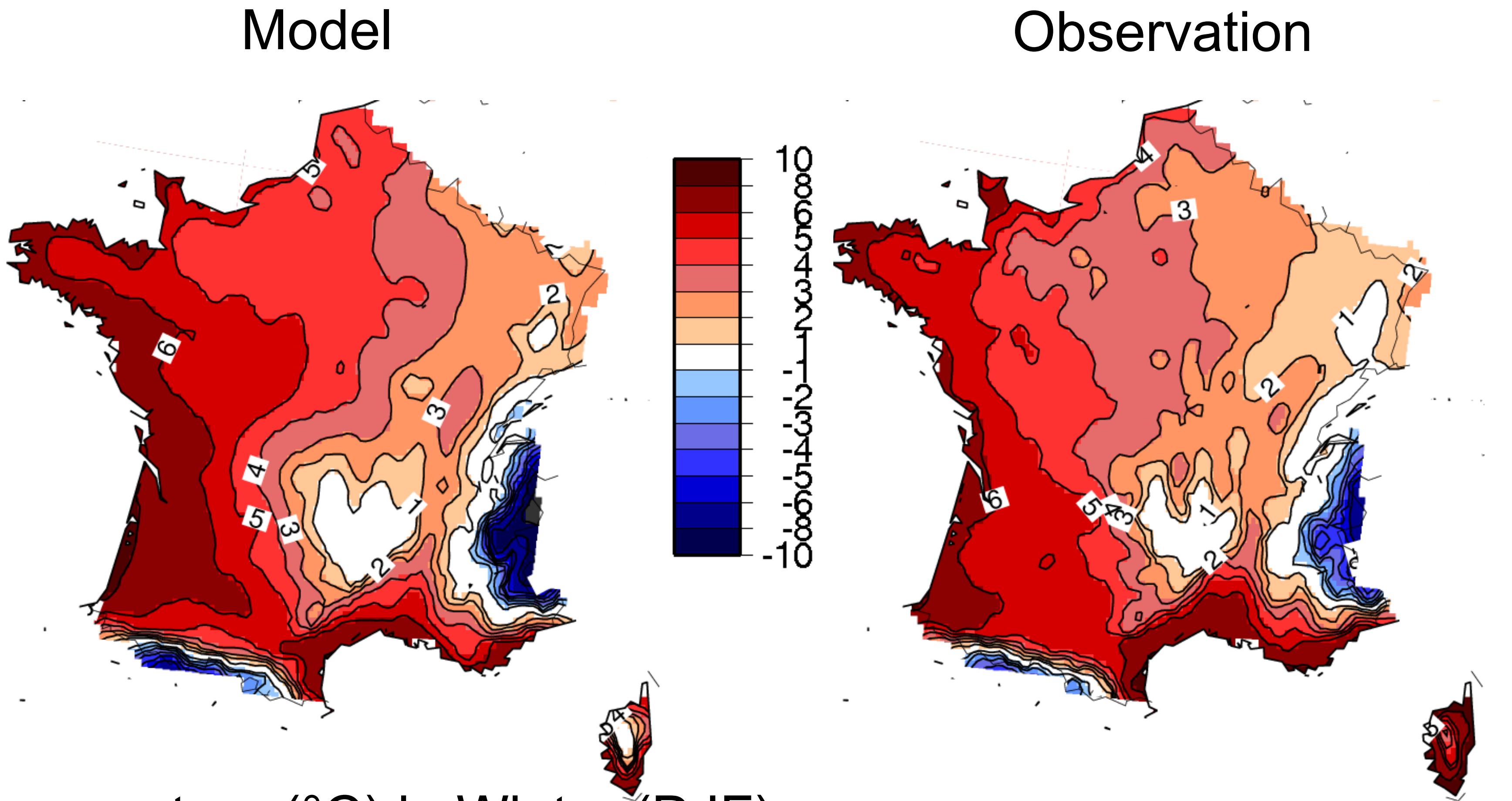
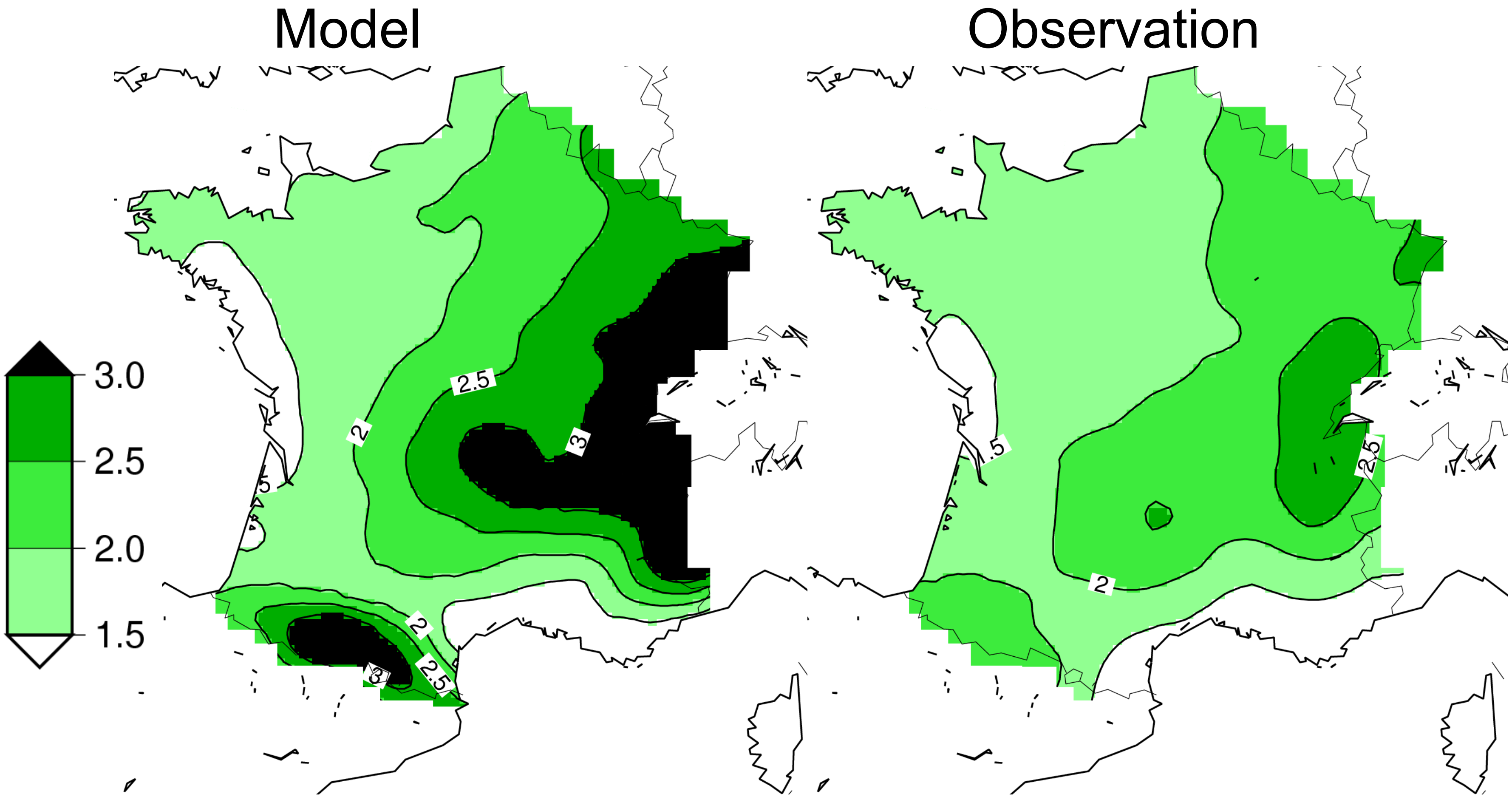
Illustration of RCM evaluation



Temperature (°C) in Winter (DJF)
ALADIN-Climat RCM, 12 km (1961-1990)

Source: Météo-France

Illustration of RCM evaluation



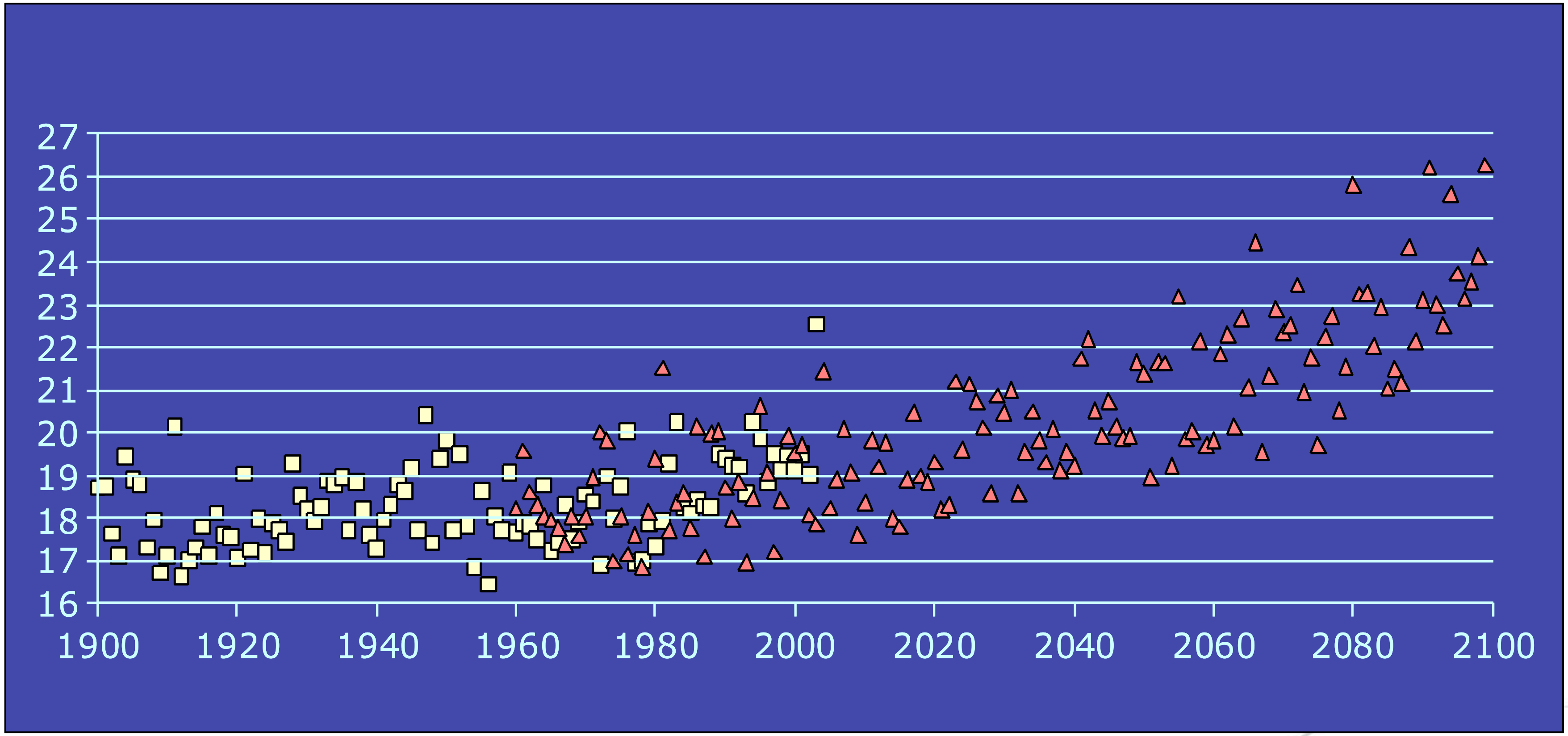
Precipitations (mm/d) in Summer (JJA)
ARPEGE-Climat, 50 km (1961-1990)

Source: Météo-France

Illustration of RCM evaluation and scenario

Average temperature over France in Summer (JJA, °C)

Observations

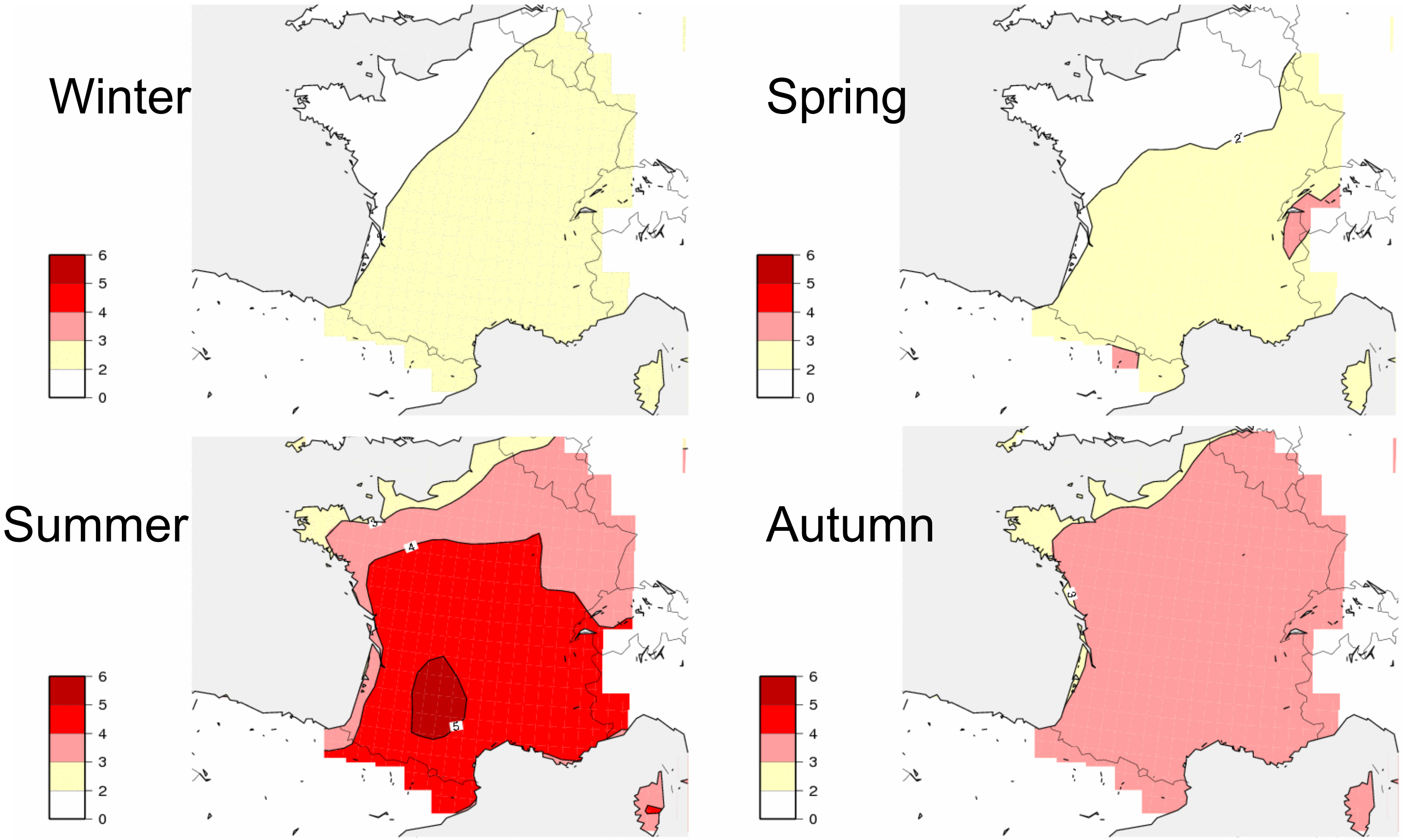


ARPEGE-Climat, 50 km, A2 scenario

Source: Météo-France

Illustration of regional climate change scenario

Temperature change (Scenario A2 / CNRM-CM5 / 2070-2099)

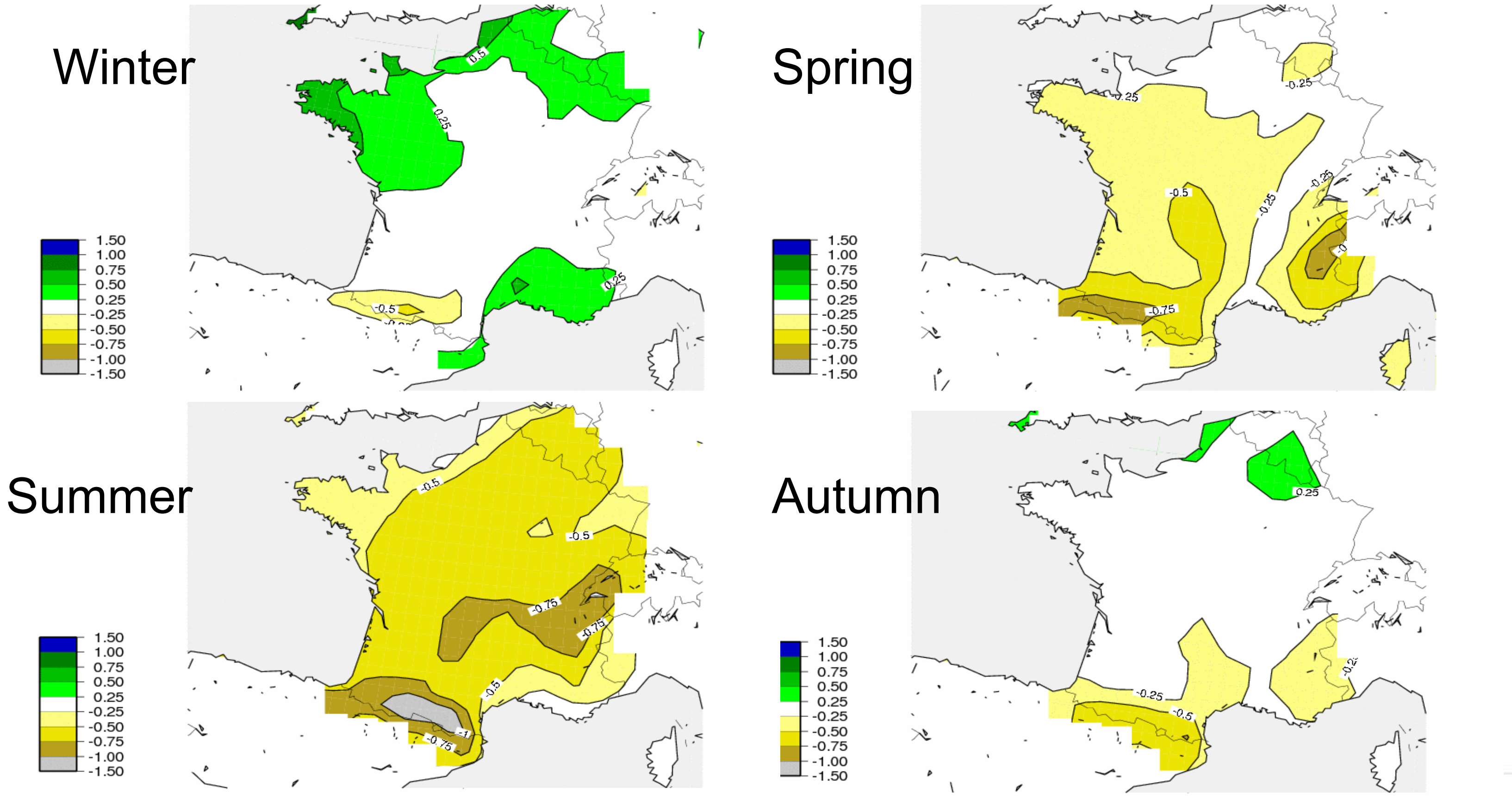


ARPEGE-Climat RCM, 50 km, [2070-2099] - [1960-1989]

Source: Météo-France

Illustration of regional climate change scenario

Precipitation change (Scenario A2 / CNRM-CM5 / 2070-2099)



ARPEGE-Climat RCM, 50 km, [2070-2099] - [1960-1989]

Source: Météo-France

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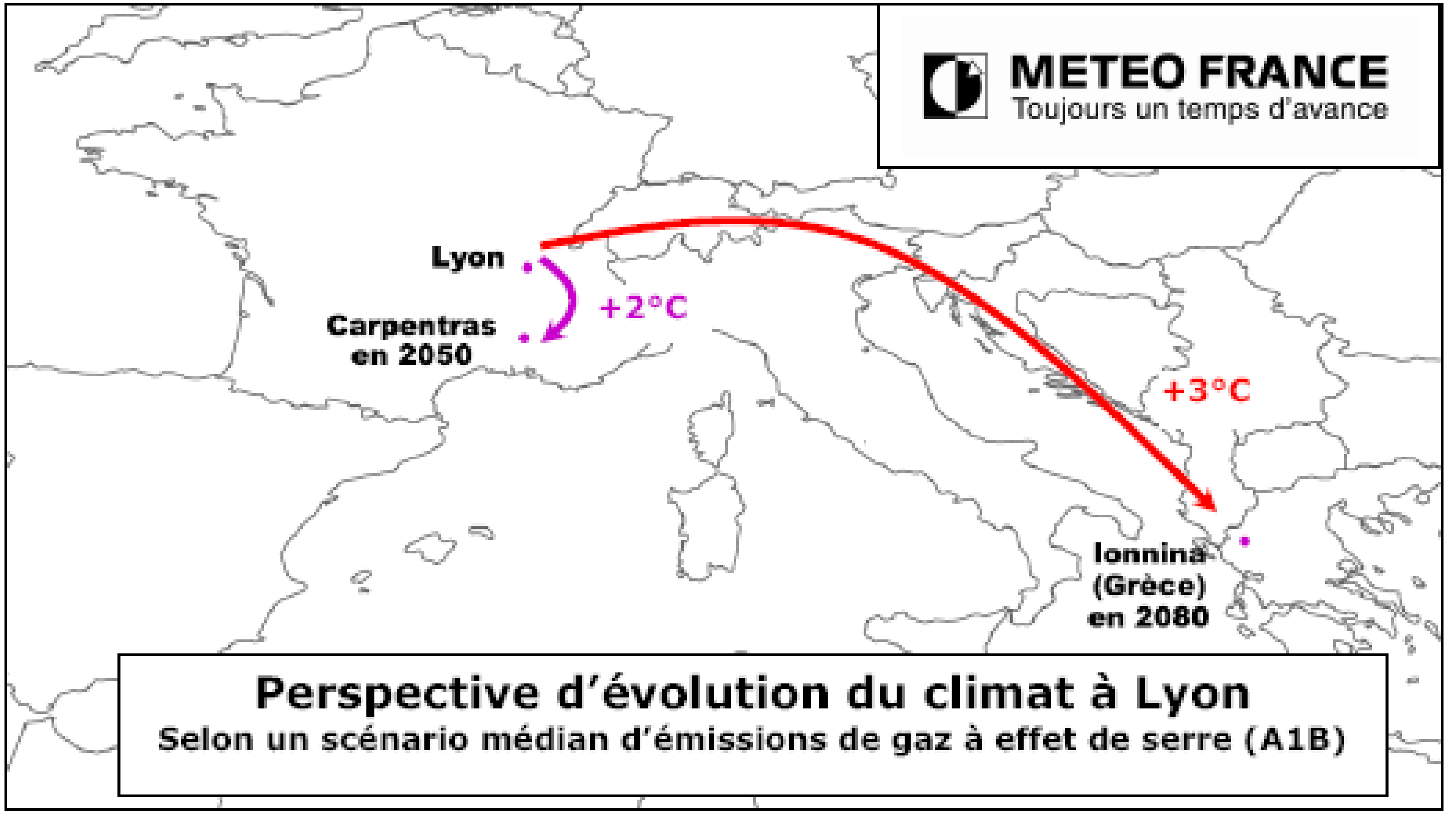
Illustration of regional climate change scenario

Future-climate Lyon city analogue



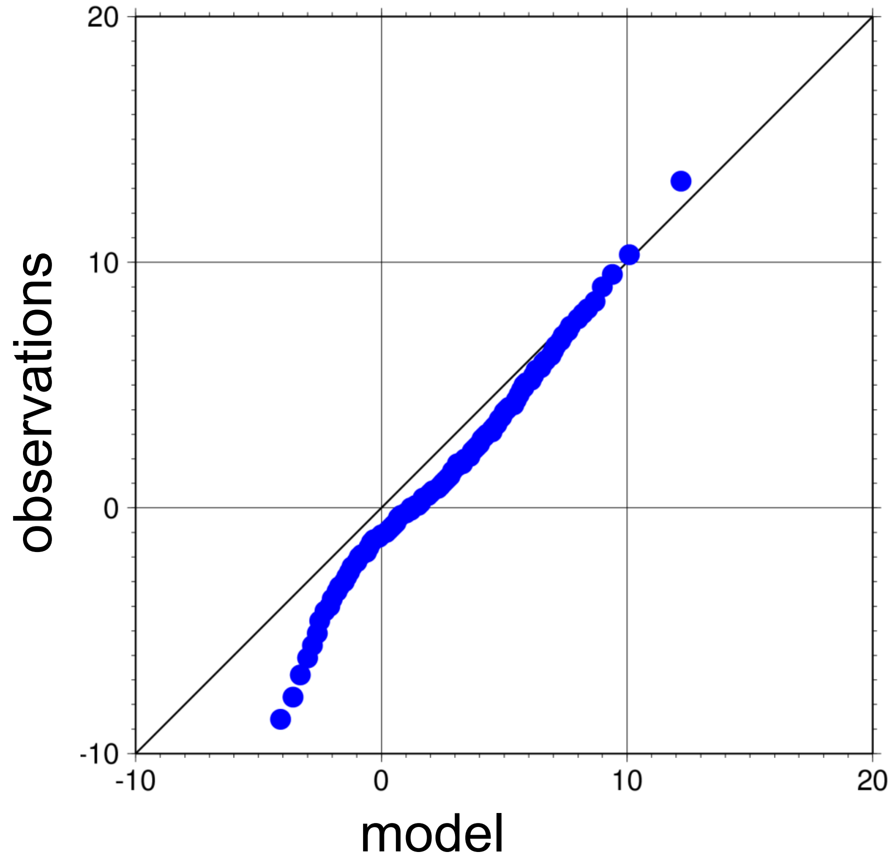
Results based on temperature and precipitation change
(Scenario A1B / ARPEGE-Climate RCM 50 km)

Source: Météo-France

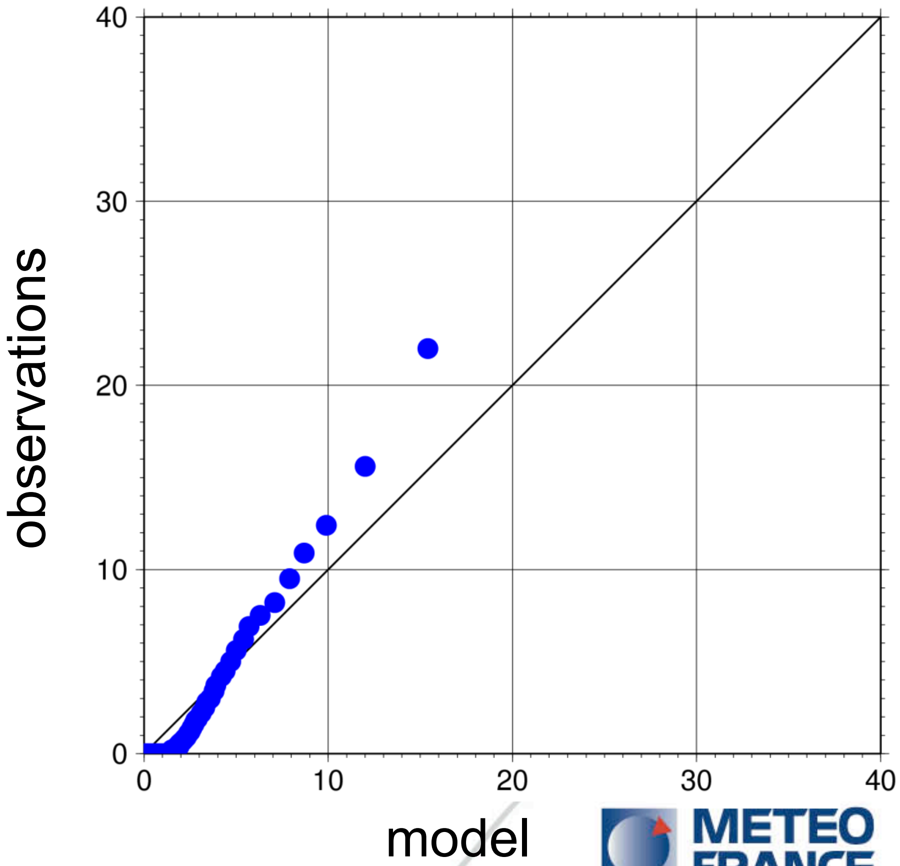
Illustration of RCM evaluation:
daily distribution and extreme

Quantile-Quantile plot for Paris (1960-1989)

Winter minimum temperature (DJF, °C)



Summer precipitation (JJA, mm/d)



Source: Météo-France

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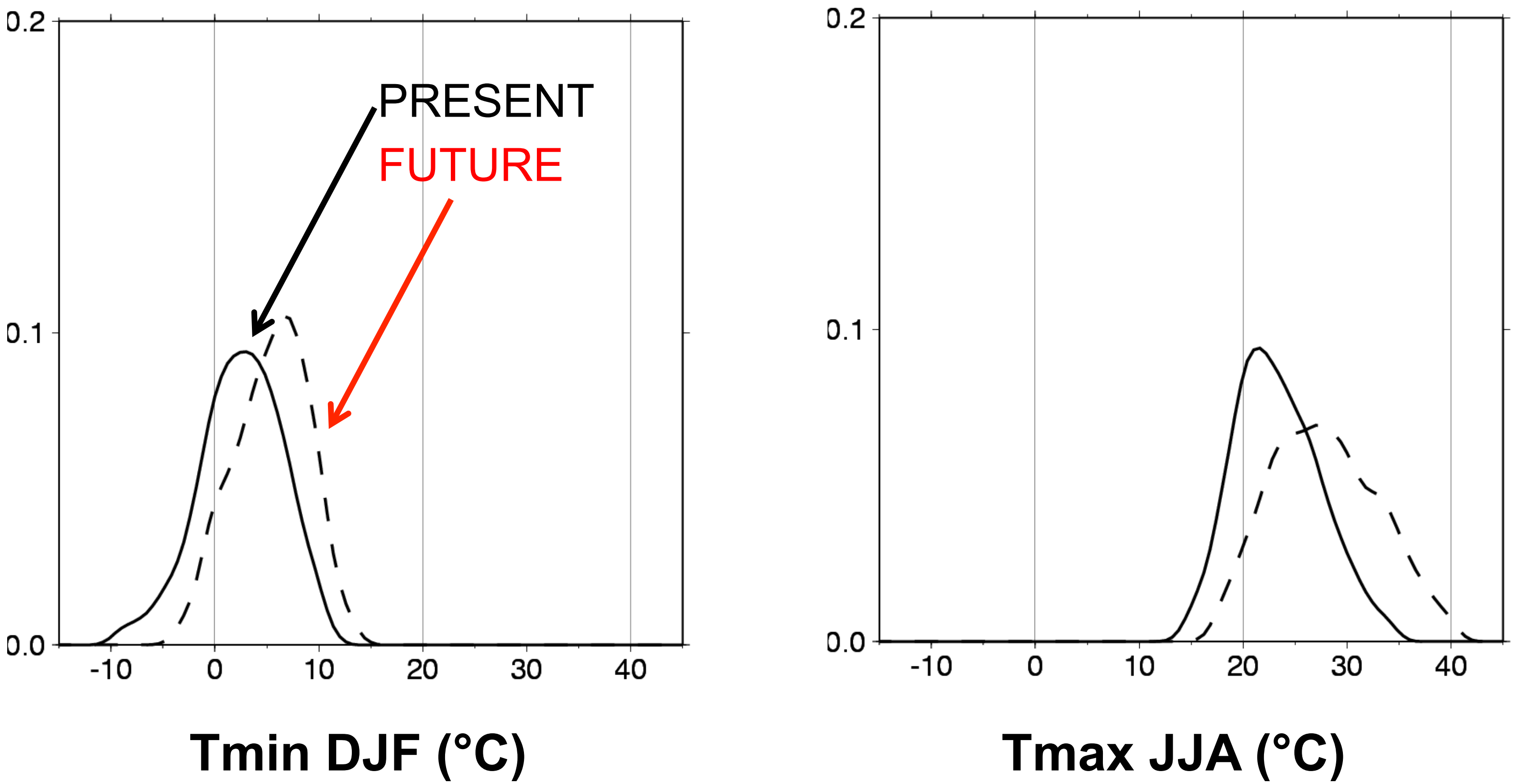
Illustration of RCM scenario:
daily distribution and extreme

Temperature daily probability density functions (Paris)



Scenario A2, ARPEGE-Climat RCM 50 km, 2070-2099 vs 1960-1989

Source: Météo-France

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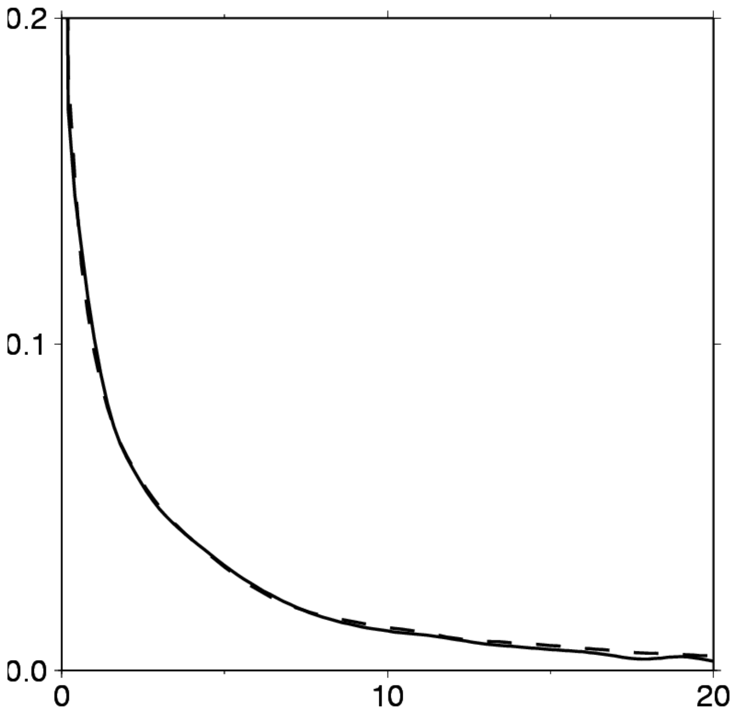
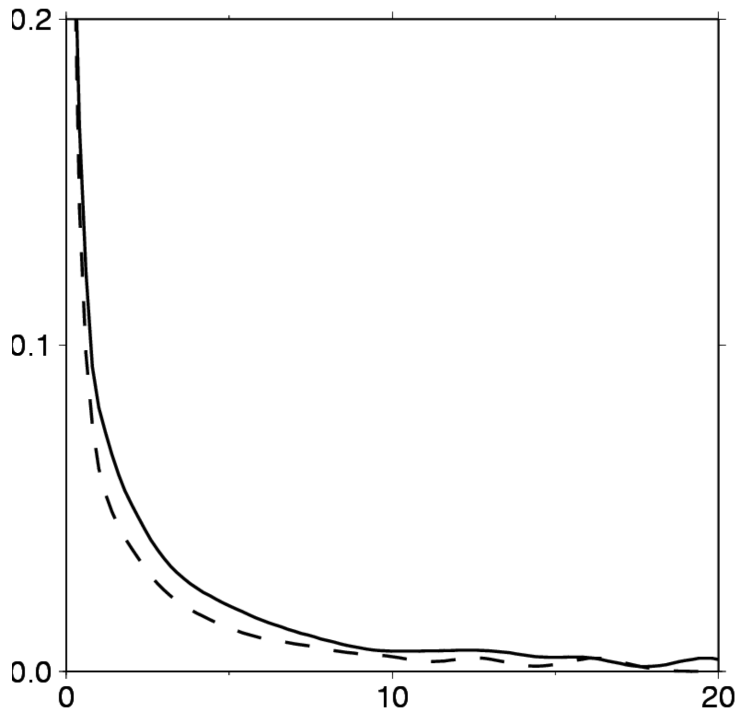
Illustration of RCM scenario:
daily distribution and extreme

Precipitation daily probability density functions (Paris)



Precipitation DJF (mm/d)



Precipitation JJA (mm/d)

Scenario A2, ARPEGE-Climat RCM 50 km, 2070-2099 vs 1960-1989

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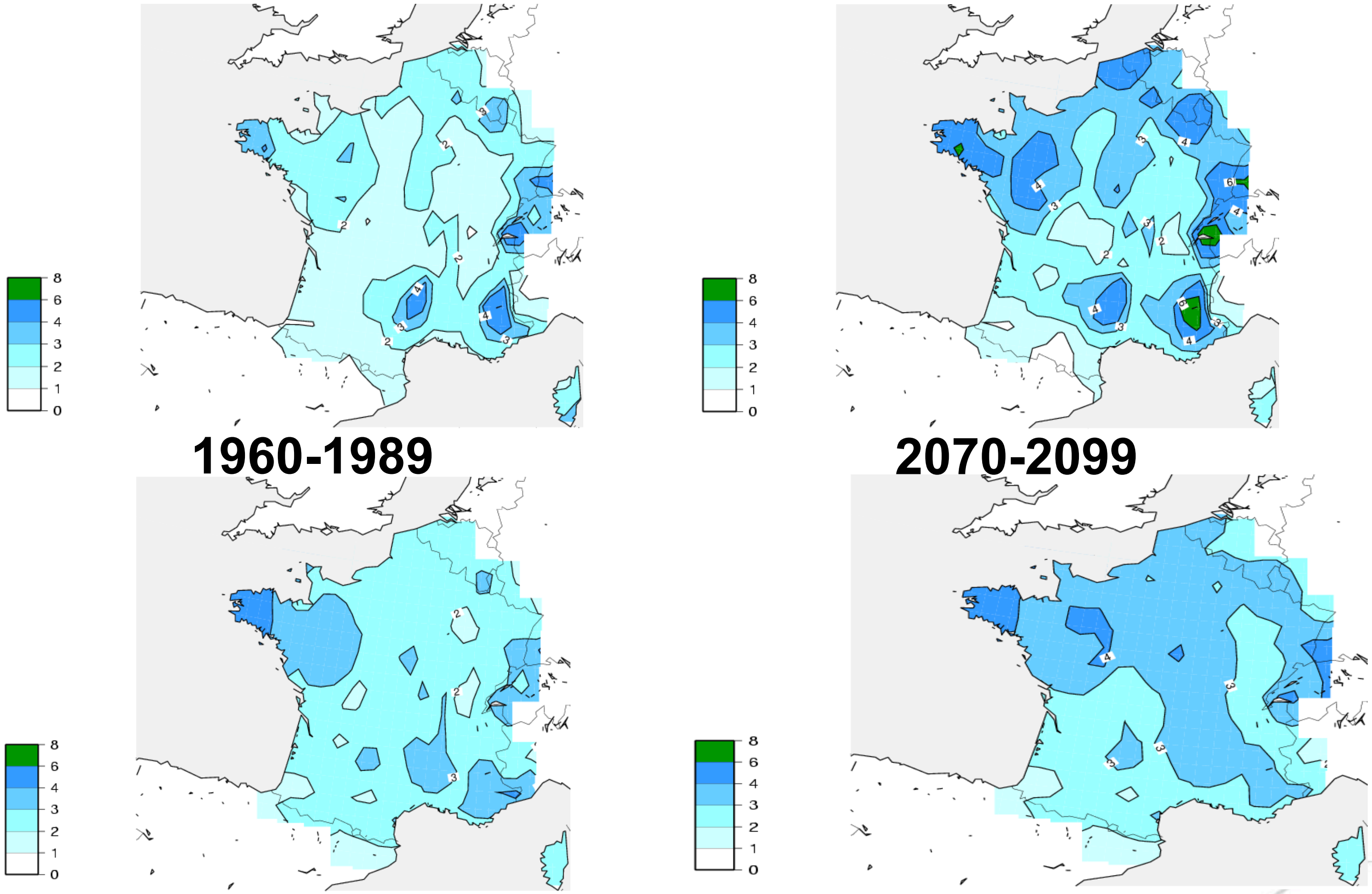
Source: Météo-France

Illustration of RCM scenario:
extreme indices

Number of days per year with precipitation >20mm

Winter (DJF)

Autumn (SON)



ARPEGE-Climat RCM, 50 km, A2

Source: Météo-France

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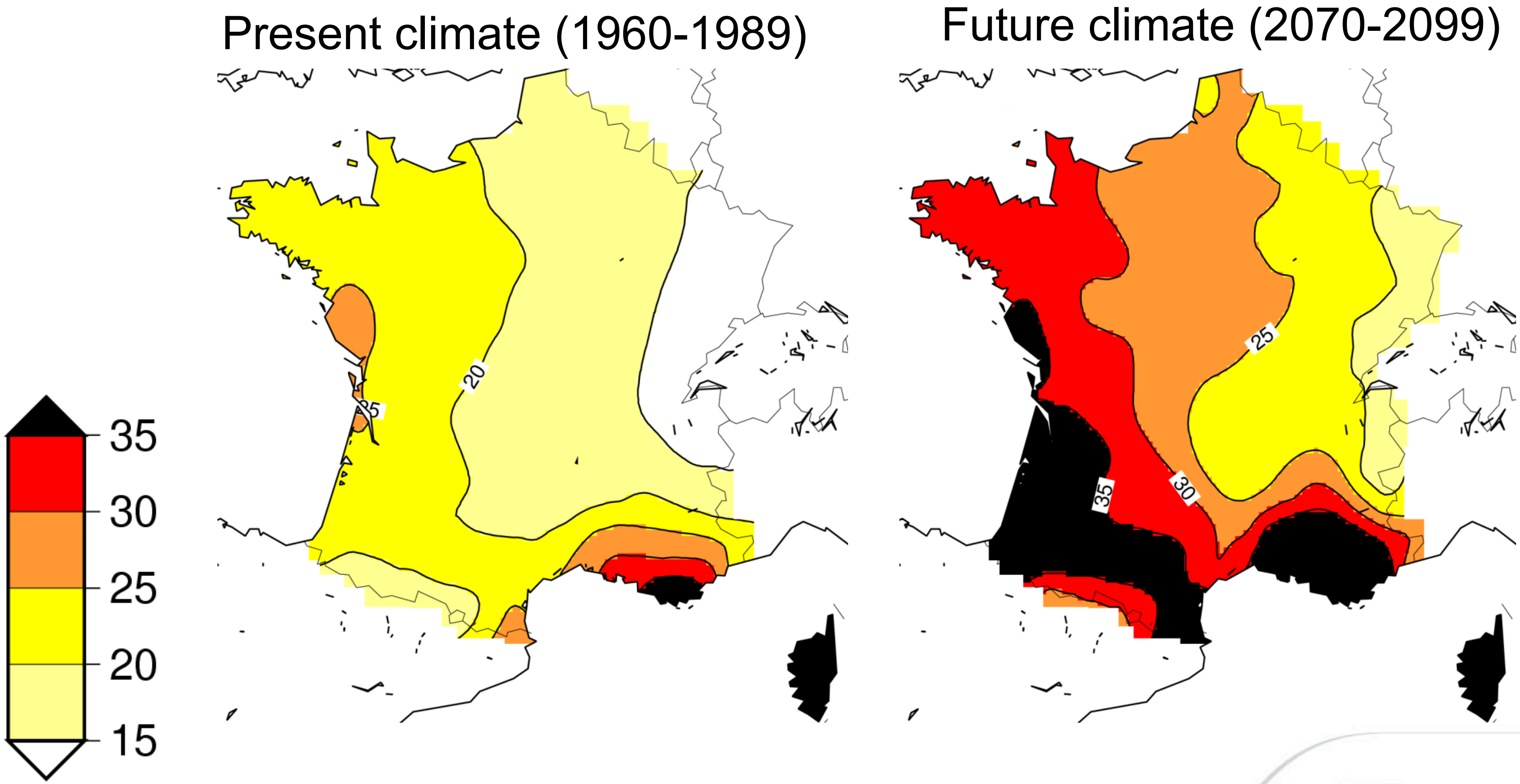
Illustration of RCM scenario:
extreme indices

Drought indice: Maximum number of consecutive dry days (JJA)

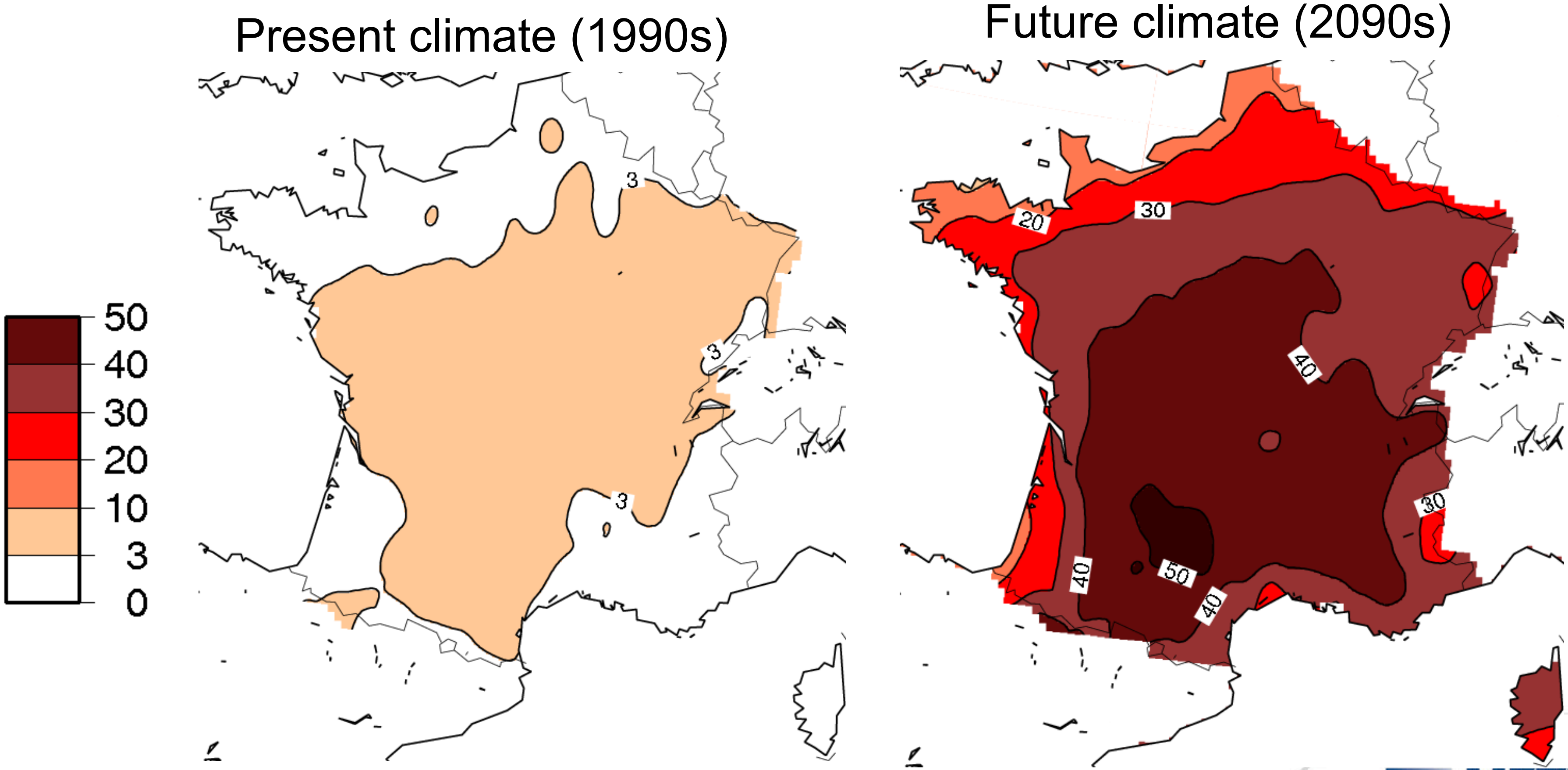


ARPEGE-Climat RCM, 50 km, A2

Source: Météo-France

Illustration of RCM scenario:
extreme indices

Number of Summer heat wave days per year
(Tmax anomaly of +5°C during at least 6 consecutive day)

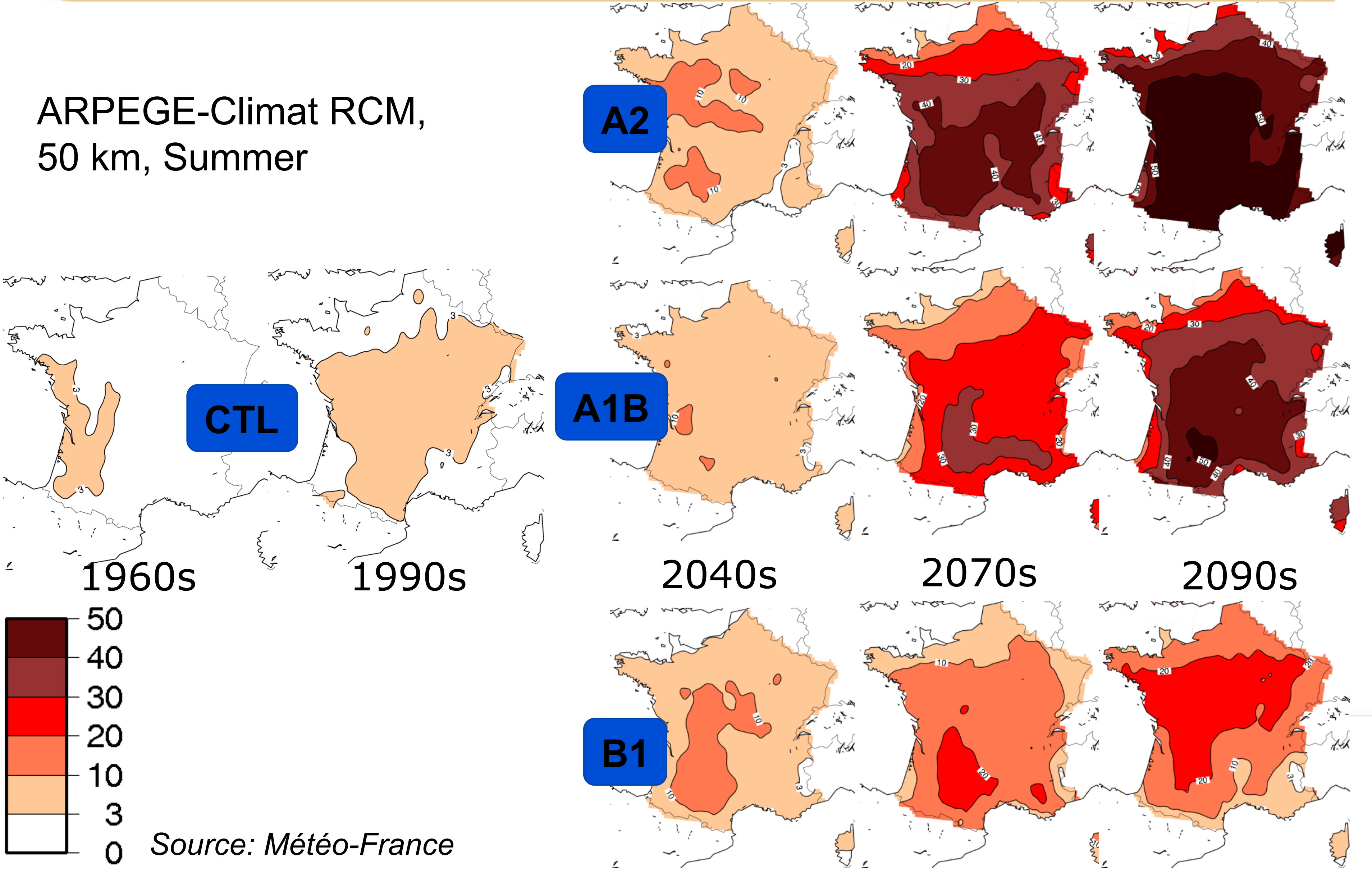


ARPEGE-Climat RCM, 50 km, scenario A1B, Summer

Source: Météo-France

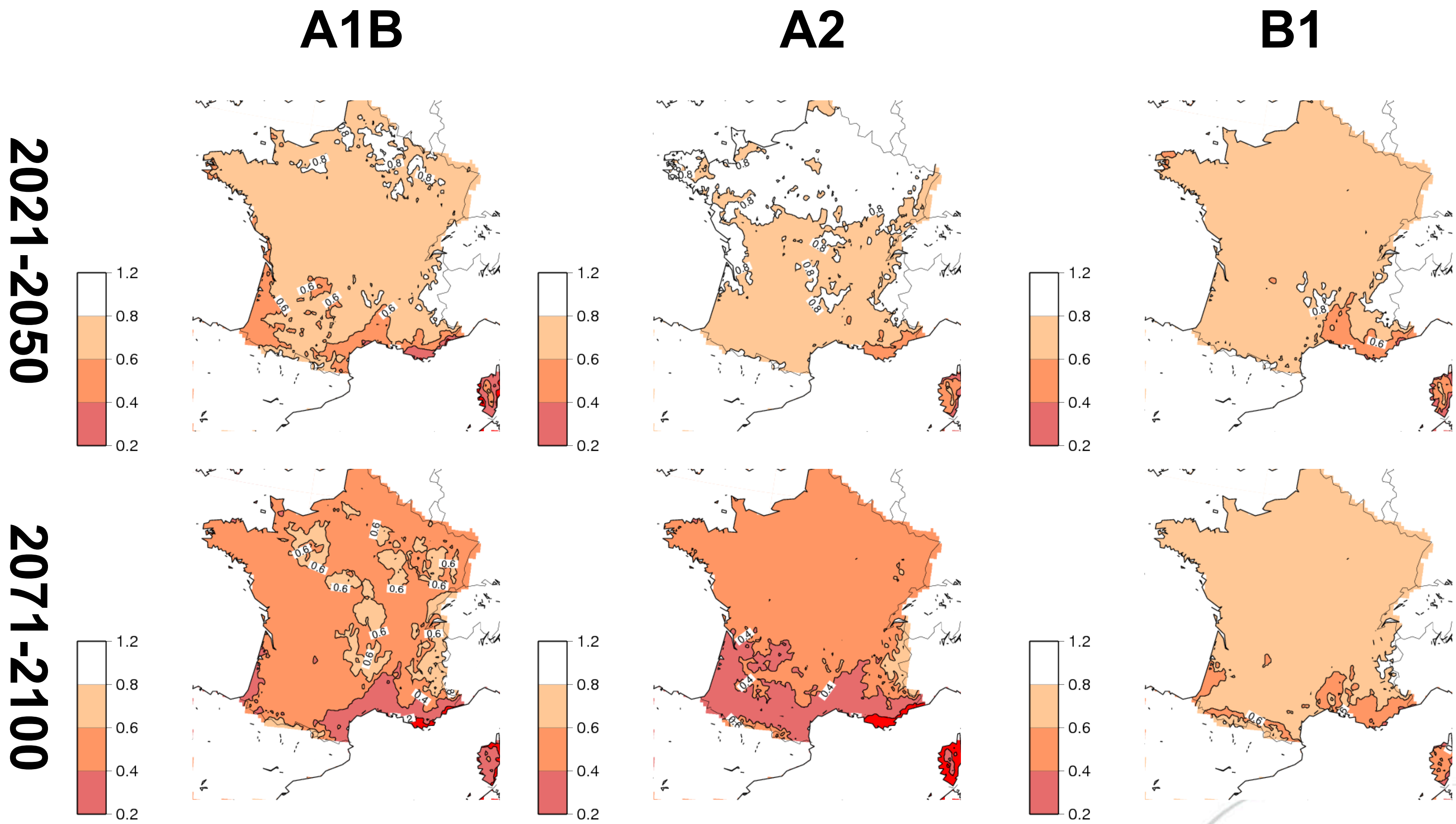
Number of Summer heat wave days per year
(Tmax anomaly of +5° during at least 6 consecutive day)

ARPEGE-Climat RCM,
50 km, Summer



Source: Météo-France

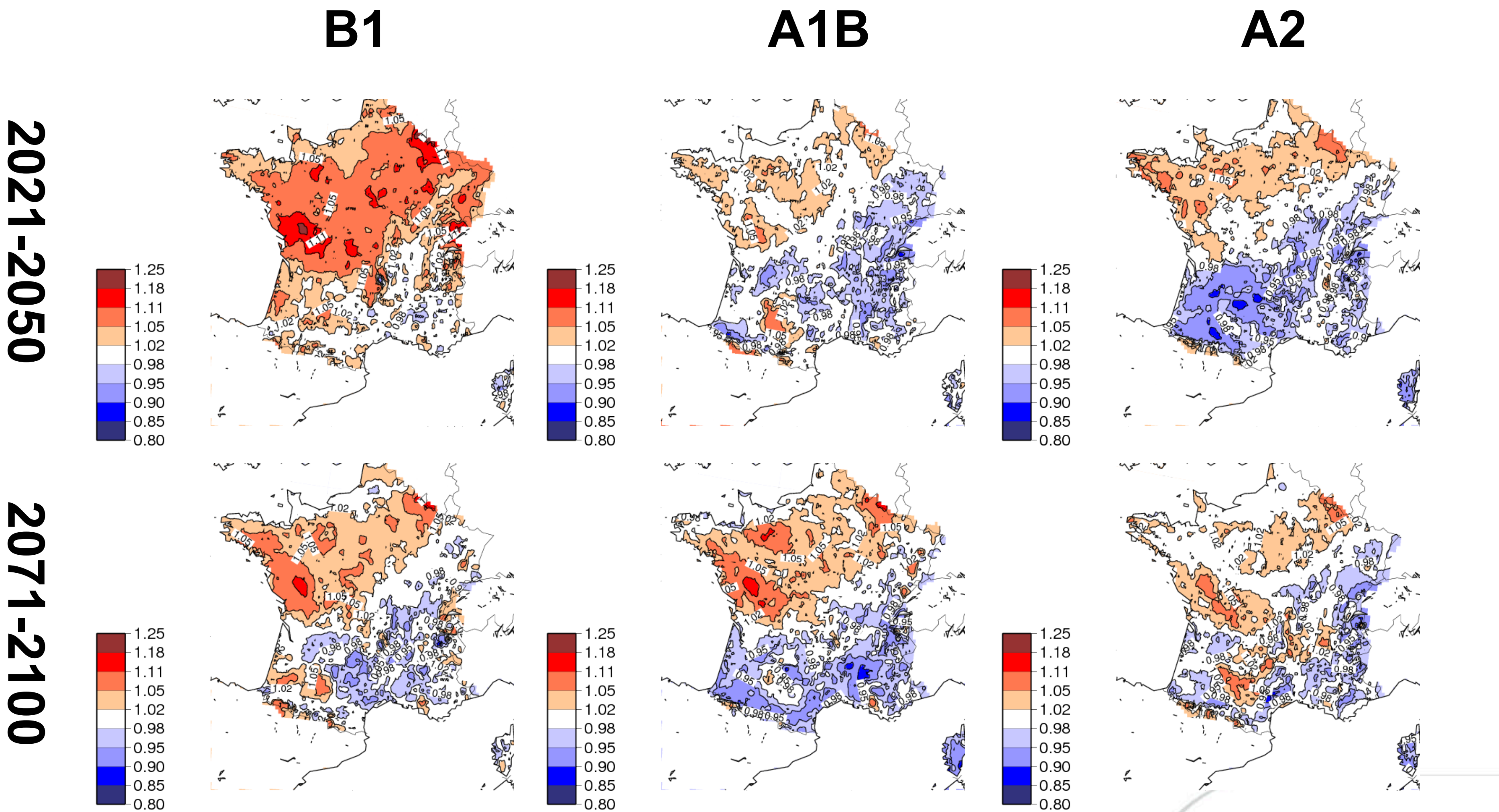
Change in the number of drozen days
(Ratio Future/Present)



ALADIN-Climat, 12 km, Reference: 1961-1990

Source: Météo-France, ANR-SCAMPEI

Change in Winter (DJF) maximum wind speed
Ratio Future/Present



ALADIN-Climat, 12 km, Reference: 1961-1990

Source: Météo-France, ANR-SCAMPEI

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Uncertainty in regional climate change scenarios

- Uncertainty for the GCM simulations (CMIP models)
  - Socio-economic assumptions
  - Emission and concentration scenarios (B1, A1B, A2, …)
  - Choice of the GCM (model configuration, model systematic error)
  - Internal climate variability

- Uncertainty for the RCM simulations
  - The one inheritated from the GCM

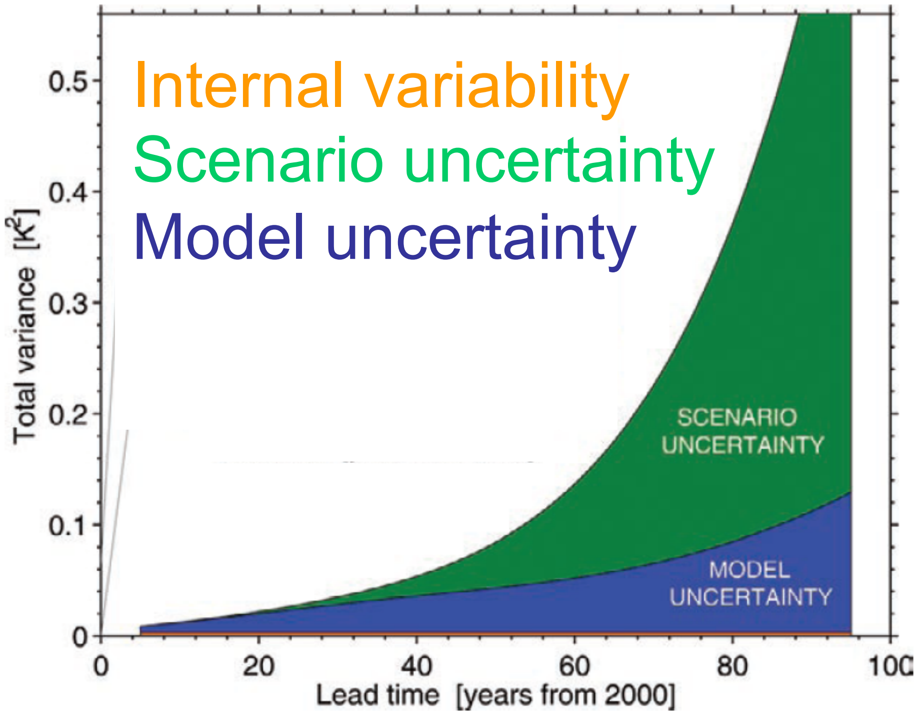
  PLUS
  - Choice of the RCM (model configuration, model systematic error)
  - Internal variability

- Currently, the RCM numerical cost and the large uncertainty range lead to the impossibility to cover all the uncertainties in regional climate change scenarios
  - Results based on limited number of GCM-RCM pairs for some scenarios
  - Methods combining RCM runs and statistics are used to virtually full-fill the SCENxGCMxRCMxIV matrix

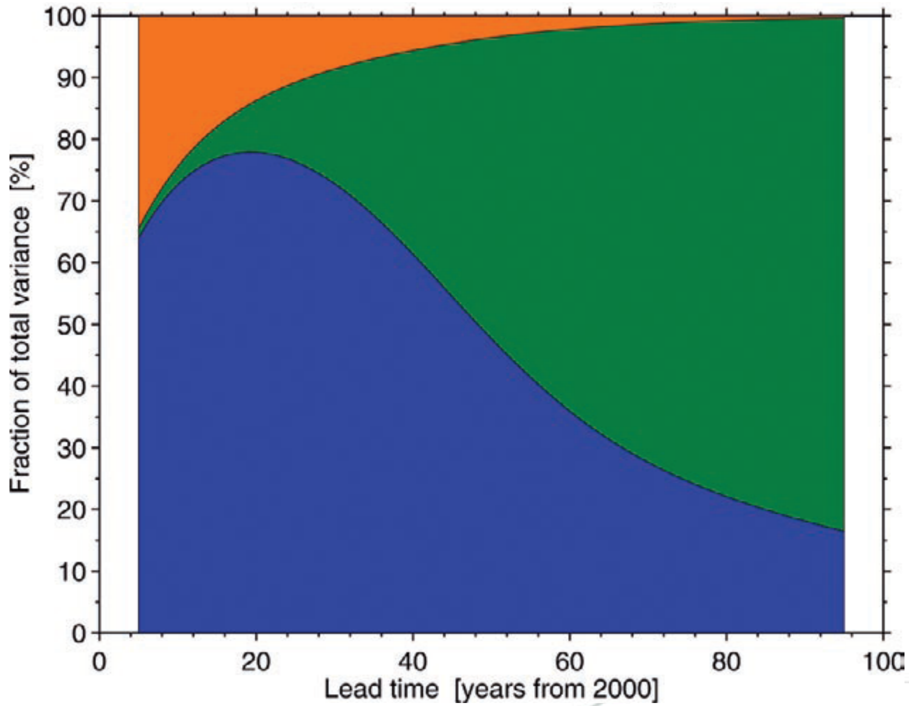
Source of climate change uncertainty

Fraction of uncertainty explained by different sources as a function of lead time

Temperature (average. per decade), global average, CMIP3 models



Absolute uncertainty

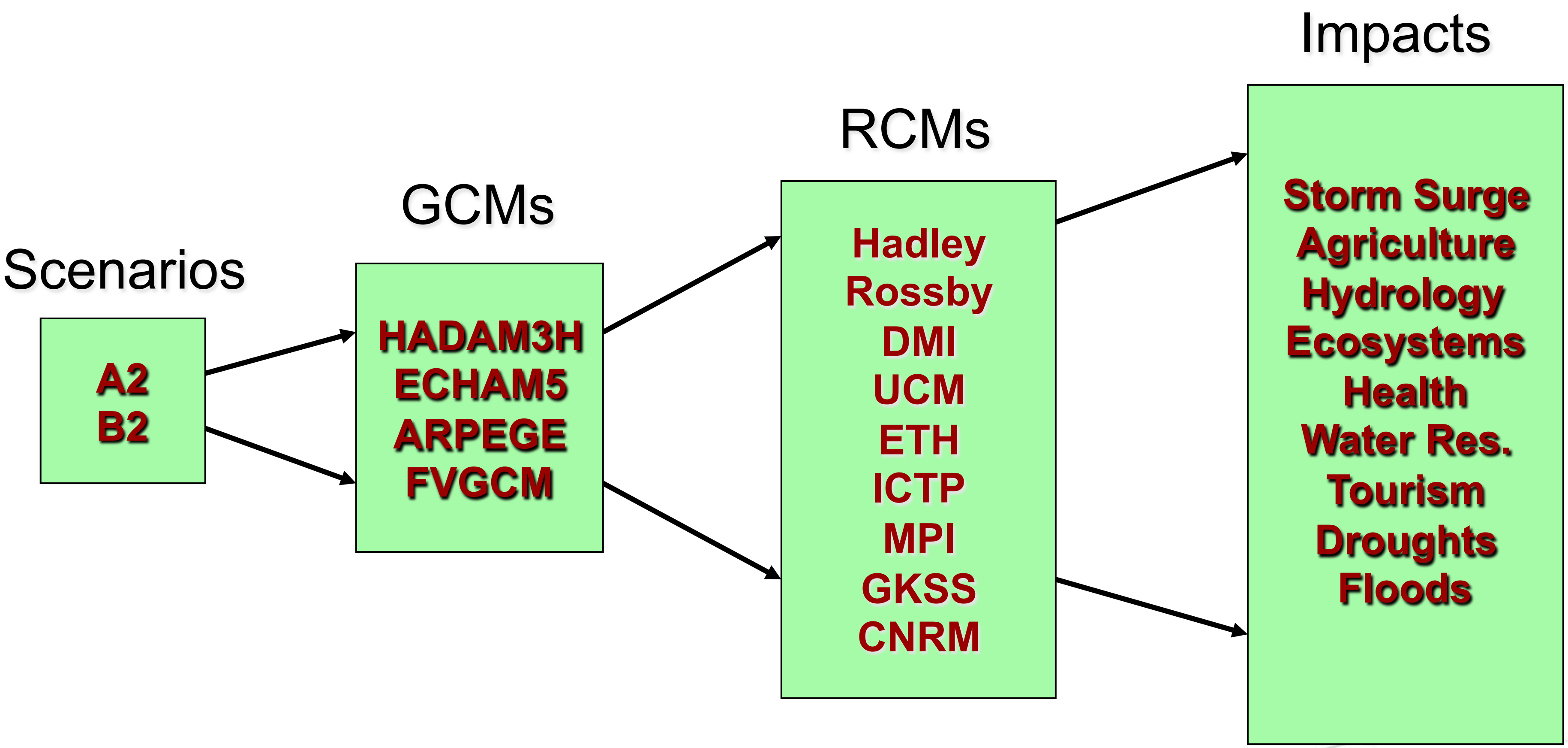


Relative uncertainty

Source: Hawkins et Sutton, BAMS, 2009

Uncertainty in regional climate change scenarios

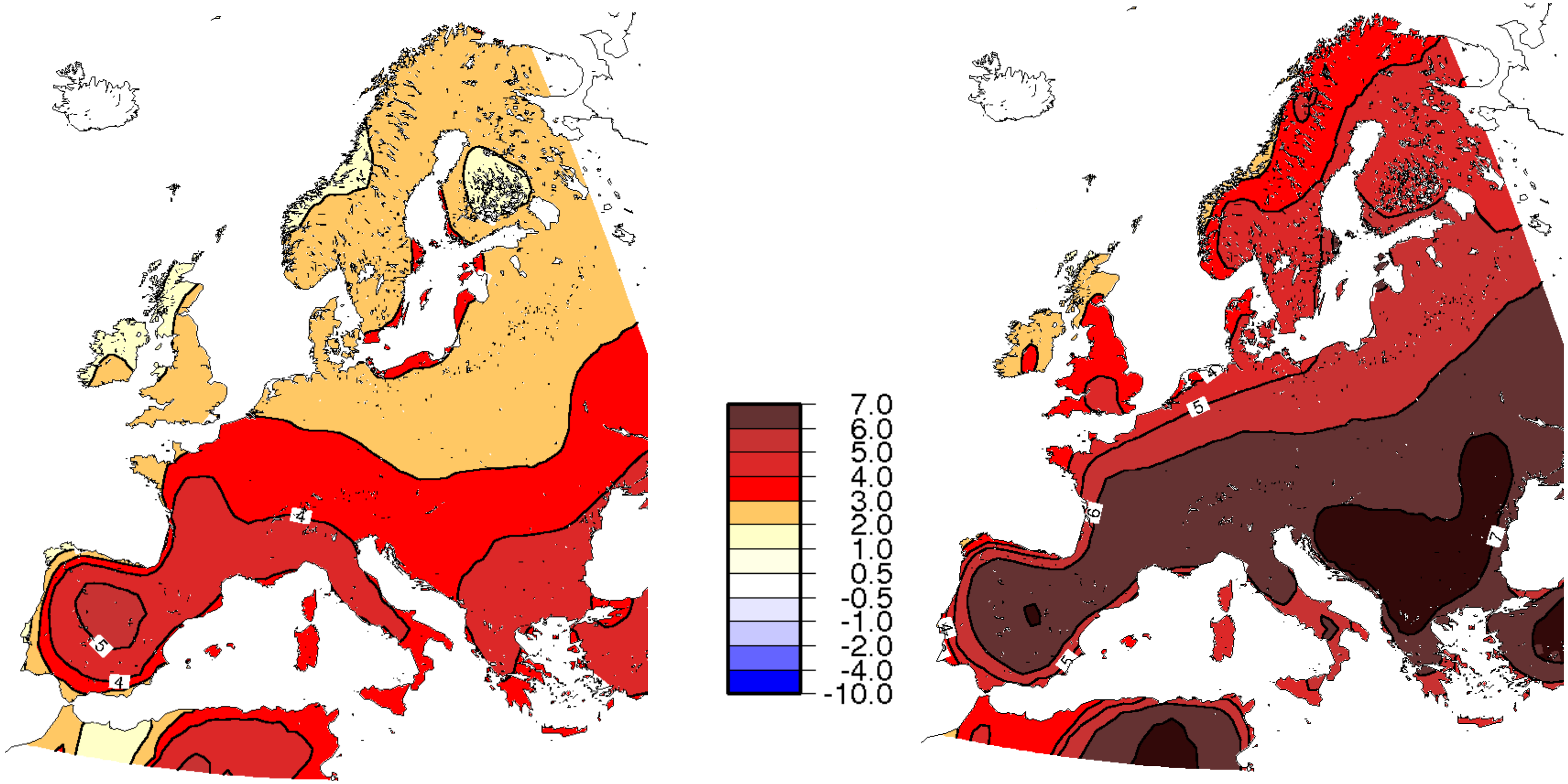
The PRUDENCE project strategy



Source: Giorgi, FP5-PRUDENCE project

Uncertainty in regional climate change scenarios

Choice of the RCM: change in temperature (Summer, °C)



Mini (10 models)

Maxi (10 models)

Scenario A2, 2070-2099 vs 1960-1989, 50 km

Source: PRUDENCE: http://prudence.dmi.dk/ (2004)

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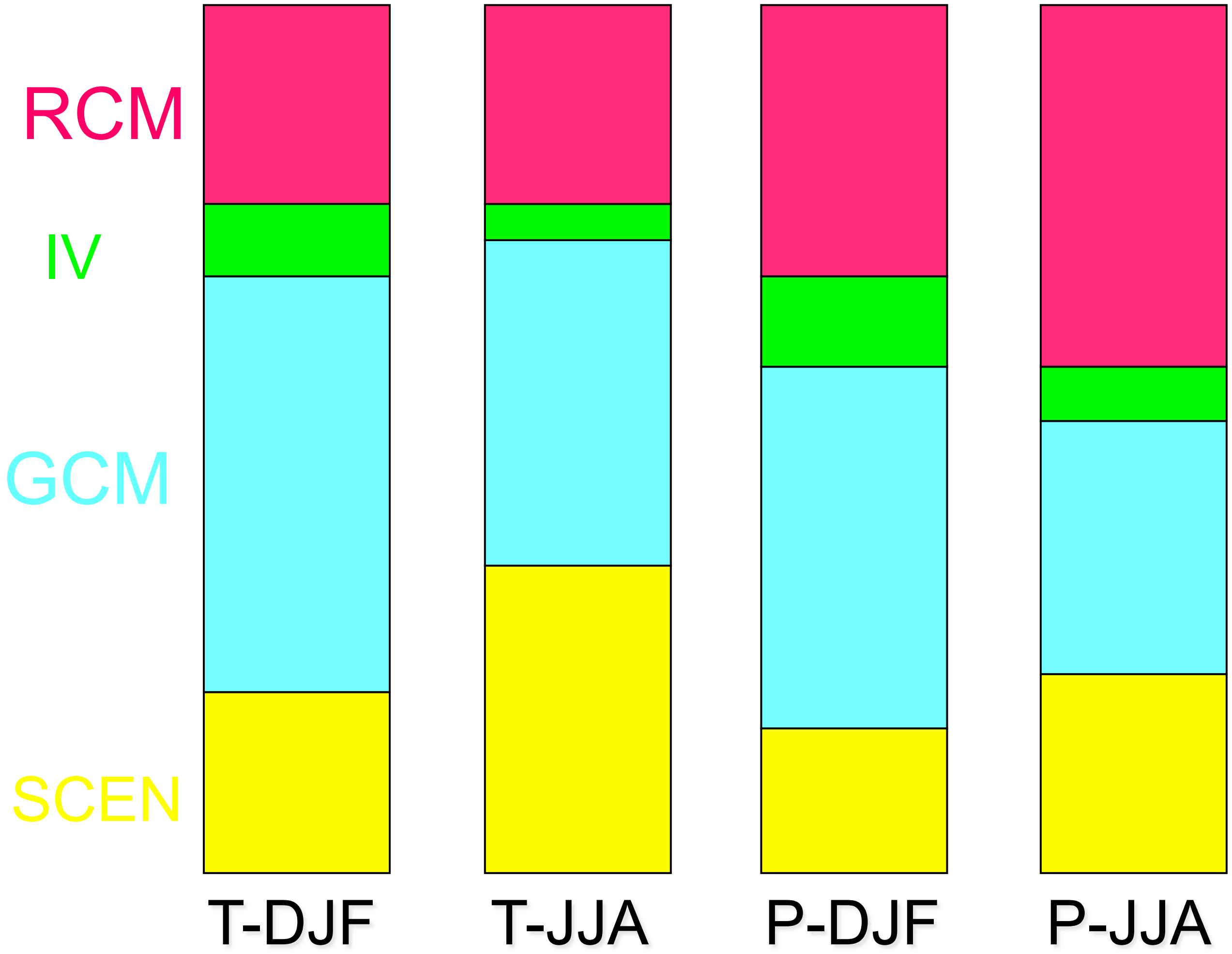
Uncertainty in regional climate change scenarios

Sources of uncertainty in the simulation of temperature and precipitation change (2071-2100 minus 1961-1990) over Europe



- Note1: the scenario range is about half of the full IPCC range

- Note 2: the GCM range does not cover the full IPCC range

Source: adapted from Déqué et al. 2006, PRUDENCE project

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Uncertainty in regional climate change scenarios

The ENSEMBLES project (European project, FP6)

- The whole European domain
- ERA-40 driven runs + transient scenario A1B
- 7 GCMs (CNRM, METOHC(3), MPI, BCM, CGCM)
- 14 RCMs (C4I, CNRM, DMI, ETHZ, ICTP, KNMI, METNO, METOHC(3), MPI, SMHI, UCLM, OURANOS)
- 25 km resolution
- 19 available runs for the period 1950-2050
- 13 available runs for the period 2051-2100
- Weighted models
- Statistical methods to complete the GCMxRCM matrix
- Probablistic view of the regional climate change
- Data available: http://ensemblesrt3.dmi.dk/

GCMxRCM matrix

	BCM	CNRM	HC-lo	HC-med	HC-hi	MPI
C4I					X	
CNRM		X				
DMI	X	X				X
ETHZ				X		
HC-lo			X			
HC-med				X		
HC-hi					X	
ICTP						X
KNMI						X
METN	X			X		
MPI						X
SMHI	X		X			X
UCLM				X		

Source: FP6-ENSEMBLES project

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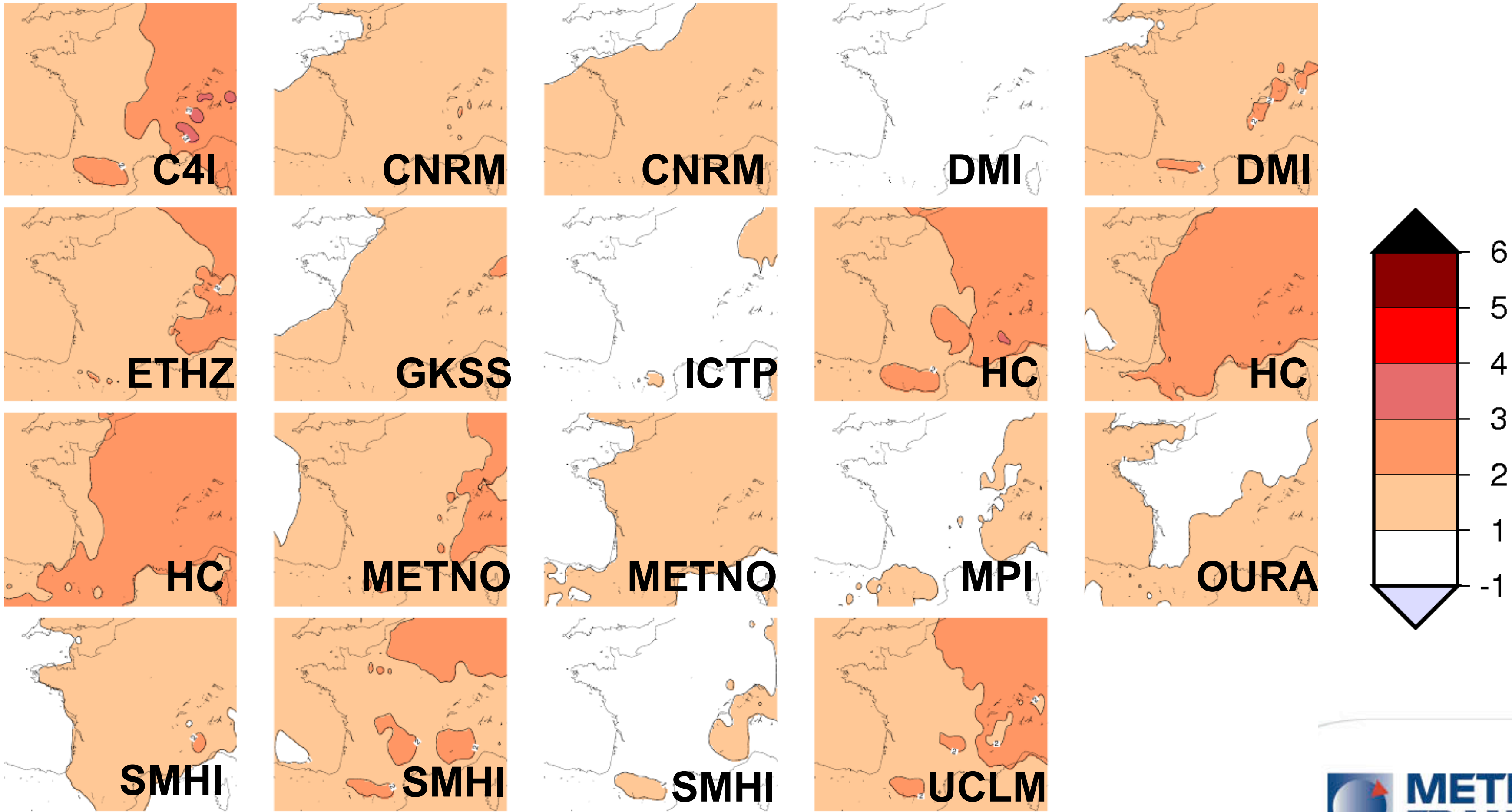
Uncertainty: ENSEMBLES project results

Temperature change (°C) in Winter,
2021-2050 vs 1961-1990, 19 runs, 25 km, A1B



Source: Météo-France, FP6-ENSEMBLES

METEO FRANCE
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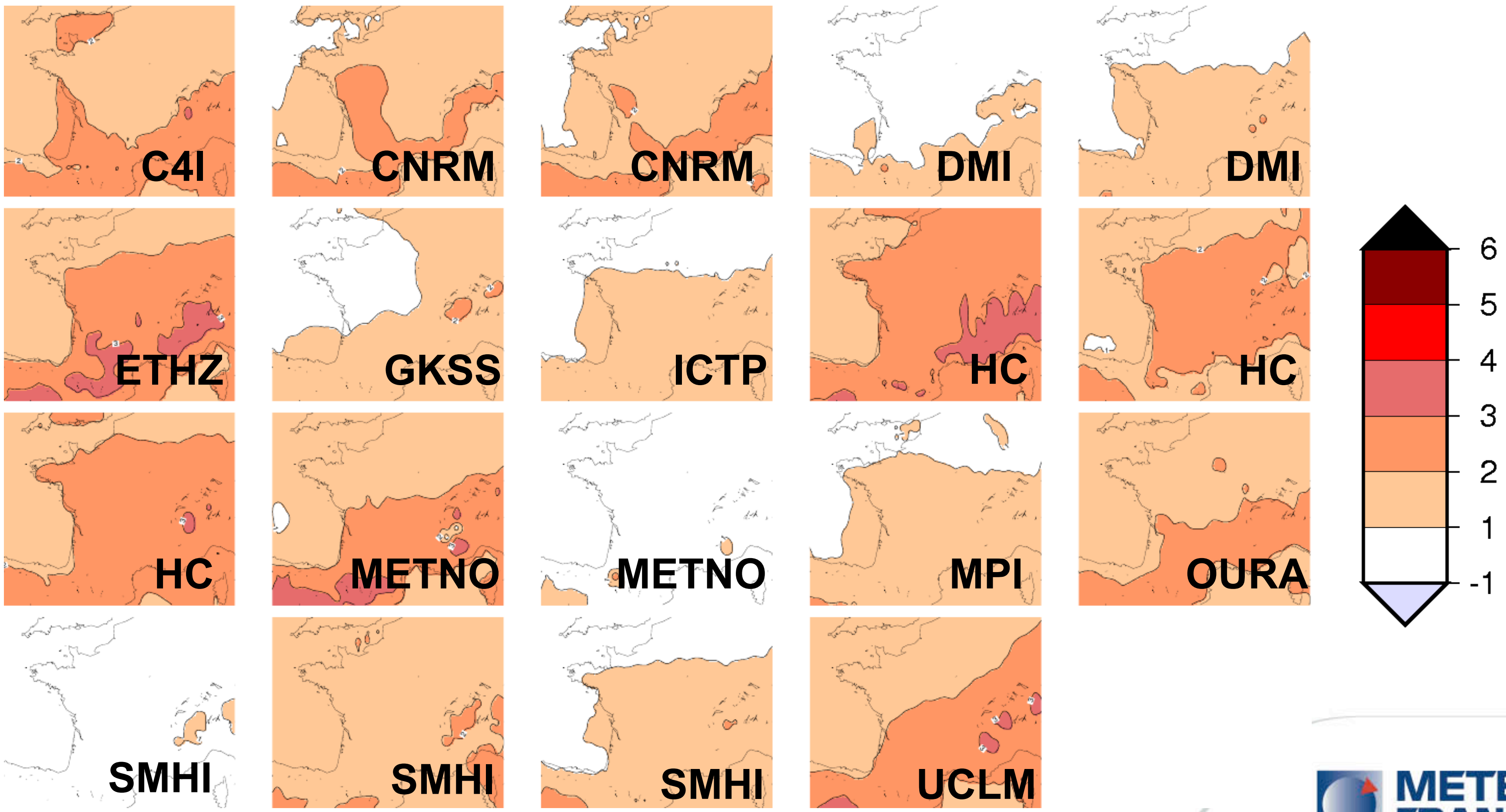
Uncertainty: ENSEMBLES project results

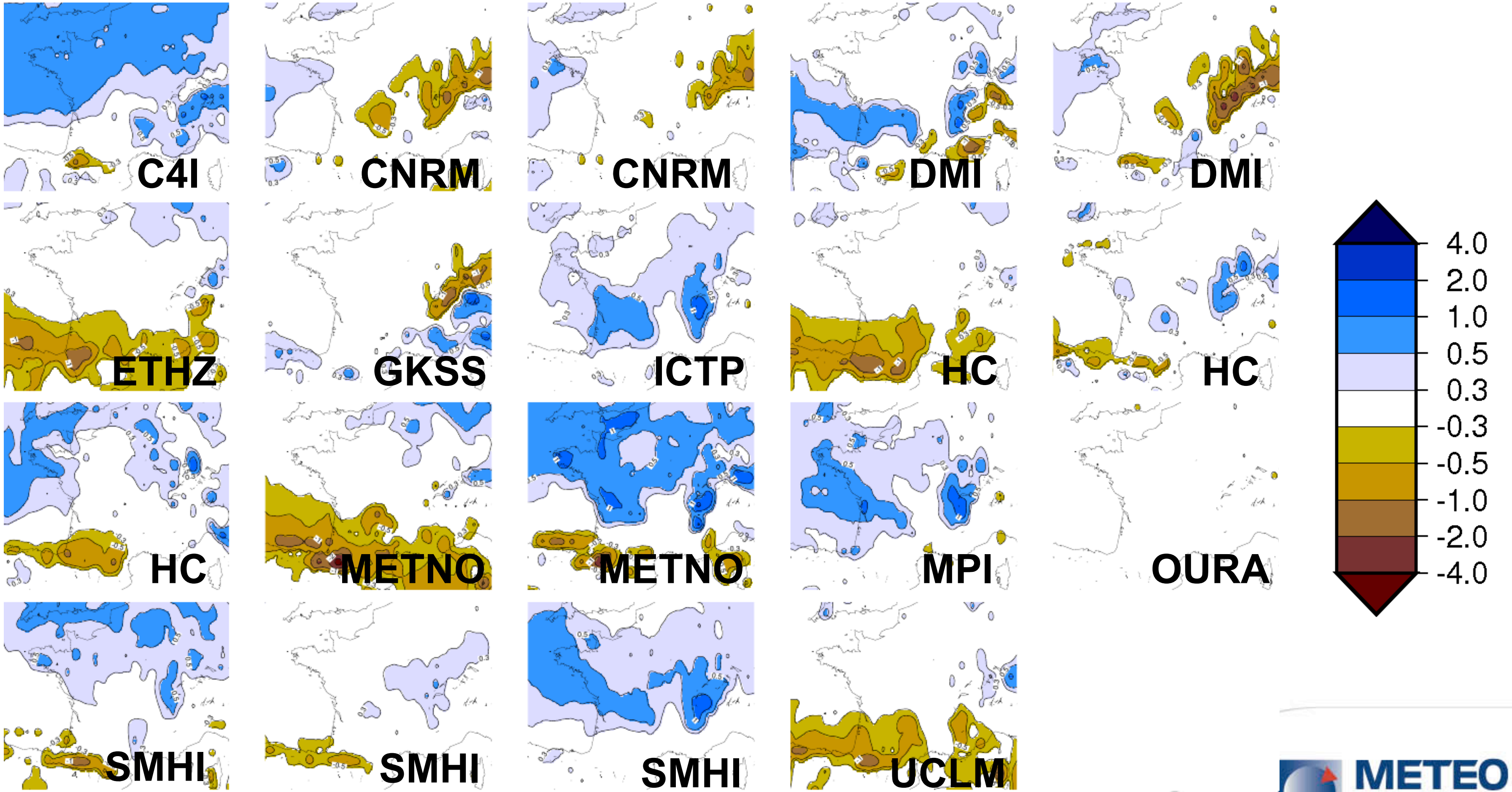
Temperature change (°C) in Summer,
2021-2050 vs 1961-1990, 19 runs, 25 km , A1B



Source: Météo-France, FP6-ENSEMBLES

Uncertainty: ENSEMBLES project results

Precipitation change (mm/d) in Winter,
2021-2050 vs 1961-1990, 19 runs, 25 km , A1B



Source: Météo-France, FP6-ENSEMBLES

METEO FRANCE
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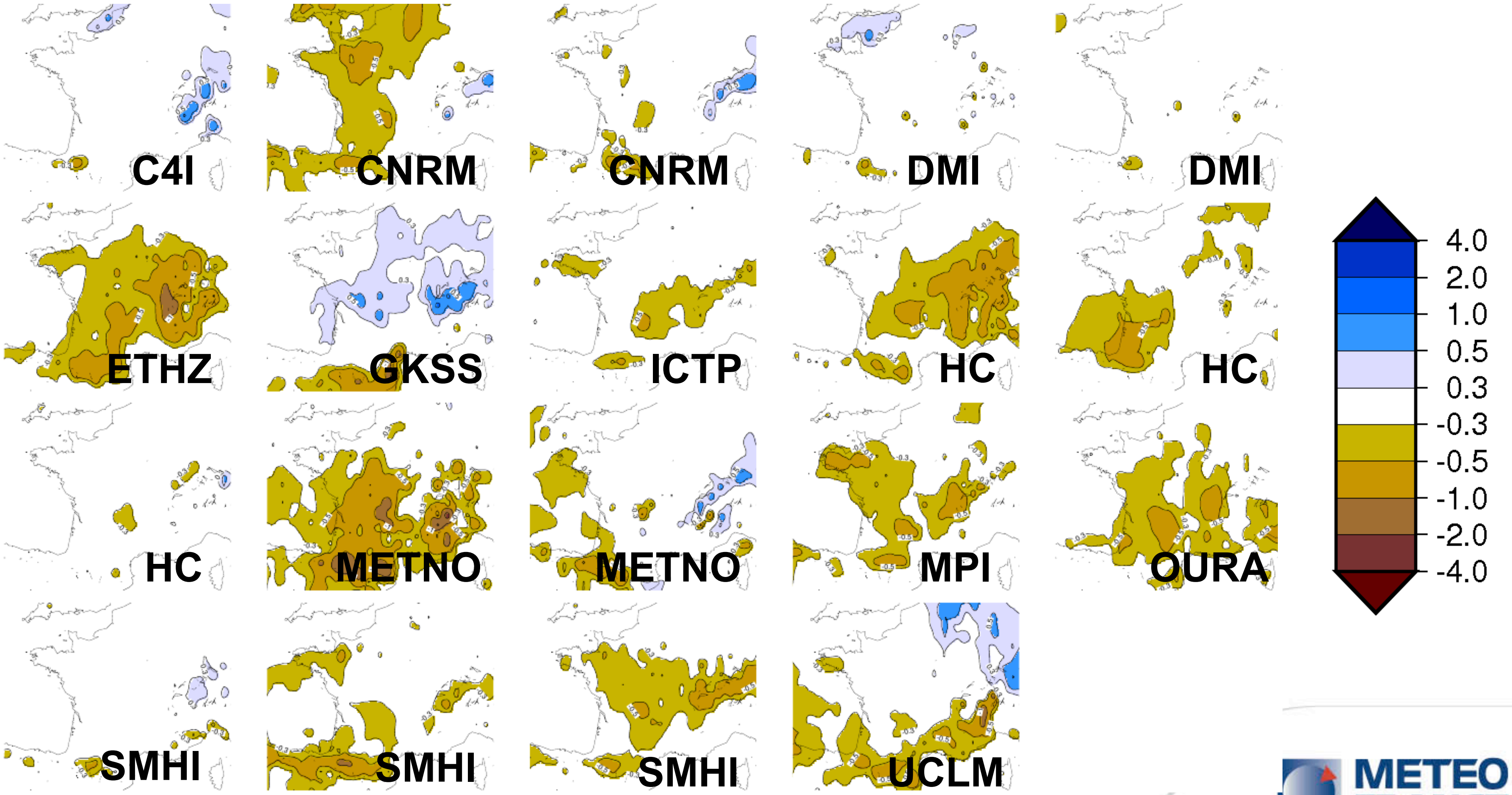
Uncertainty: ENSEMBLES project results

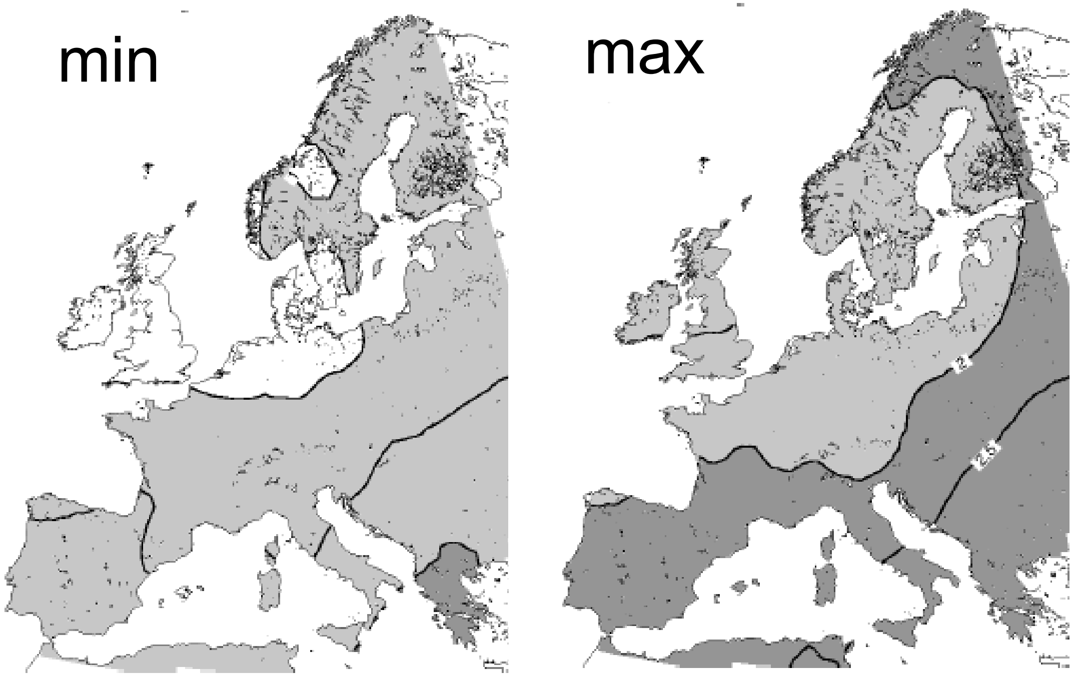
Precipitation change (mm/d) in Summer,
2021-2050 vs 1961-1990, 19 runs, 25 km , A1B



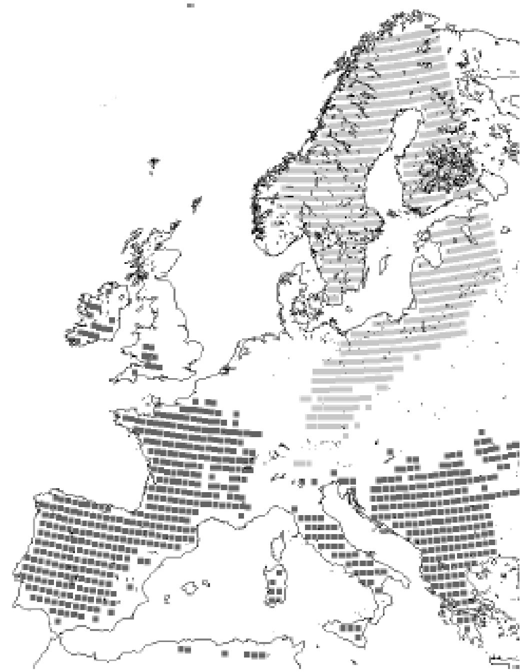
Source: Météo-France, FP6-ENSEMBLES

Uncertainty: ENSEMBLES project results

Confidence interval (at 99%) of the temperature change in Summer (°C)



Grid point with significant change in precipitation in Summer

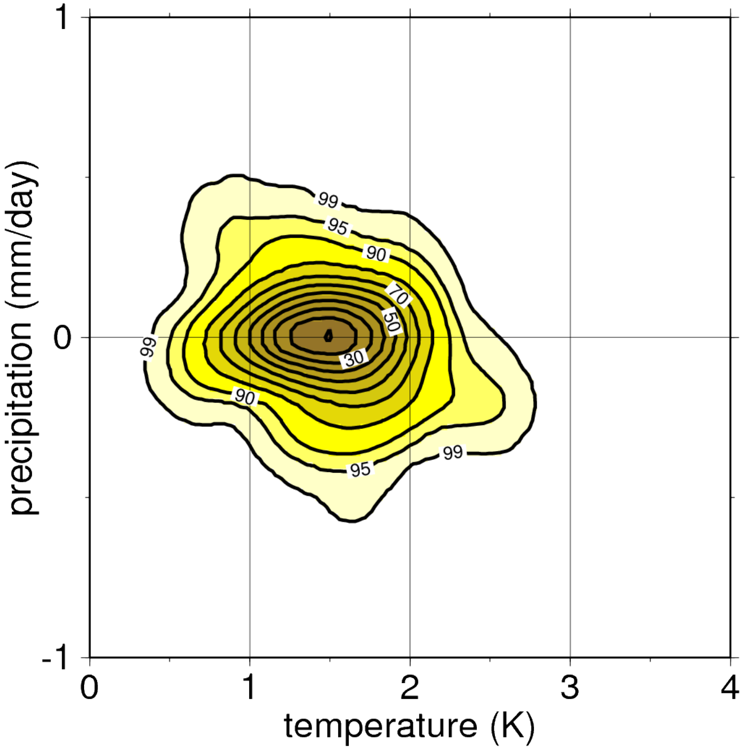


Scenario A1B, 2021-2050 vs 1961-1990, 25 km, 18 runs

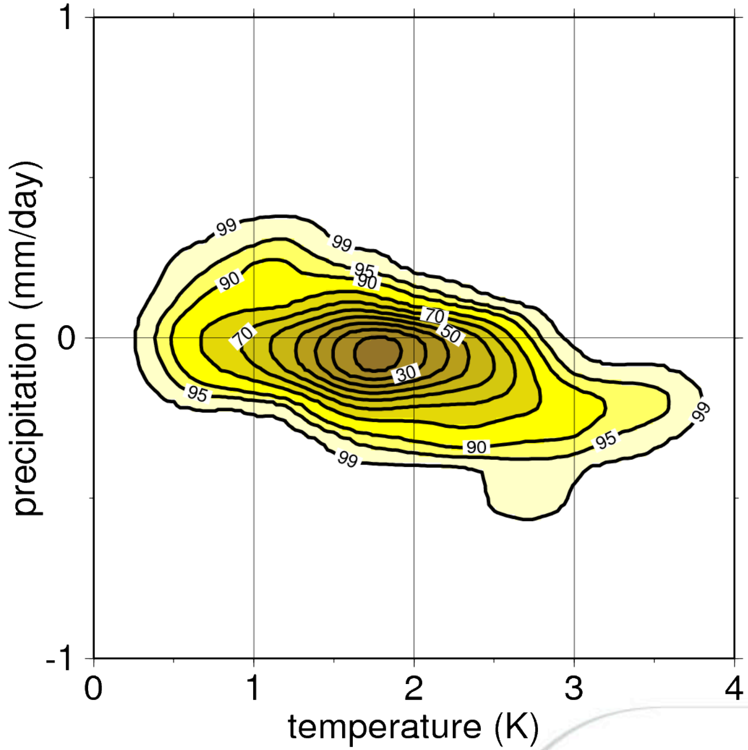
Source: FP6-ENSEMBLES, Déqué et al. 2012

Uncertainty: ENSEMBLES project results

Bivariate (temp, prec) climate change pdf for Barcelona
Scenario A1B, 2021-2050 vs 1961-1990, 25 km
Using 78 virtual runs after filling the matrix with statistics



Winter

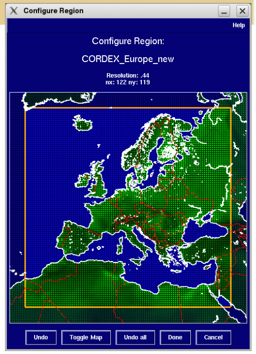


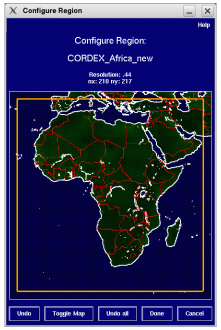
Summer

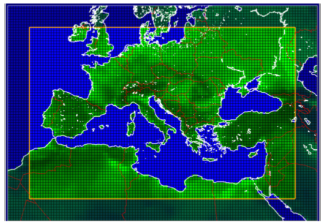
Source: FP6-ENSEMBLES, Déqué and Somot 2010; Déqué et al. 2012

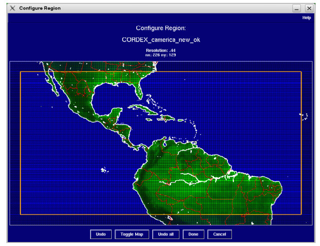
The CORDEX international programme

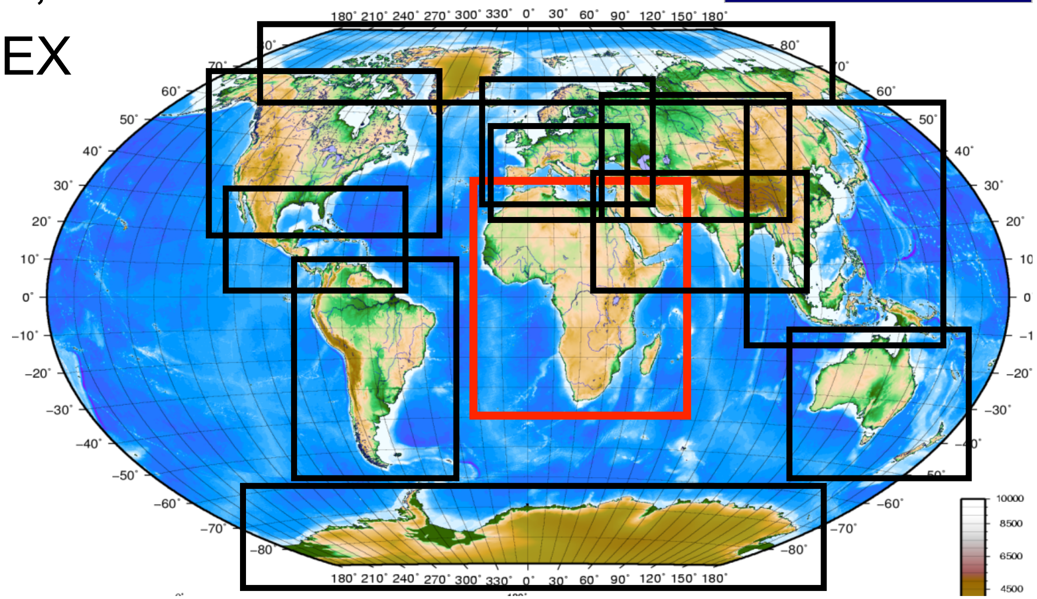
- Launched by WCRP (first meeting in Toulouse, February, 2009)
- Coordinated by F. Giorgi (ICTP) and C. Jones (SMHI)
- Evaluation: ERA-Interim, 1989-2008
- Scenario: CMIP5, RCP8.5, RCP4.5, 1950-2100
- Many GCMs and many RCMs
- 50 km resolution, 12 official domains
- Priority domain: Afro-CORDEX
- 50 km and 12 km : Euro-CORDEX, Med-CORDEX
- ARCM and AORCM: Med-CORDEX
- DMI central archive, ESG, regional database

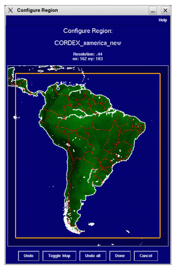


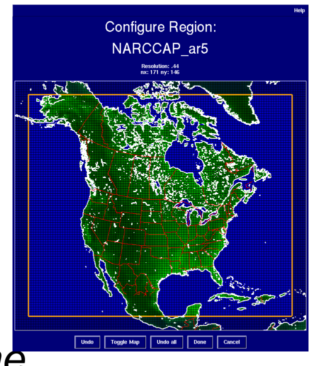












Source: CORDEX programme

Conclusion: Regional climate modelling

- **Regional climate models are mature tools to study regional climate change : a lot of results already available**

- **They can bring clear added-value wrt GCM or reanalysis for chosen spatial and temporal scales**

- **RCM are not perfect and sometimes do not add value to driver**

- **They are an additional layer of uncertainty to be taken into account**

- **RCM are useful in the following conditions:**
  - You want to prove an added-value for a given process/area
  - You are interested in small spatial scales, extreme events, coastal areas, moutainuous areas, islands, …
  - The RCM used has been well evaluated over the area of interest
  - GCMs agree on the climate change signal over the area of interest
  - Different runs (or better large coordinated projects) are available over the area of interest

Further work: Regional climate modelling

- **Improve uncertainty estimates of regional climate change**
  - Decrease in GCM uncertainties (GCM community)
  - Use statistical methods to full-fill the GCMxRCM matrix
  - Probabilistic climate change using the past large coordinated project outputs (ENSEMBLES)
  - Promote new large coordinated projects for new areas in the world (CORDEX, ocean area, small islands)

- **Develop the next generation of the Regional Climate Models**
  - Improve the quality of the RCM (improved evaluation, physics and dynamics)
  - Add new coupled components of the regional climate system: ocean, rivers, aerosol, land use, lake, city, chemistry, irrigation, dam (CIRCE, HyMeX, CLIM-RUN)
  - Increase the resolution of the regional climate model: 10 km, 2 km (CECILIA, SCAMPEI, CLIM-RUN, Med-CORDEX, Euro-CORDEX)

- **Transfer the data and expertise to the various users**
  - Set-up of operational climate services (DRIAS, CLIM-RUN)

ENSEMBLES ensembles-eu.metoffice.com/
CORDEX wcrp.ipsl.jussieu.fr/RCD_CORDEX.html
CIRCE www.circeproject.eu
CECILIA www.cecilia-eu.org/
HyMeX www.hymex.org/
SCAMPEI www.cnrm.meteo.fr/scampei/
DRIAS www.drias-climat.fr
CLIM-RUN www.climrun.eu

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