UNIVERSIDADE DE LISBOA

IDL | Instituto Dom Luiz | Ciências ULisboa

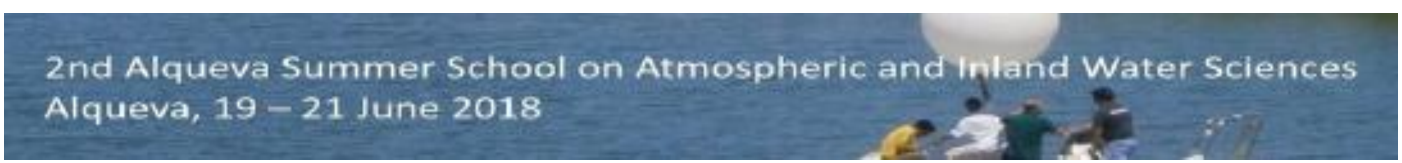
Regional climate modelling and future climate in Portugal

Pedro Matos Soares
(pmsoares@fc.ul.pt)

ALOP Alentejo Observation and Prediction systems

ICT Instituto de Ciências da Terra

UNIVERSIDADE DE ÉVORA
ESCOLA DE CIÊNCIAS E TECNOLOGIA



Agradecimentos:Rita Cardoso, Daniela Lima, Álvaro Semedo, Miguel Nogueira, Ricardo Tomé, Clarisse Magarreiro

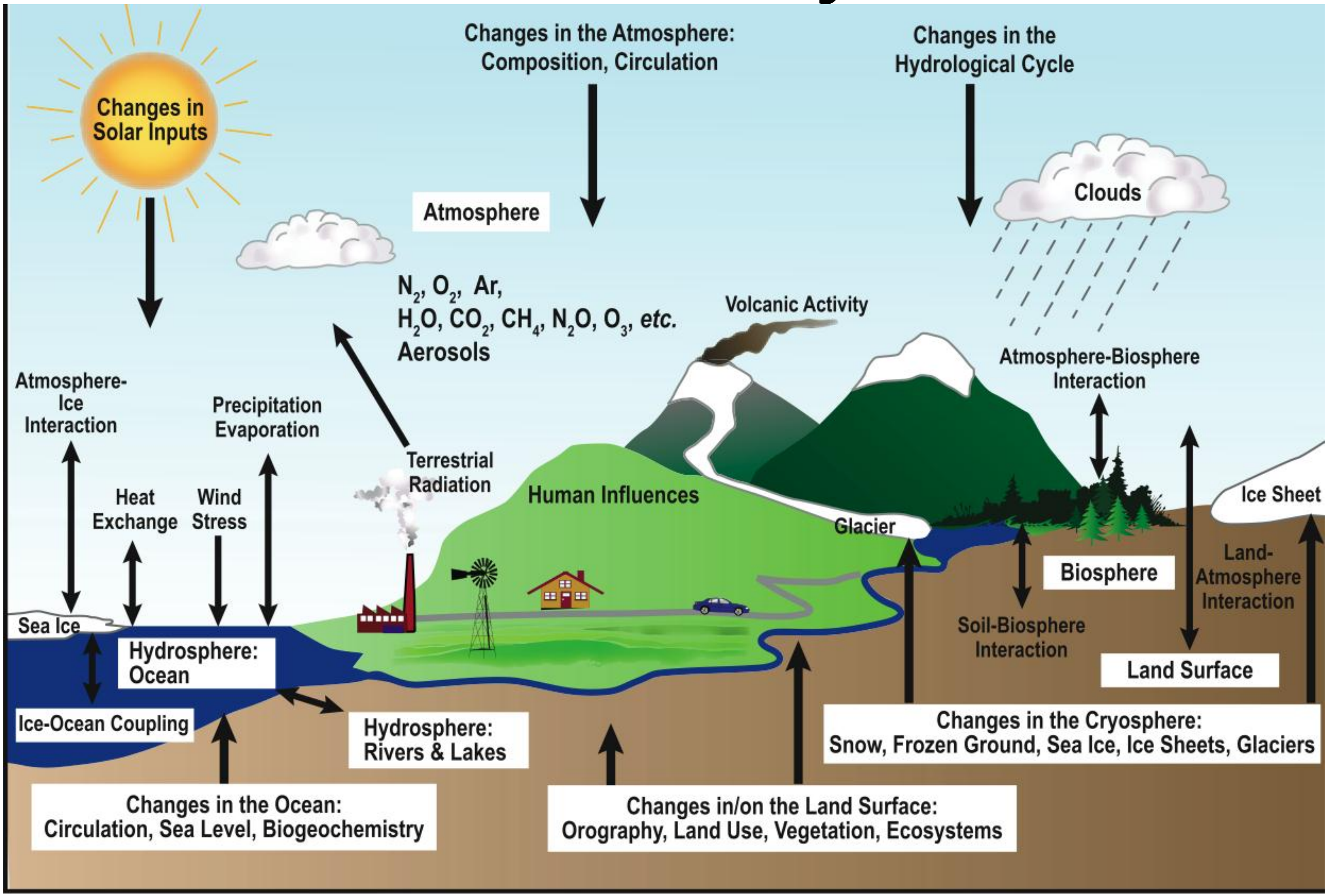
Outline

1. Brief overview on Climate Models: GCMs and RCMs (ESMs e RESMs);

2. Regional Climate Modelling in IDL/FCUL;

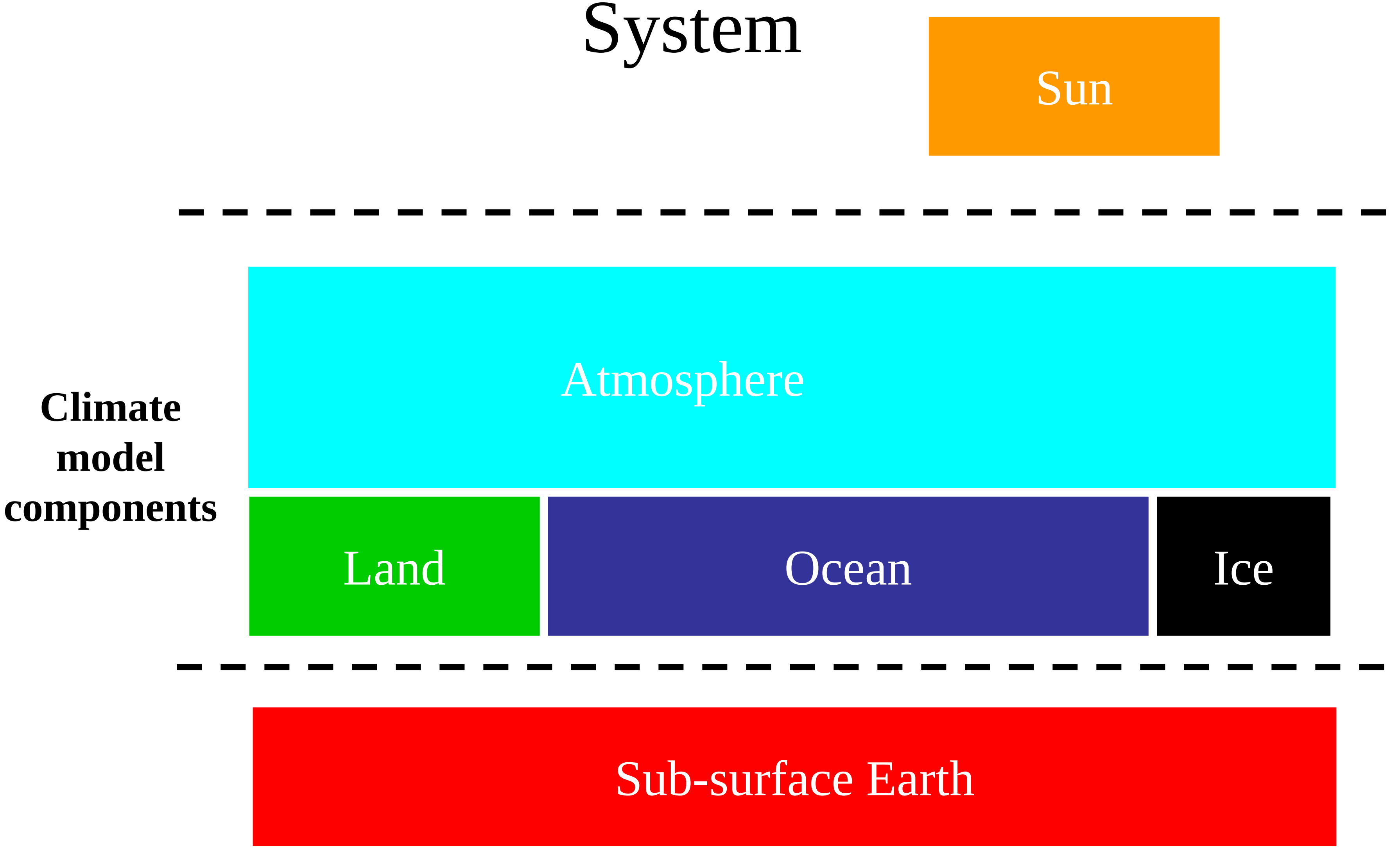
3. Future projections for precipitation and temperature in Portugal.

The Climate system

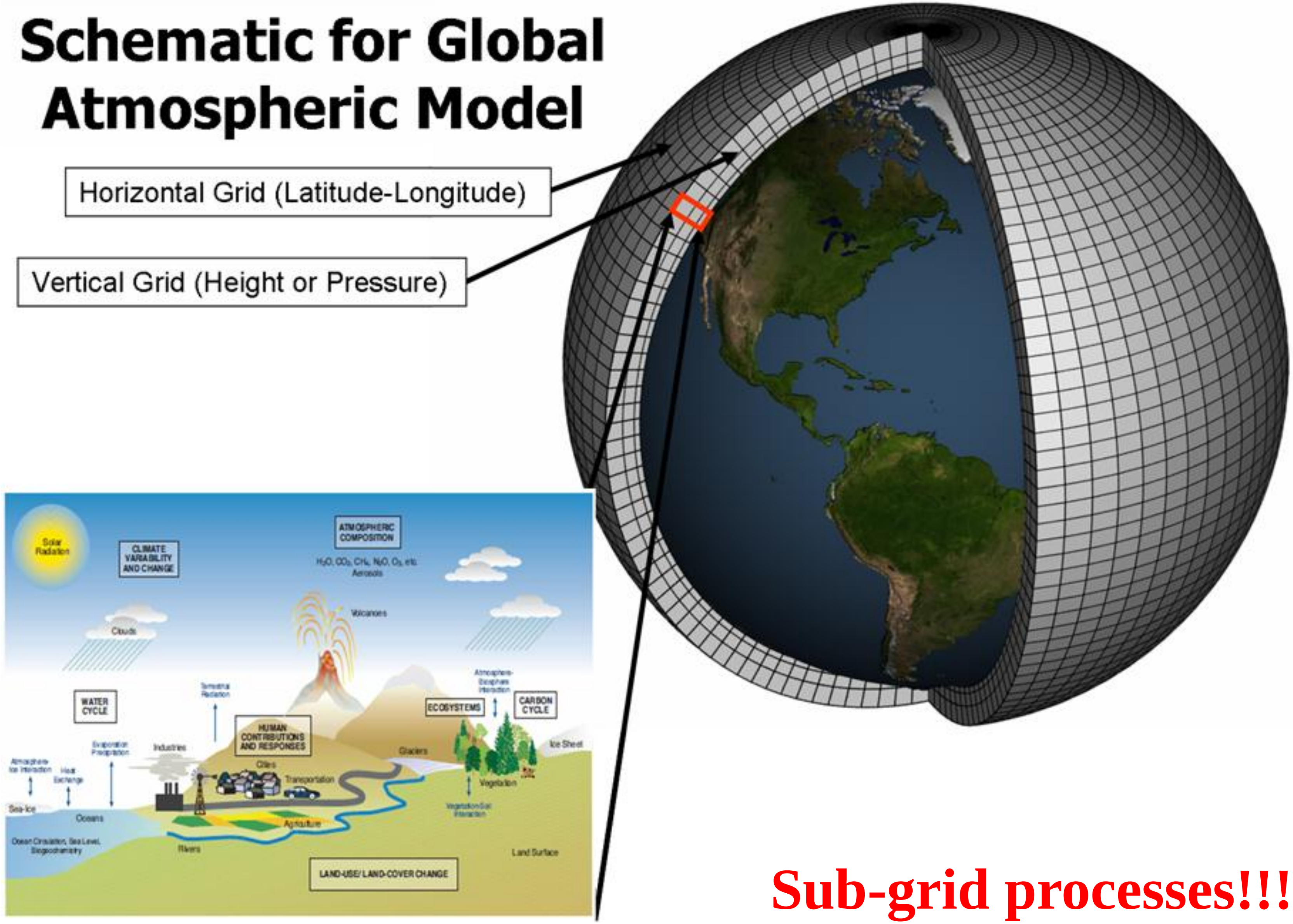


How we simulate it?

Earth's Climate System



Schematic for Global Atmospheric Model



Sub-grid processes!!!

The need of parametrizations!!!

The equations of a climate model

Conservation of momentum

$$\frac{\partial \overline{V}}{\partial t} + \overline{V} \cdot \nabla \overline{V} = -\frac{\nabla p}{\rho} - 2\overline{\Omega} \times \overline{V} + \overline{g} + F_{\overline{V}}$$

Conservation of energy

$$C_p\left(\frac{\partial T}{\partial t} + \overline{V} \cdot \nabla T\right) = \frac{1}{\rho}\frac{dp}{dt} + Q + F_T$$

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \overline{V} \cdot \nabla \rho = -\rho \nabla \cdot \overline{V}$$

Conservation of water

$$\frac{\partial q}{\partial t} + \overline{V} \cdot \nabla q = \frac{S_q}{\rho} + F_q$$

Equation of state

$$p = \rho R T$$

Planetary boundary layer processes

Clouds and precipitation

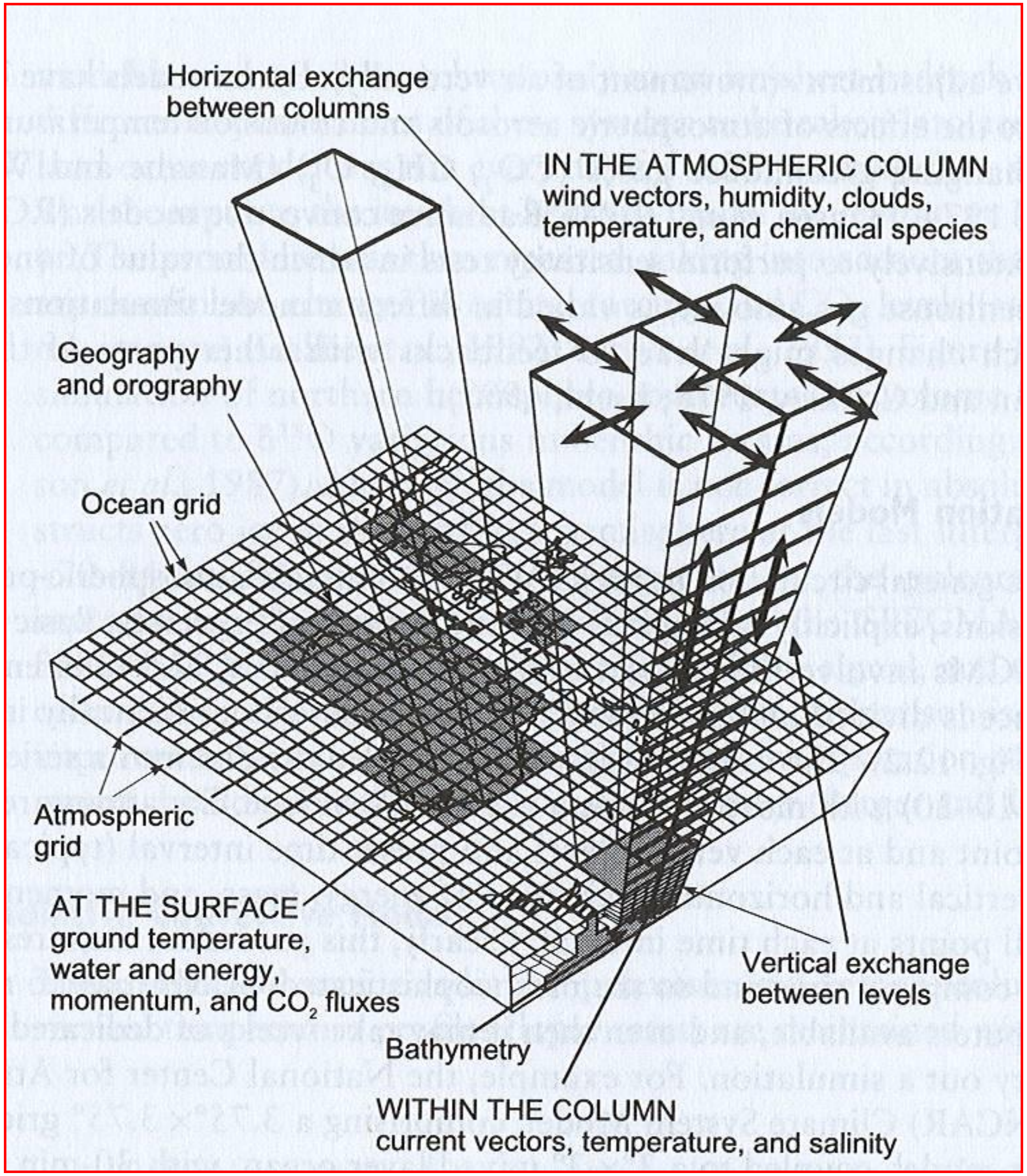
The “Physics” of a climate model

Land ocean surface processes

Radiative Transfer

Sub-grid processes!!!

Global Climate Models: Structure

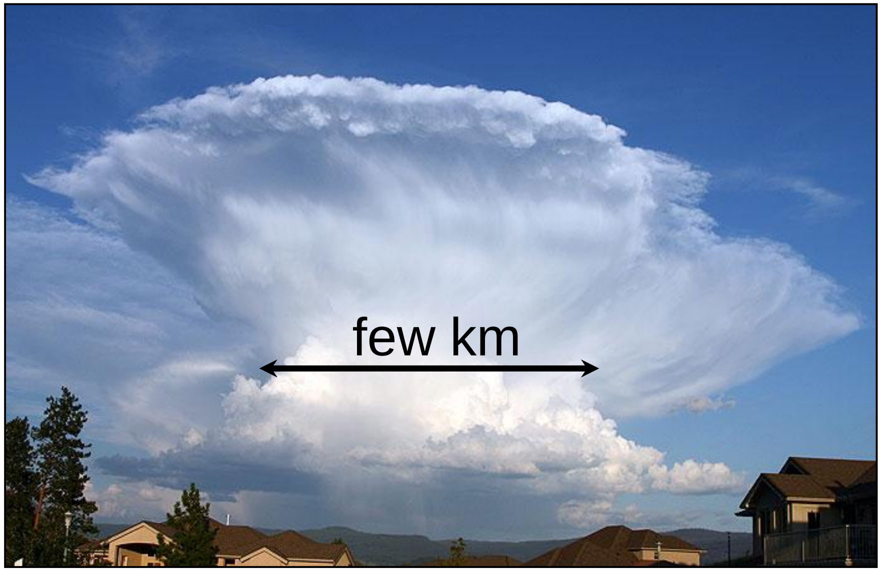


(Bradley, 1999)

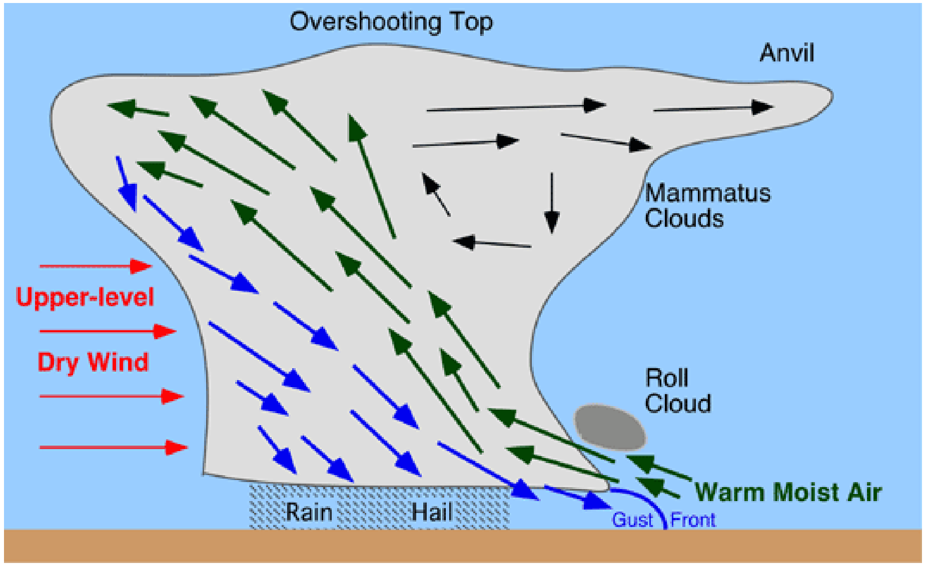
Global Climate Models: Parameterization

Important processes smaller than a grid box:

e.g., thunderstorms (atmospheric convection)



(www.physicalgeography.net)

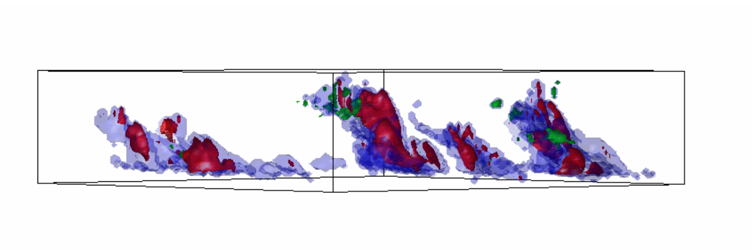


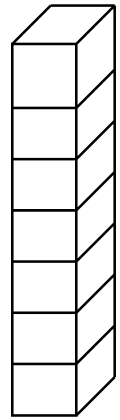
(www.physicalgeography.net)

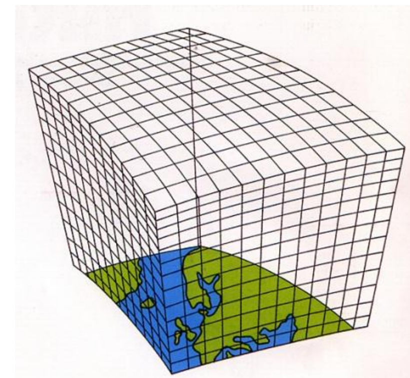
What's a model to do?

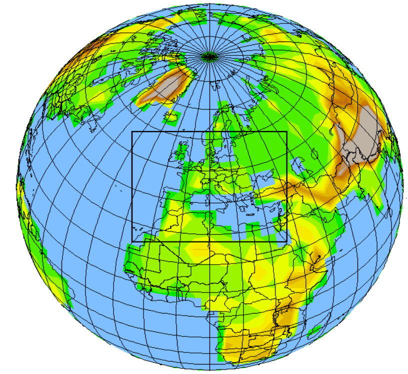
Parameterization: Represent the effects of the unresolved processes on the grid. Assume that unresolved processes are at least partly driven by the resolved climate.

Example of the development of a parametrization: clouds…









Large Eddy Simulation (LES)
Cloud Resolving Models (CRM)
(Local High resolution models)

Single Column Model versions of NWP and Climate Models

3d-Climate Models
NWP's

Observations from Field Campaigns

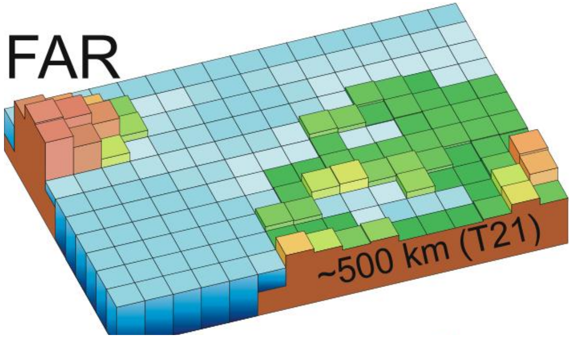
Global observational Data sets

Development

Testing

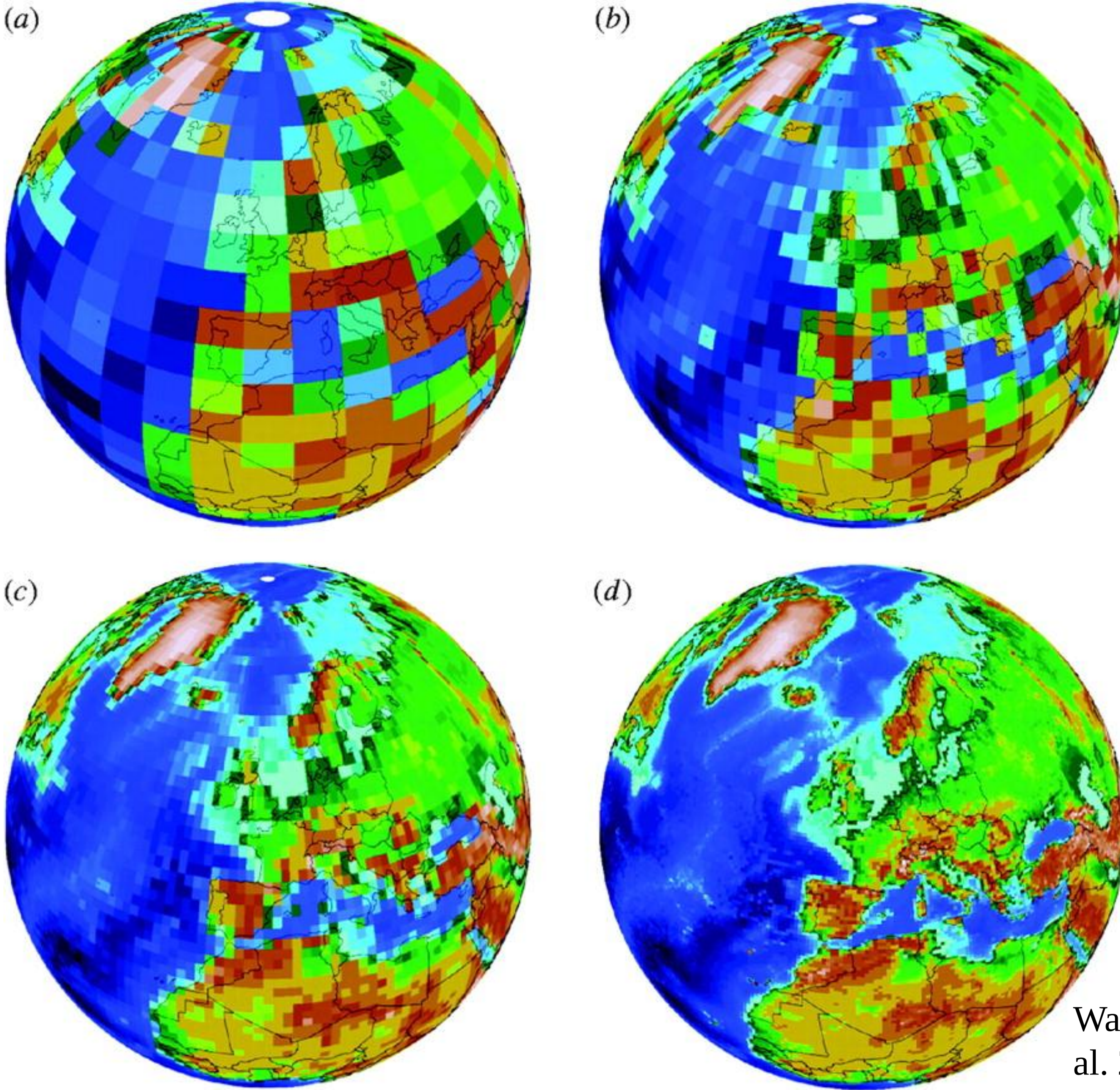
Evaluation

Development of Global Climate Models (GCMs)



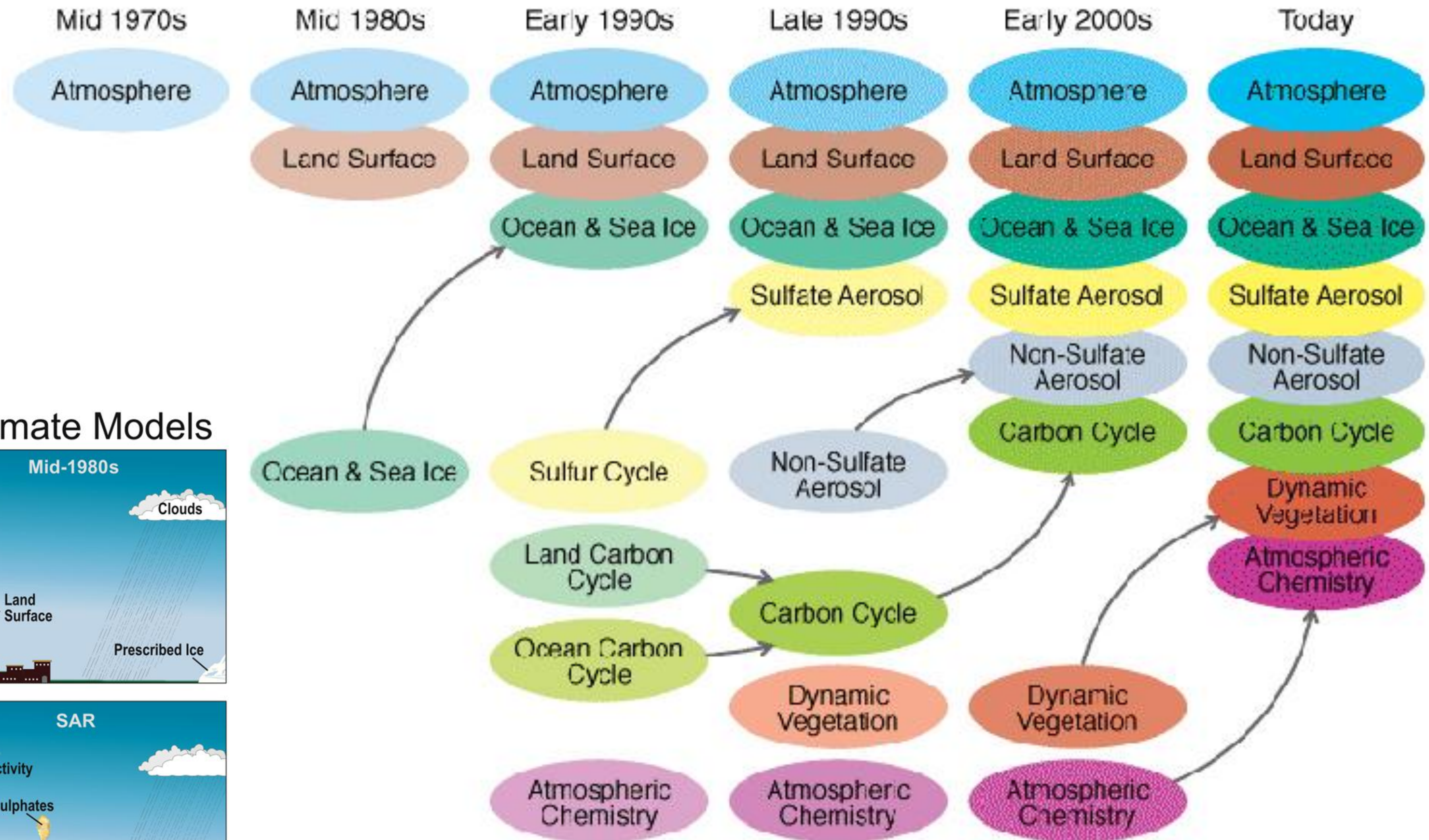
Computing demand increases inversely with *cube* of horizontal resolution.

Increased computing power has allowed increased resolution …

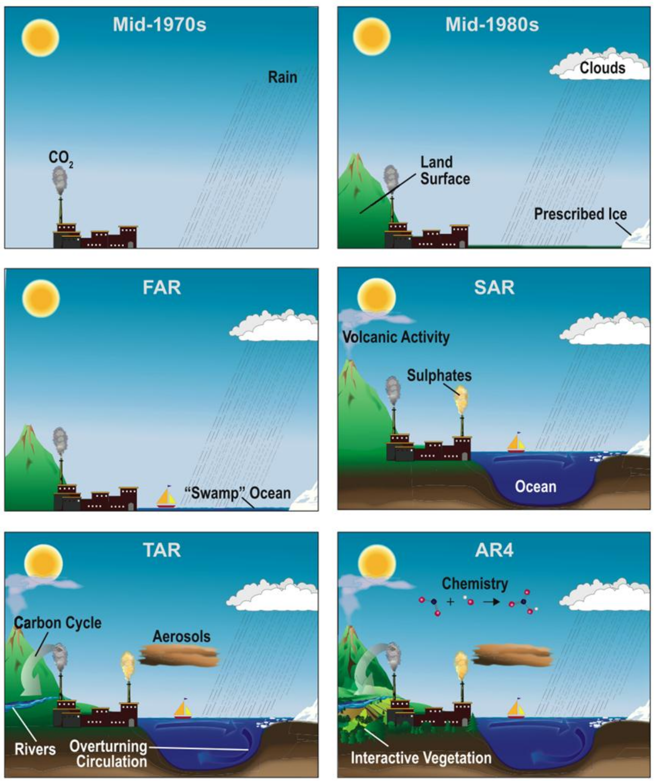


Washington et al. 2009

Development of Climate Models



The World in Global Climate Models



How Well Have GCMs performed? Attribution

Anthropogenic and natural forcings

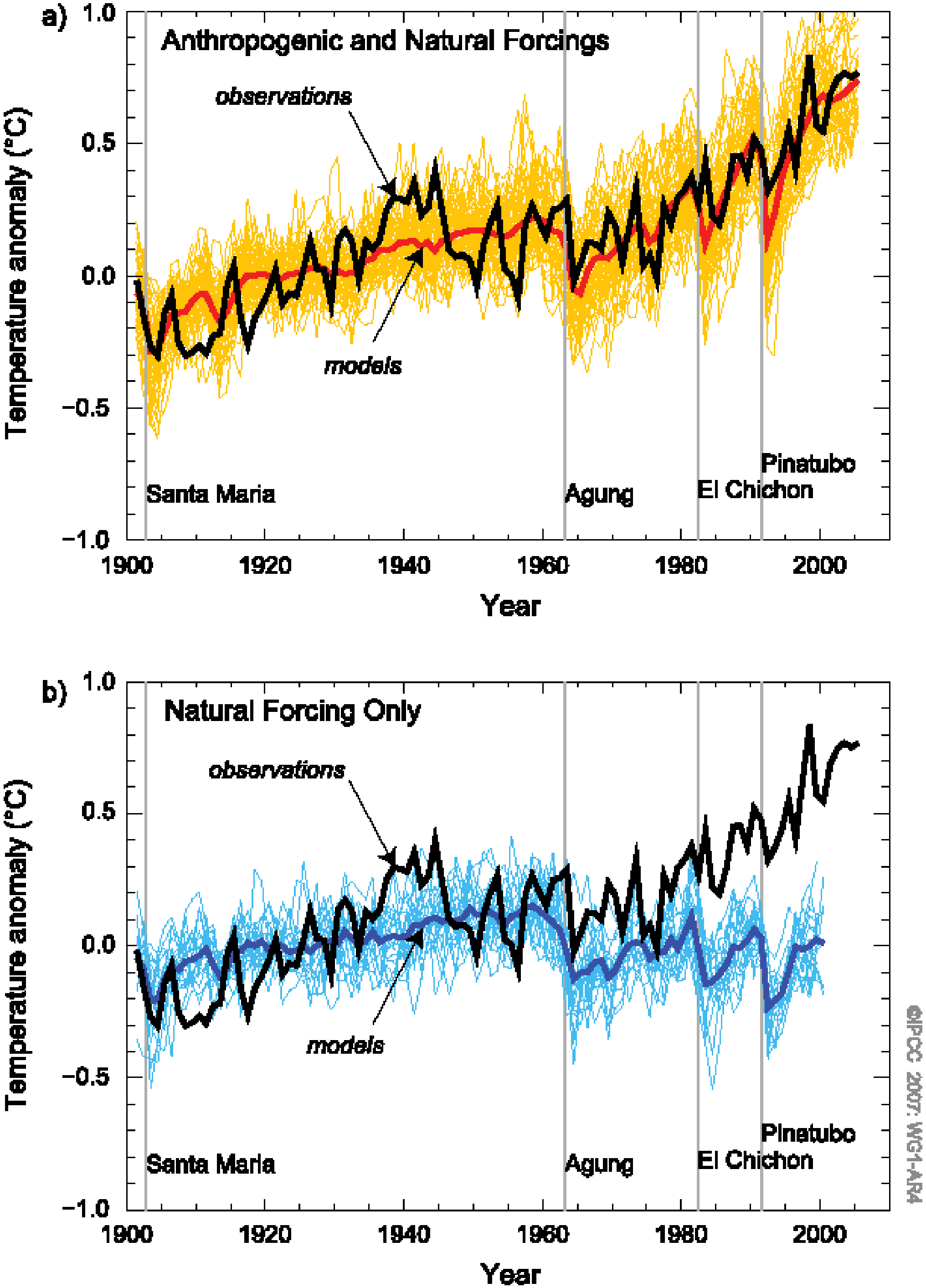
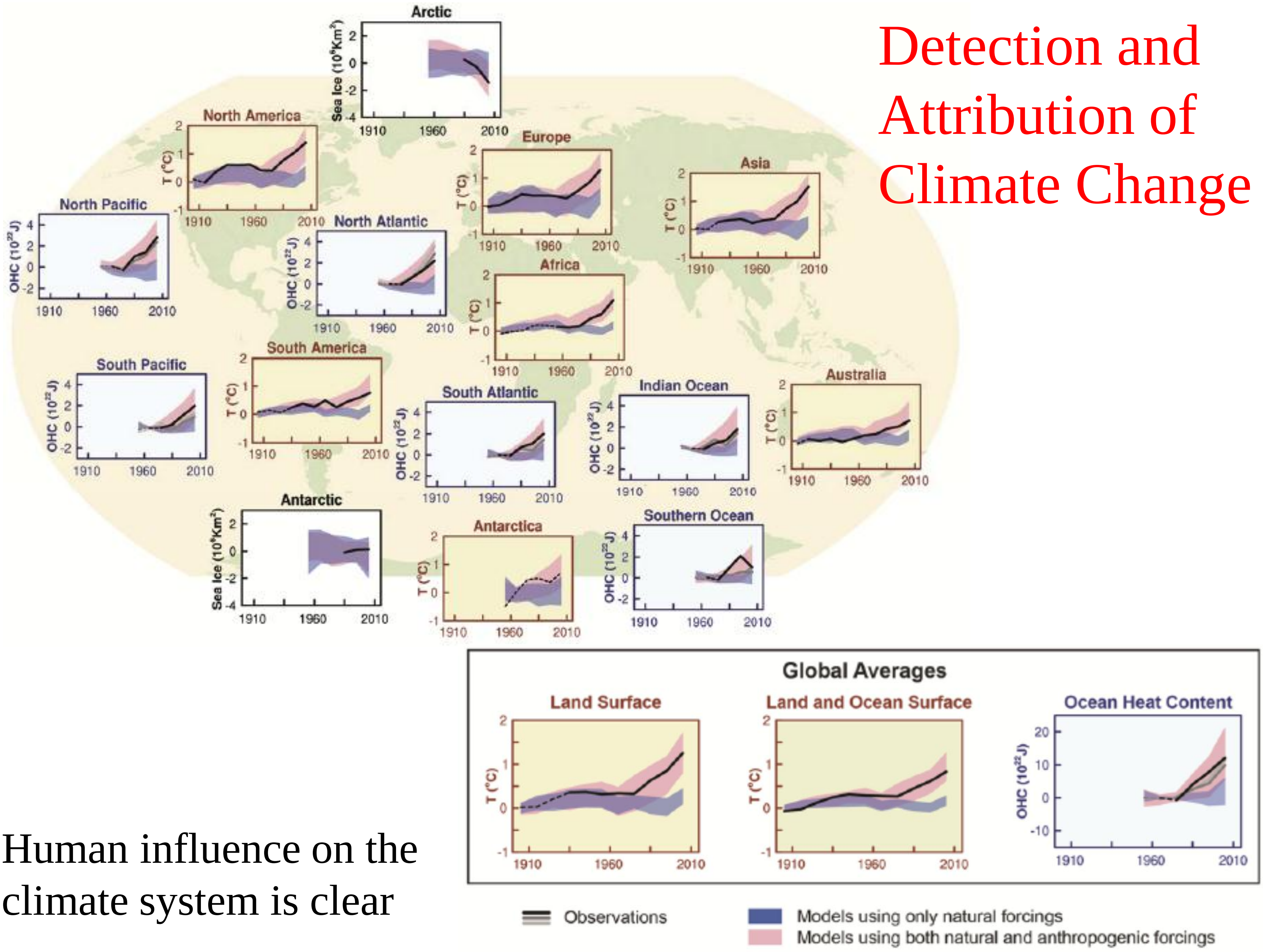


Figure TS.23. *(a) Global mean surface temperature anomalies relative to the period 1901 to 1950, as observed (black line) and as obtained from simulations with both anthropogenic and natural forcings. The thick red curve shows the multi-model ensemble mean and the thin lighter red curves show the individual simulations. Vertical grey lines indicate the timing of major volcanic events. (b) As in (a), except that the simulated global mean temperature anomalies are for natural forcings only. The thick blue curve shows the multi-model ensemble mean and the thin lighter blue curves show individual simulations. Each simulation was sampled so that coverage corresponds to that of the observations. {Figure 9.5}*

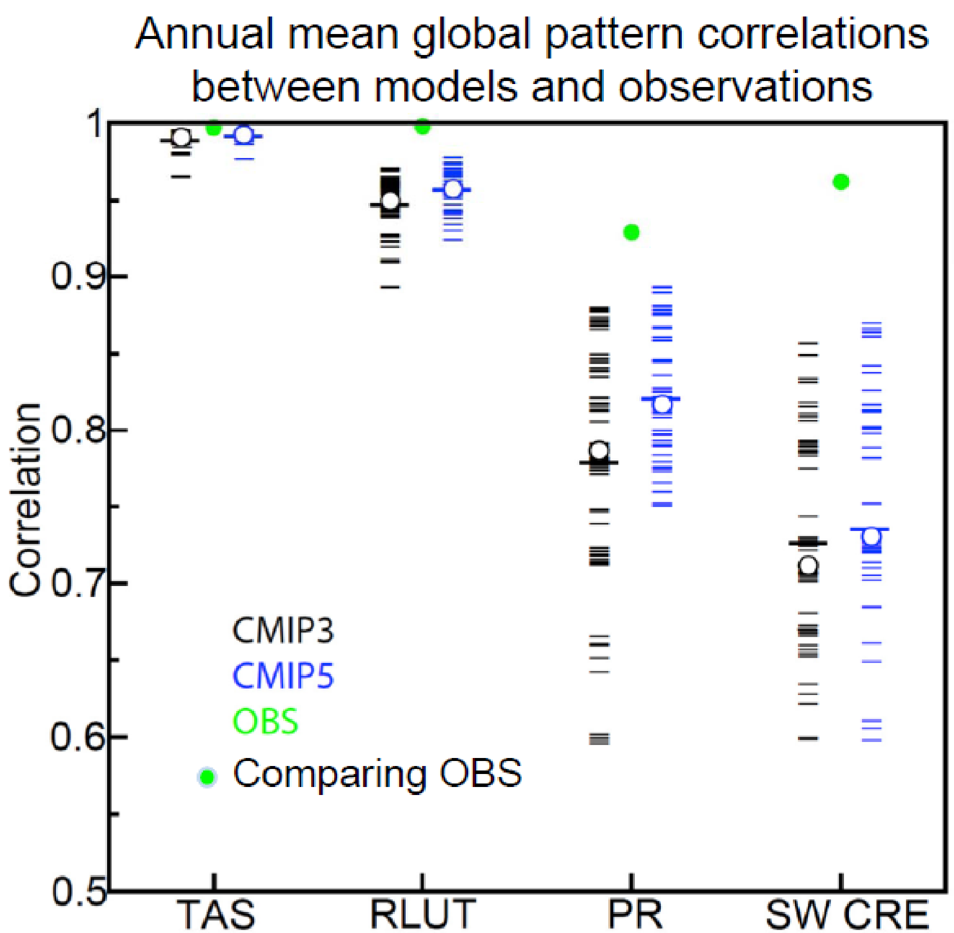
Source: IPCC 2007a (WG I TSp.62)

Detection and Attribution of Climate Change



Human influence on the climate system is clear

Are models improving?



- Many examples of incremental improvements since CMIP3
- Improvement not uniform, but little/no evidence of performance deterioration

IPCC AR5 WG1 Fig 9.6

but we need climate information at finer scales, regional and local!!!

↓

Regional climate information is critical to assess impacts of climate change

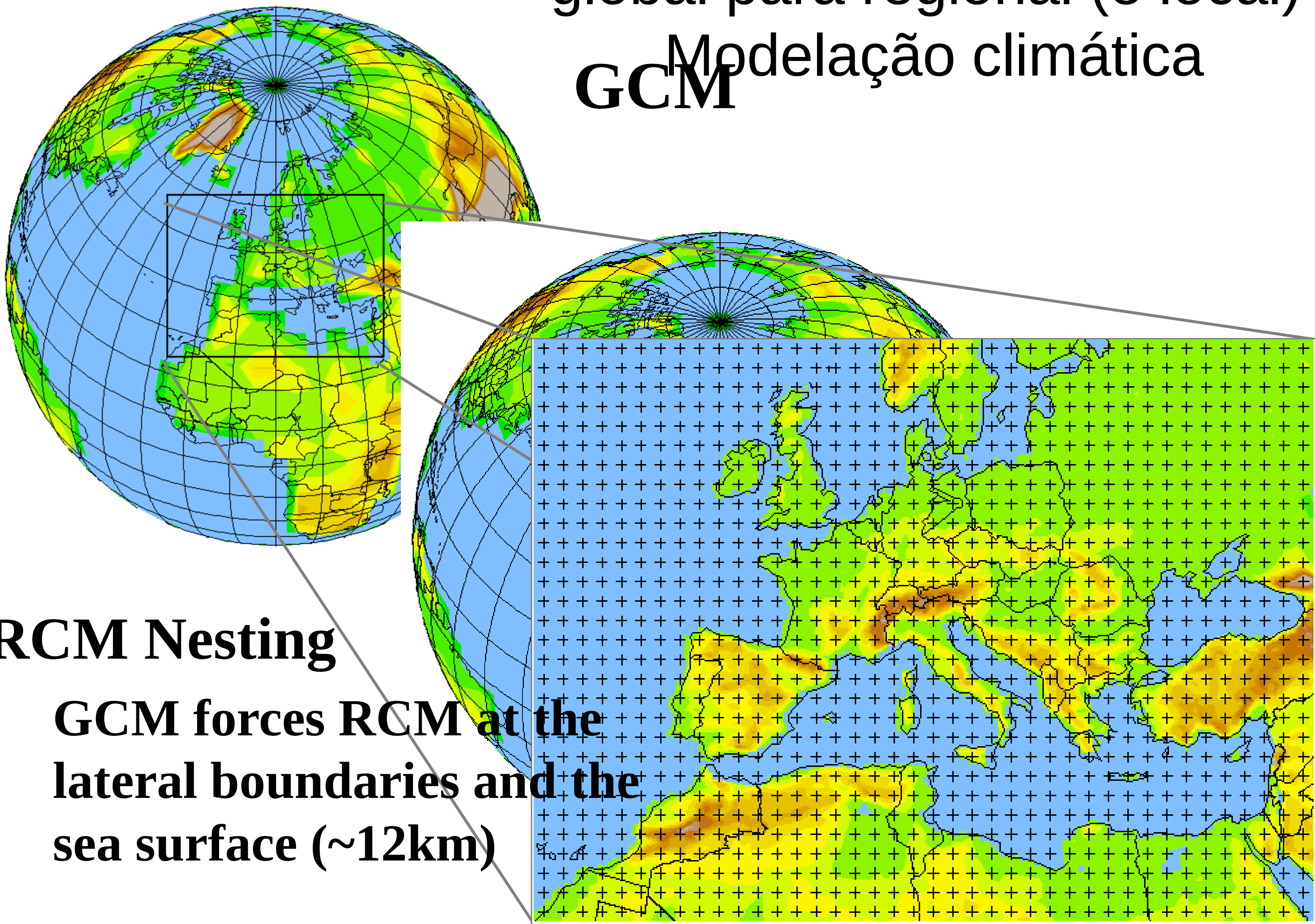
↓

Statistical downscaling
dynamical downscaling

Regional Climate Modelling

Regional Climate Models

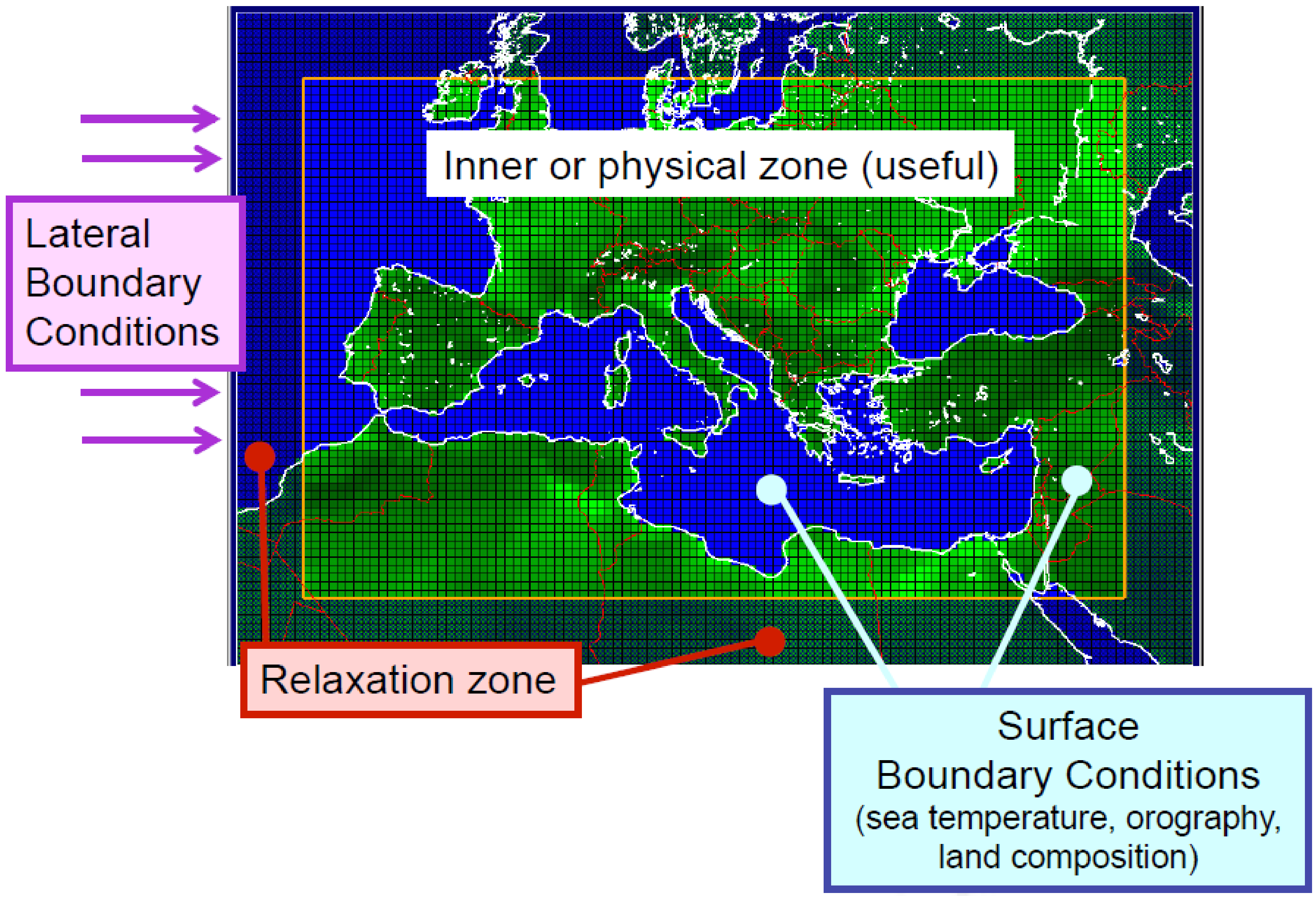
global para regional (e local)
Modelação climática



RCM Nesting

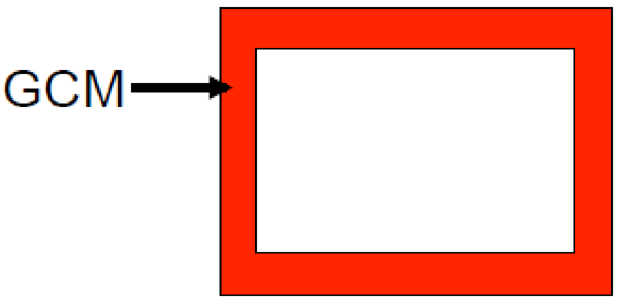
GCM forces RCM at the lateral boundaries and the sea surface (~12km)

Regional Climate Model

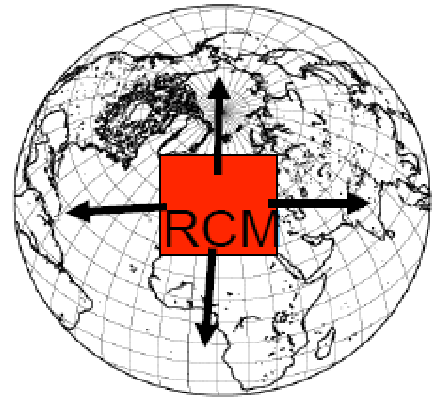


How to drive a RCM?

One-way nesting
Lateral forcing

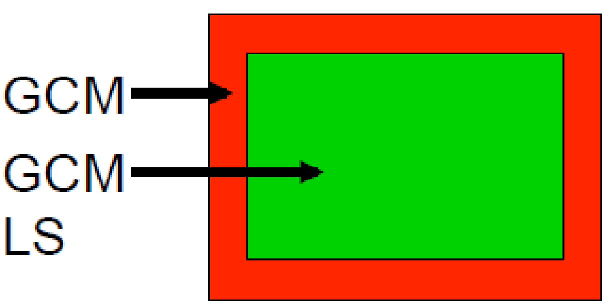


Two way-nesting



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

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? – expected!!!

Several potential sources of RCM added-value wrt the driver:
- 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, …

Convection, clouds and turbulence

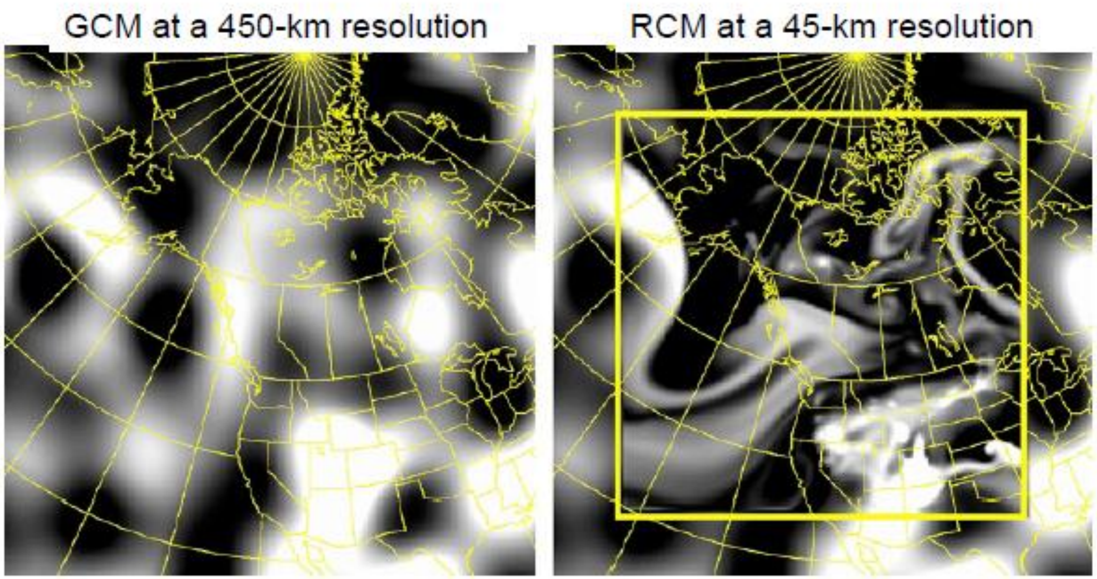
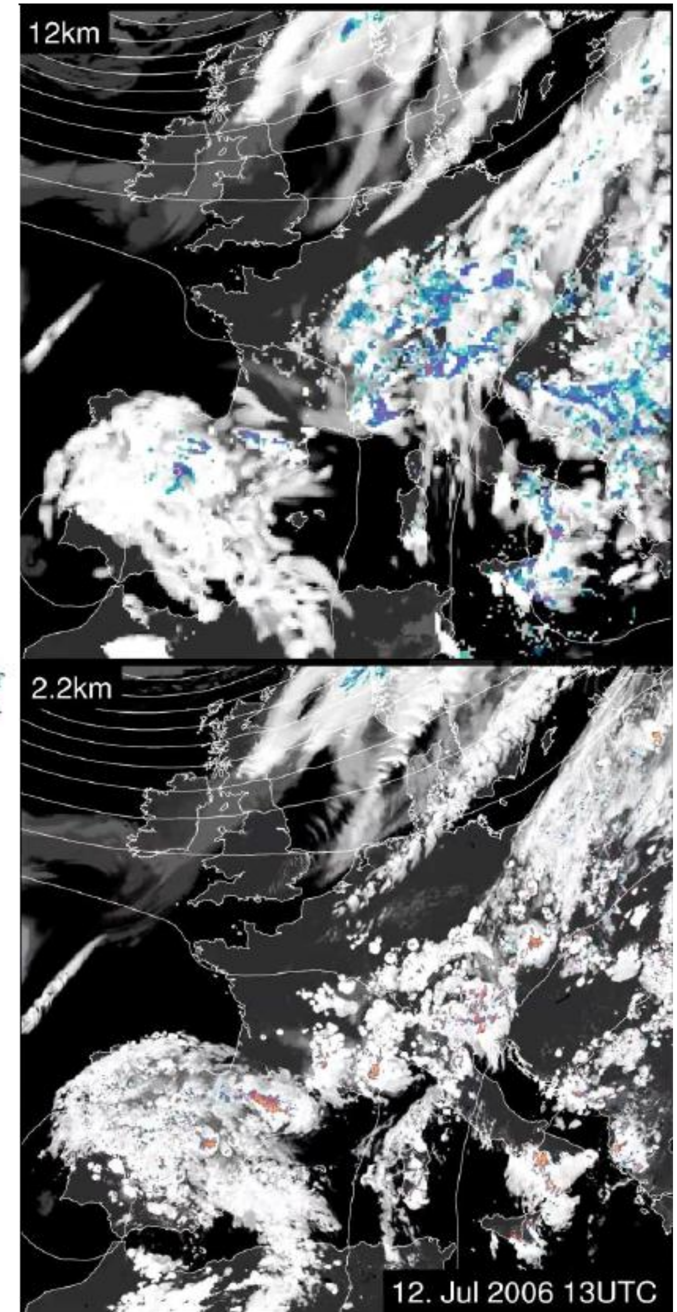
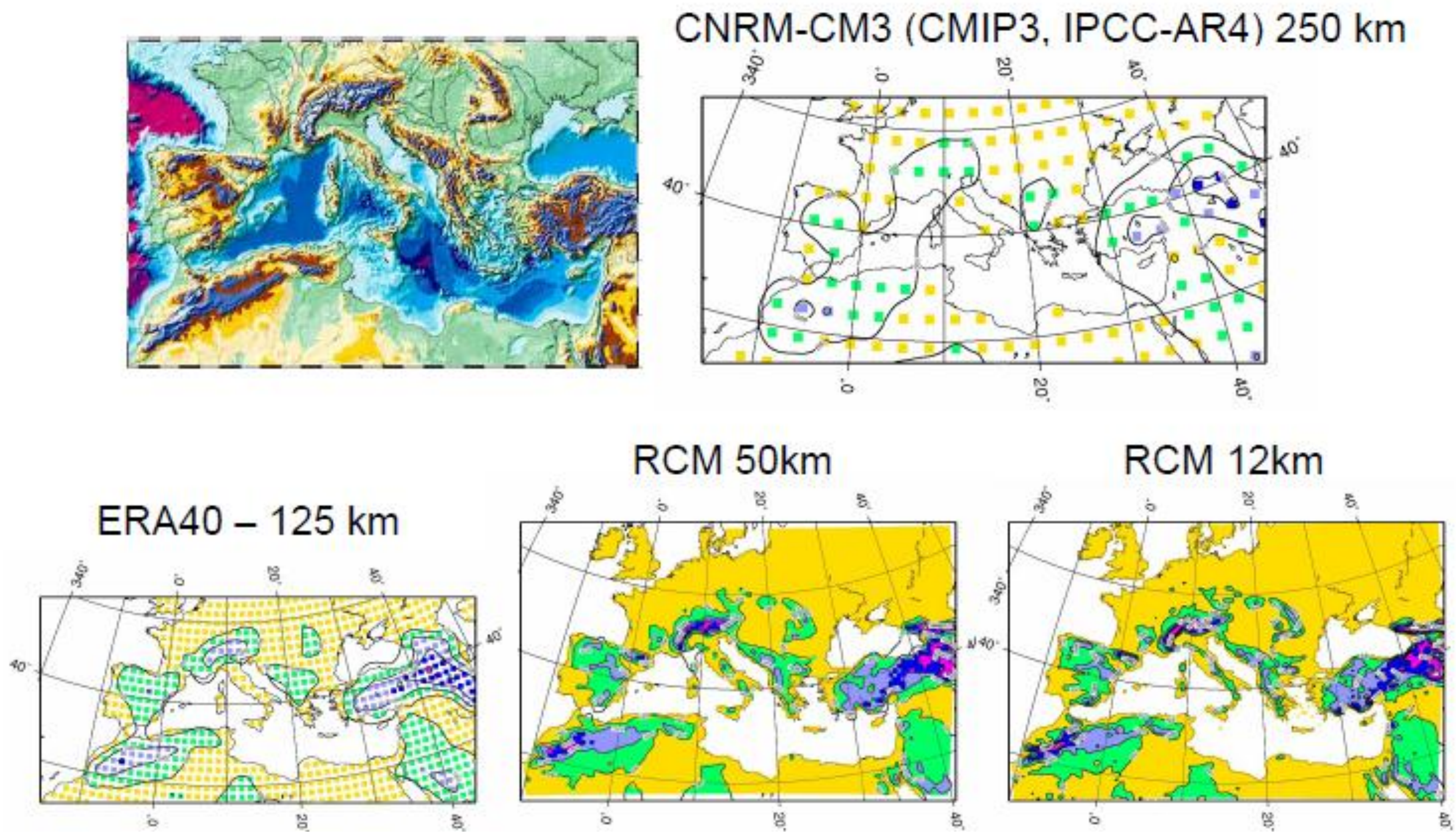


Fig. 5. Instantaneous field of clouds simulated by CGCM2 with equivalent grid mesh of 450 km (left panel) and CRCM with grid mesh of 45 km (right panel) (superimposed on the GCM-simulated field, showing the frame of the RCM domain) (figures kindly provided by Dr. Daniel Caya, Chief, Climate Simulation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



Leutwyler et al. (2016)

Resolution, orography and land-sea contrast



Geography of the RCM added-value

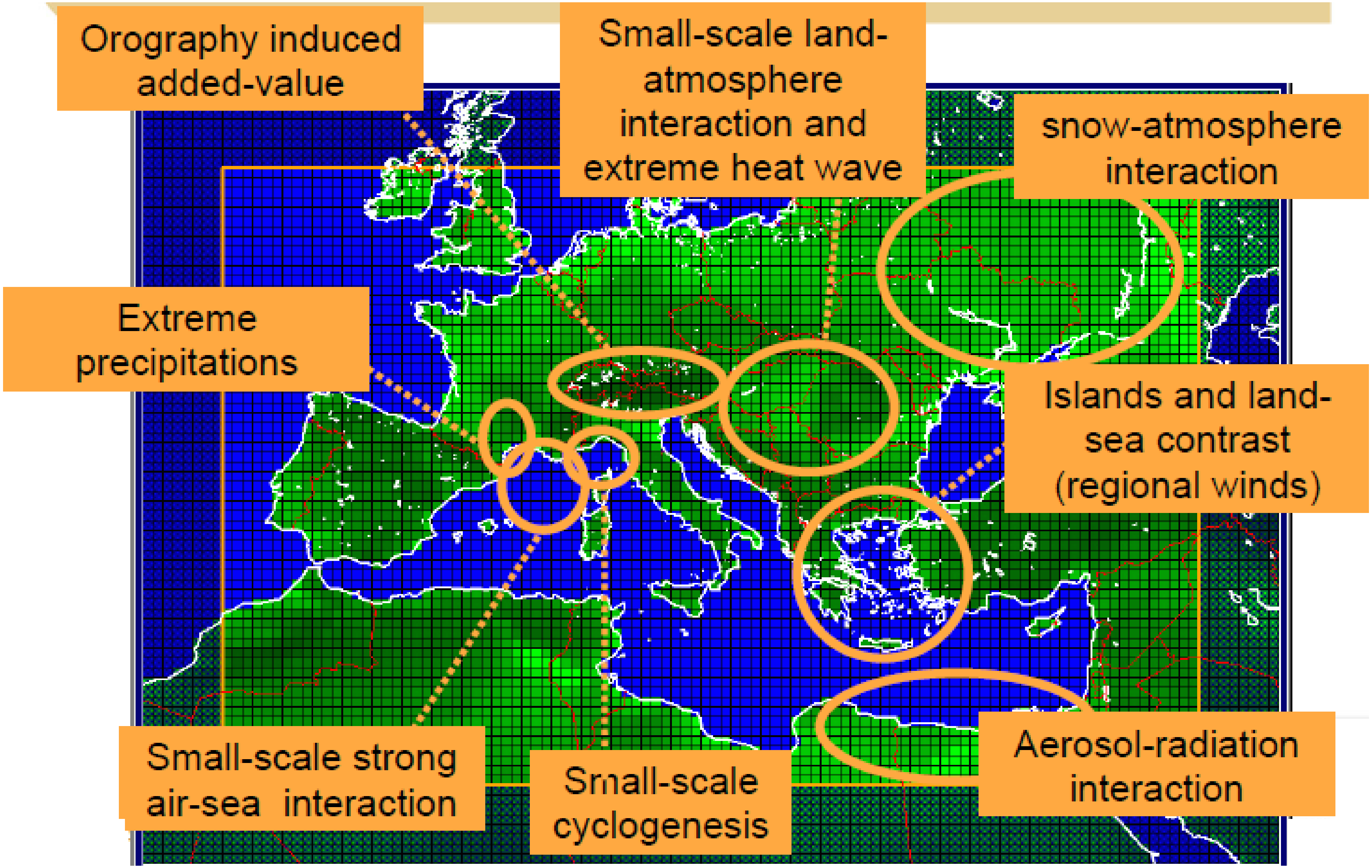
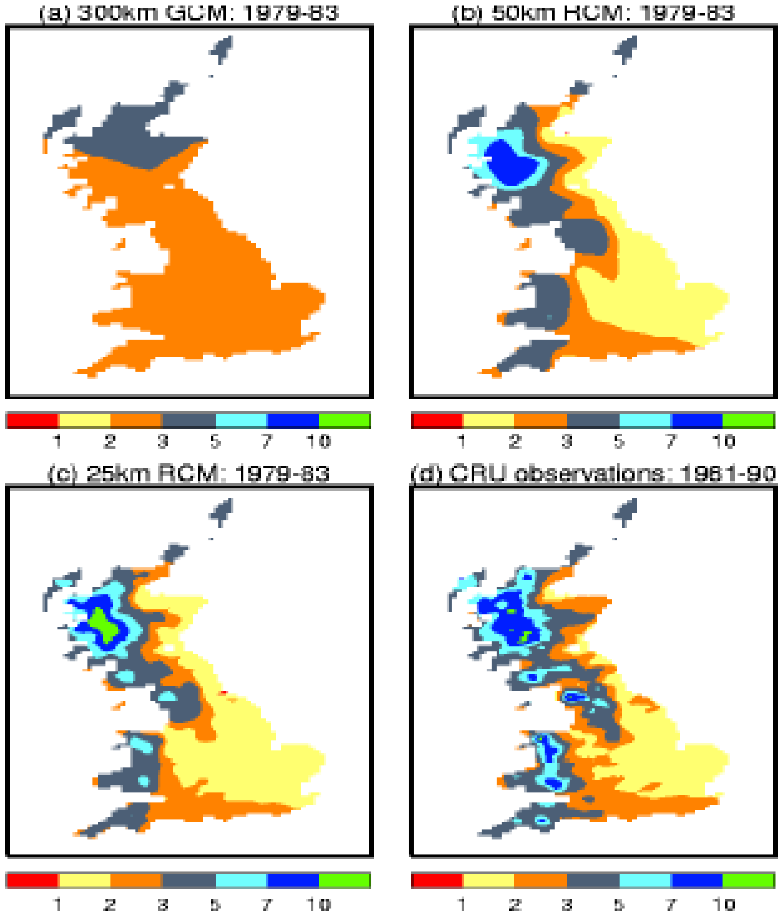


Illustration of the RCM added-value

Added-value in mean precipitation spatial pattern

300km GCM

50km RCM

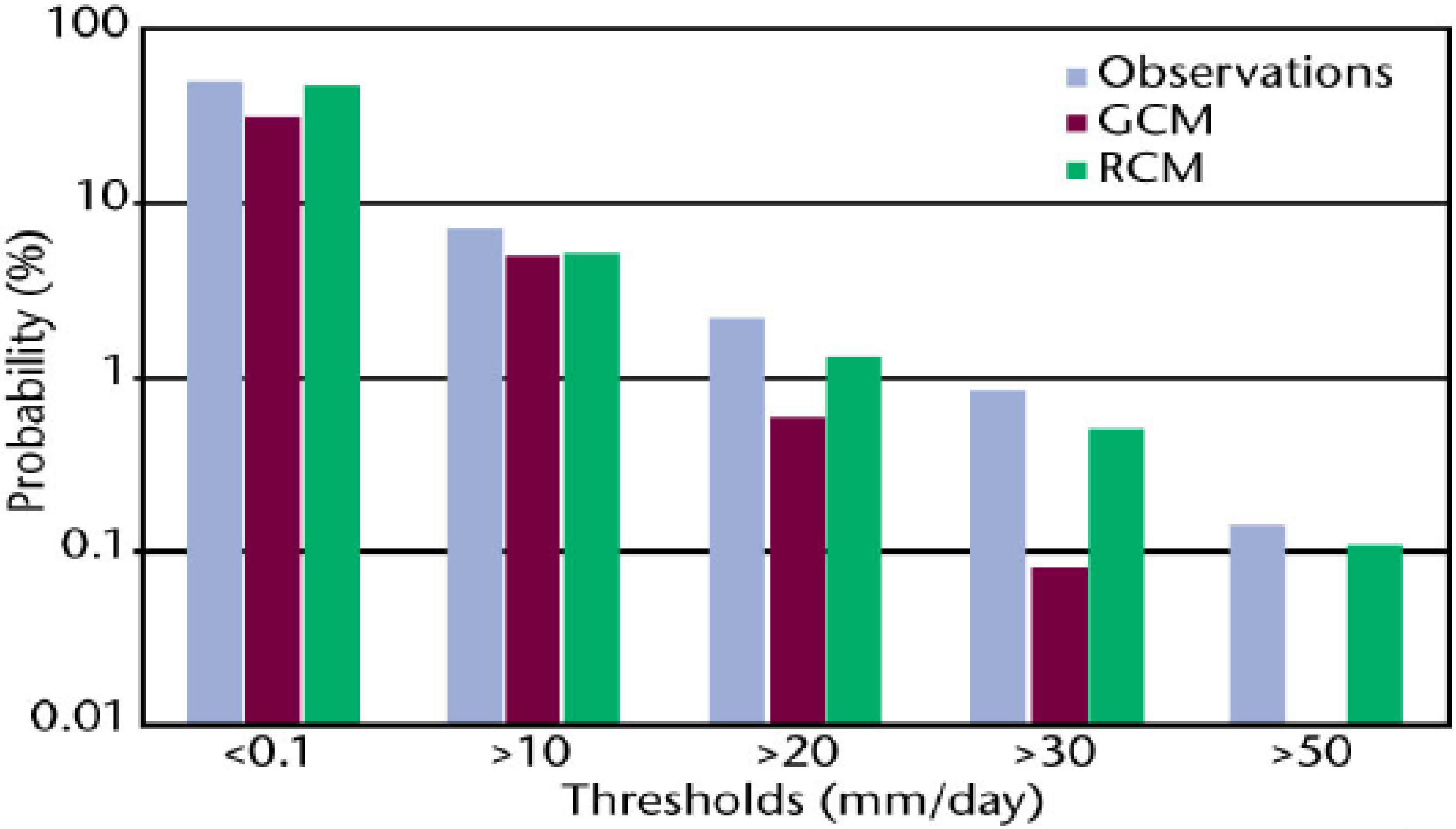


25km RCM

Observations precipitation in Winter

Illustration of the RCM added-value

Added-value in extreme precipitations



Daily precipitation distribution over the Alps

Regional Climate Models
at IDL/FCUL

Objectives

To characterize the climate change signal on the precipitation, temperature and renewable energies in Portugal

Methods

- Using the newest and highest resolution regional climate simulations available
- Evaluate extensively RCMs results against observations
- Model ranking based on model performance
- Multi-model ensembles – full, selected and weighted
- Assess the climate change signal

RCM simulations

- WRF at 9km
- EURO-CORDEX at 0.11º ~ 12km and 0.44º ~ 50km
- Present (1971-2000) and future (2071-2100) climates

Observations

- IPMA regular gridded dataset 0.2º ~ 20km (and 0.44º) for precipit.
- IPMA gound based observations for temperature

Error measures

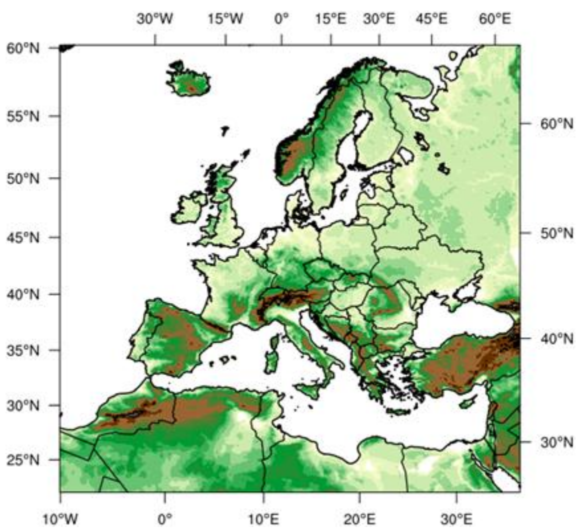
- Bias, MAE, MAPE, RMSE, PDF skill scores, Correlarion, Starndard deviation, Anderson and Darling, Yule and Kendall, etc.

Ranking and Multi-model ensemble

- Ranking normalizing the errors
- Full, selected and weighted multi-model ensemble

RCMs domains

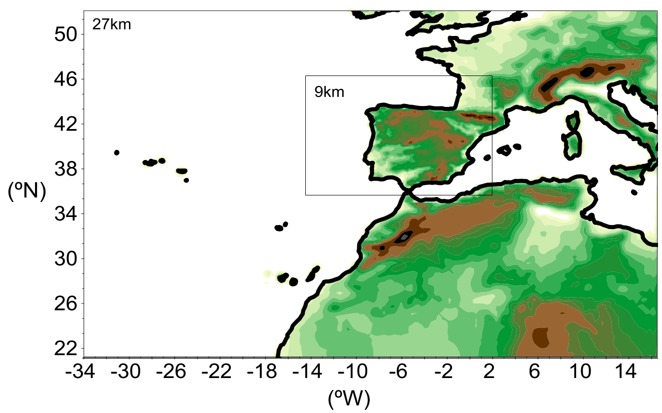
EURO-CORDEX



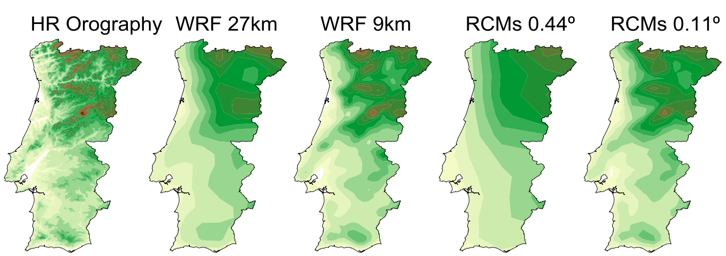
EURO-
CORDEX
Resolutions:
0.11º ~ 12km
0.44º ~ 50km

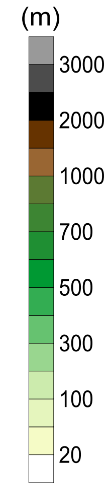
WRF-IDL

(a)

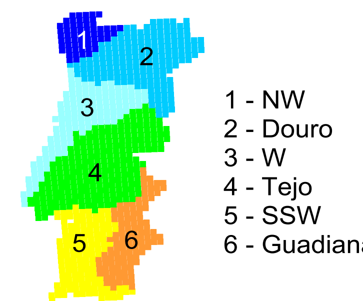


(b)





(c)



WRF-IDL
Resolution:
9km

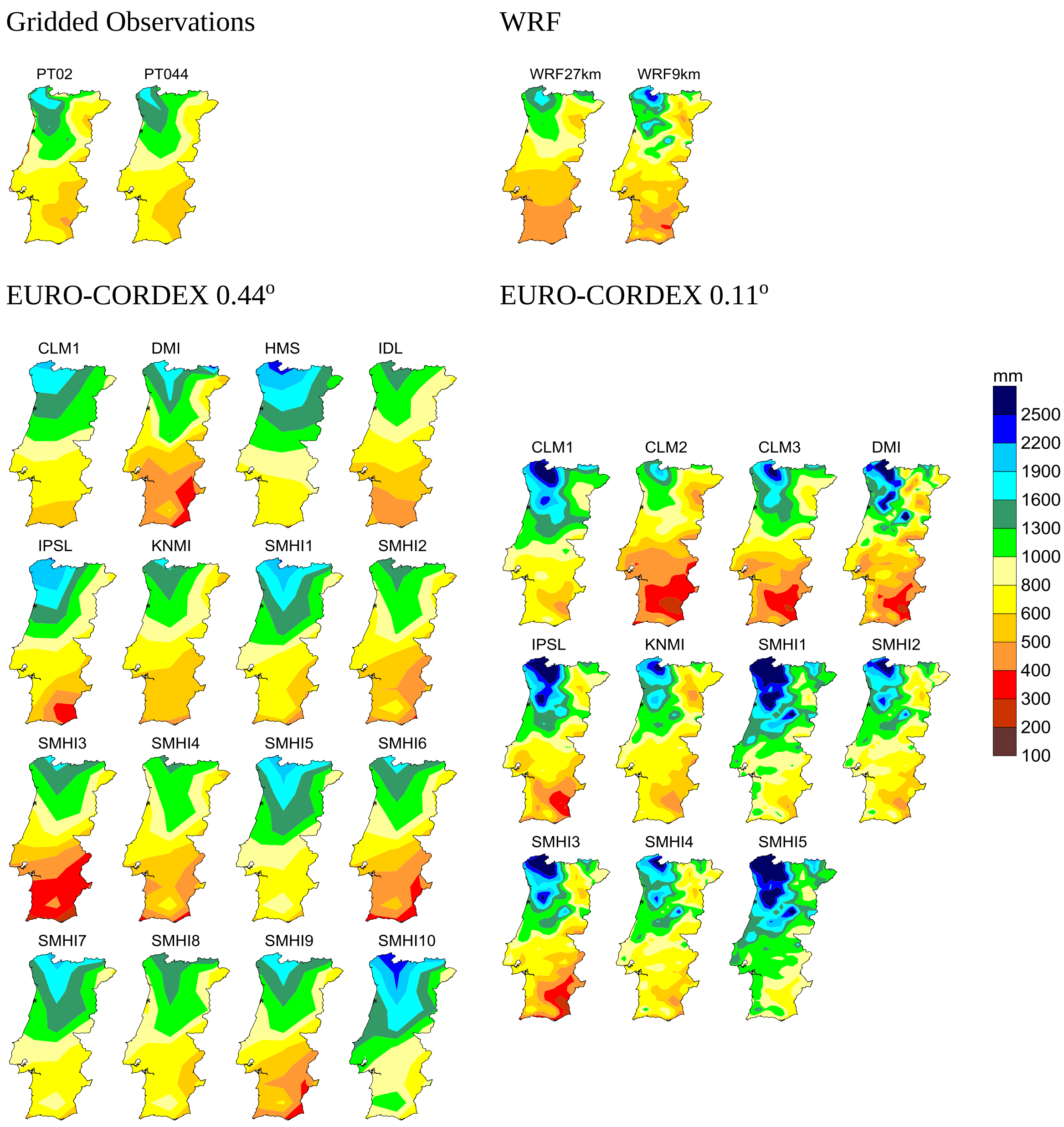
Regional Climate models (RCMs)

Table 1 EURO-CORDEX regional climate models considered in the present study, along with the responsible institution, the forcing global climate model, the acronym for each model combination (RCM-GCM) and the used resolutions

Institution	Reference	Model	Forcing model	Acronym	Resolution
Climate Limited-Area Modelling Community	Rockel et al. (2008)	CCLM4-8-17	MPI-M-MPI-ESM-LR	CLM1	0.11°/0.44°
			ICHEC-EC-EARTH	CLM2	0.11°
			CNRM-CERFACS-CNRM-CM5	CLM3	0.11°
Danish Meteorological Institute	Christensen et al. (2006)	HIRHAM5	ICHEC-EC-EARTH	DMI	0.11°/0.44°
Hungarian Meteorological Service	Colin et al. (2010)	ALADIN52	CNRM-CERFACS-CNRM-CM5	HMS	0.44°
Instituto Dom Luiz	Skamarock et al. (2008)	WRFV350D	IDL-EC-Earth	IDL	0.44°
Institut Pierre Simon Laplace and Institut National de l Environnement industriel et des RISques	Skamarock et al. (2008)	WRF331F	IPSL–IPSL-CM5A-MR	IPSL	0.11°/0.44°
Koninklijk Nederlands Meteorologisch Instituut	van Meijgaard et al. (2008)	RACMO22E	ICHEC-EC-EARTH	KNMI	0.11°/0.44°
Swedish Meteorological and Hydrological Institute	Samuelsson et al. (2011)	RCA4	CNRM-CERFACS-CNRM-CM5	SMHI1	0.11°/0.44°
			ICHEC-EC-EARTH	SMHI2	0.11°/0.44°
			IPSL–IPSL-CM5A-MR	SMHI3	0.11°/0.44°
			MOHC-HadGEM2-ES	SMHI4	0.11°/0.44°
			MPI-M-MPI-ESM-LR	SMHI5	0.11°/0.44°
			CCCma-CanESM2	SMHI6	0.44°
			CSIRO-QCCCE-CSIRO-Mk3-6-0	SMHI7	0.44°
			MIROC-MIROC5	SMHI8	0.44°
			NCC-NorESM1-M	SMHI9	0.44°
			NOAA-GFDL-GFDL-ESM2 M	SMHI10	0.44°

Precipitation

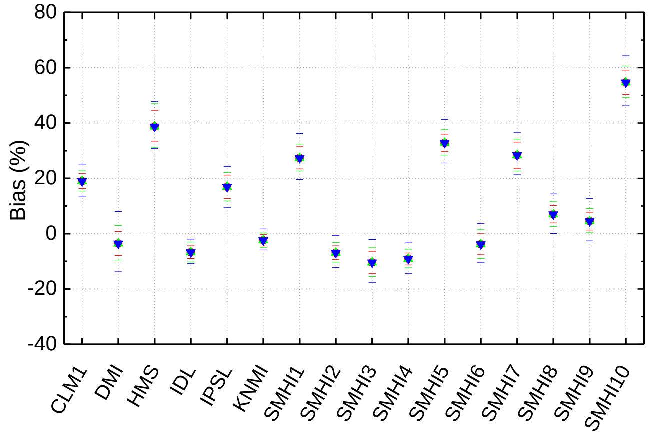
Yearly mean precipitation (1971–2000)



Error measures

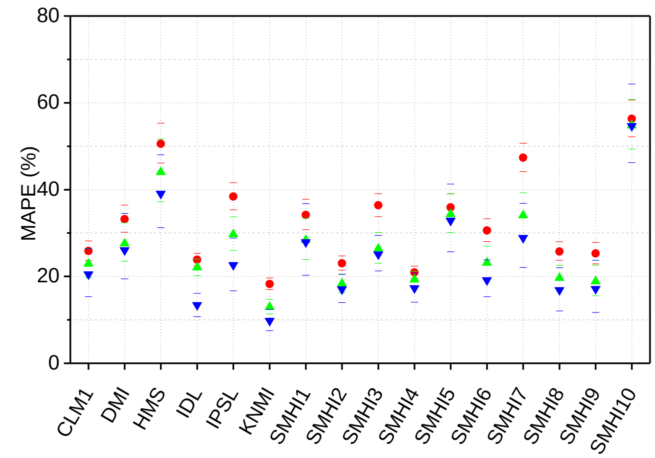
(a)

EURO-CORDEX 0.44^o



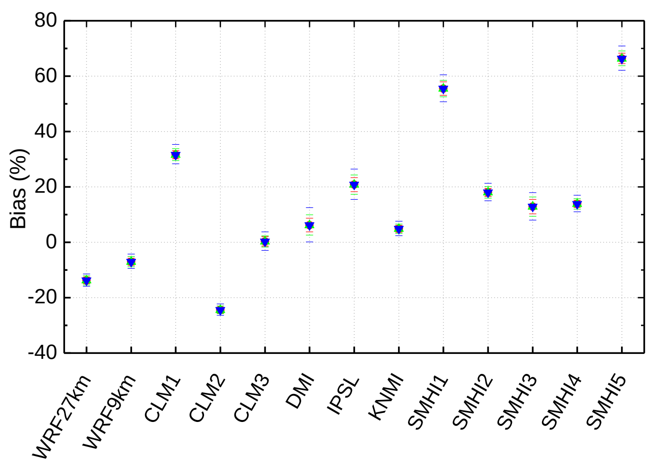
(b)

EURO-CORDEX 0.44^o



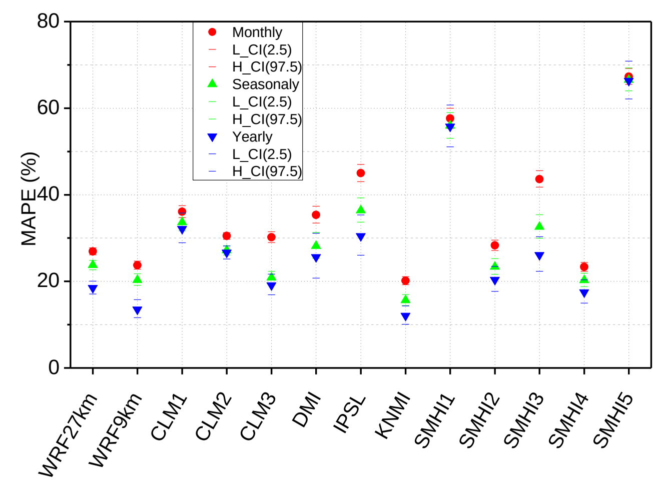
(c)

WRF27km/WRF9km/EURO-CORDEX 0.11^o



(d)

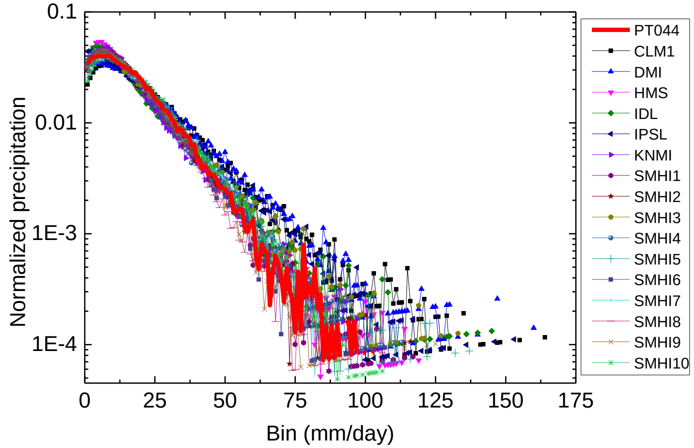
WRF27km/WRF9km/EURO-CORDEX 0.11^o



Error measures

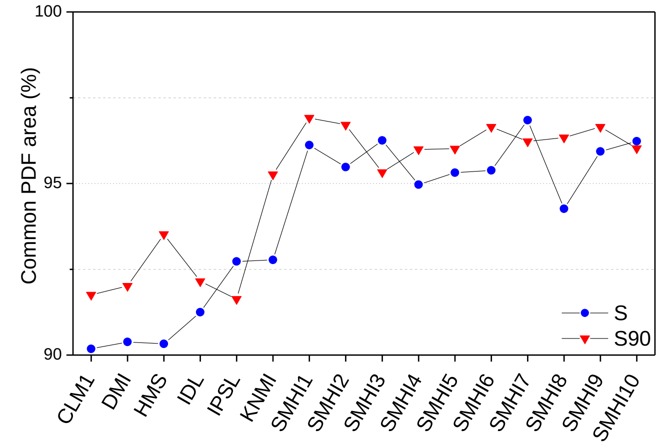
(a)

EURO-CORDEX 0.44^{o}



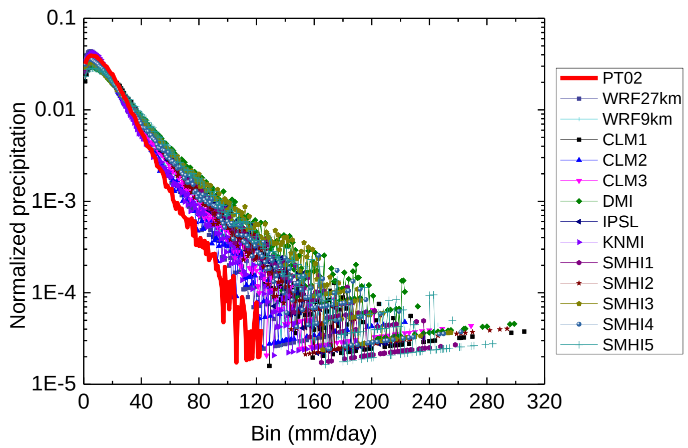
(b)

EURO-CORDEX 0.44^{o}



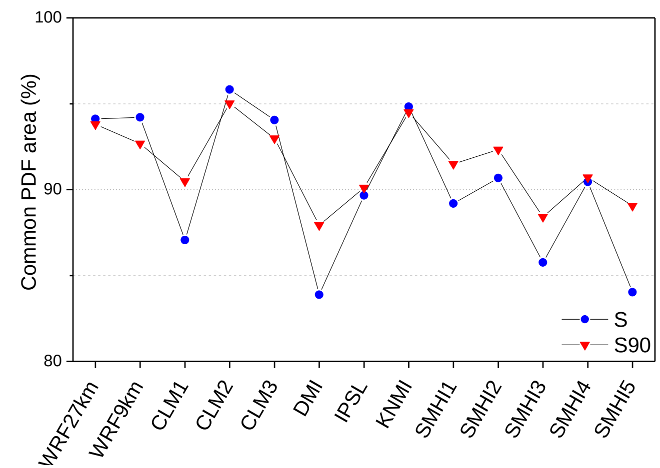
(c)

WRF27km/WRF9km/EURO-CORDEX 0.11^{o}

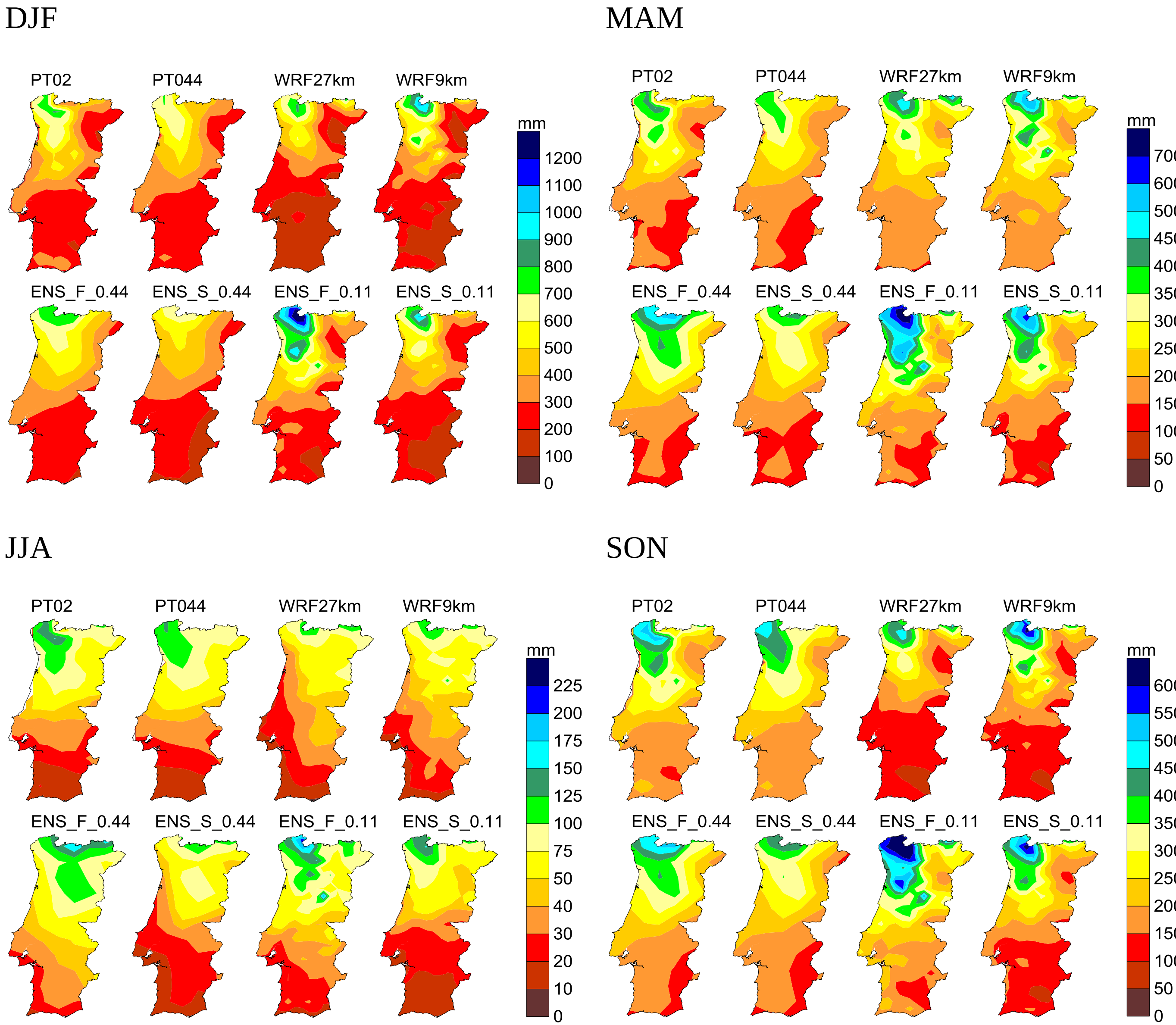


(d)

WRF27km/WRF9km/EURO-CORDEX 0.11^{o}

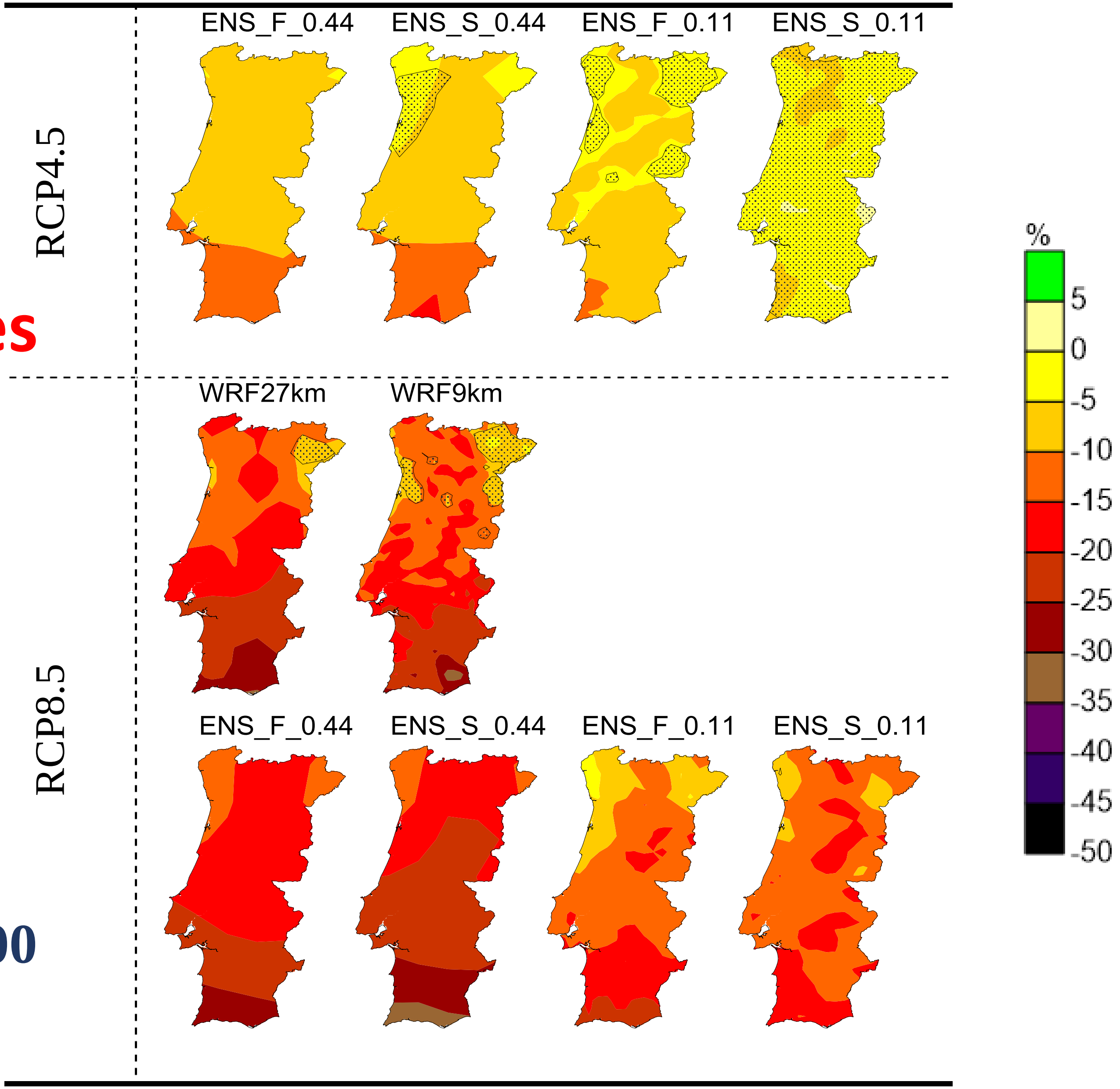


Seasonal precipitation



Precipitation

Yearly mean relative changes



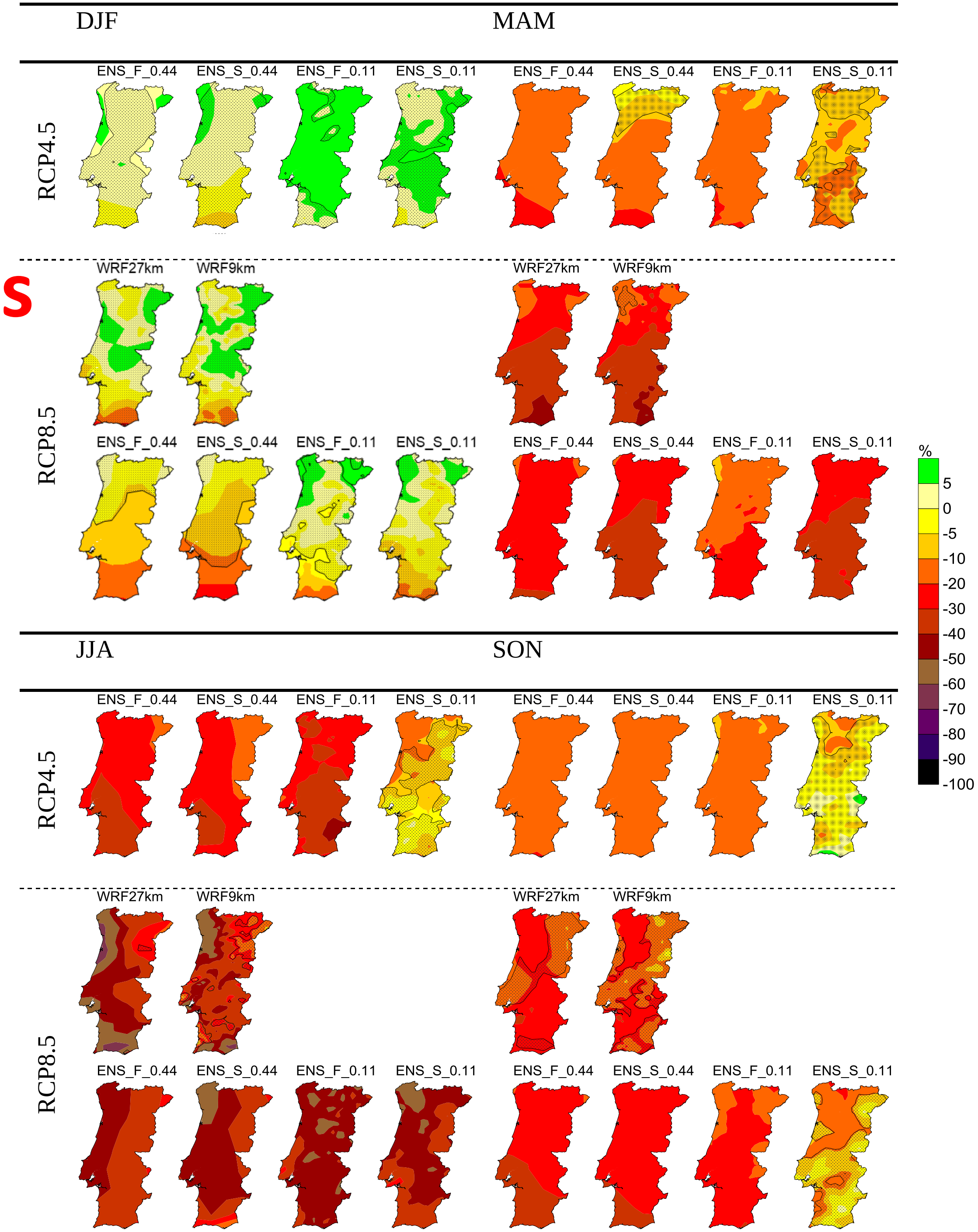
(2071-2100 minus 1971-2000)/1971-2000

Soares et al. (2017)

Precipitation

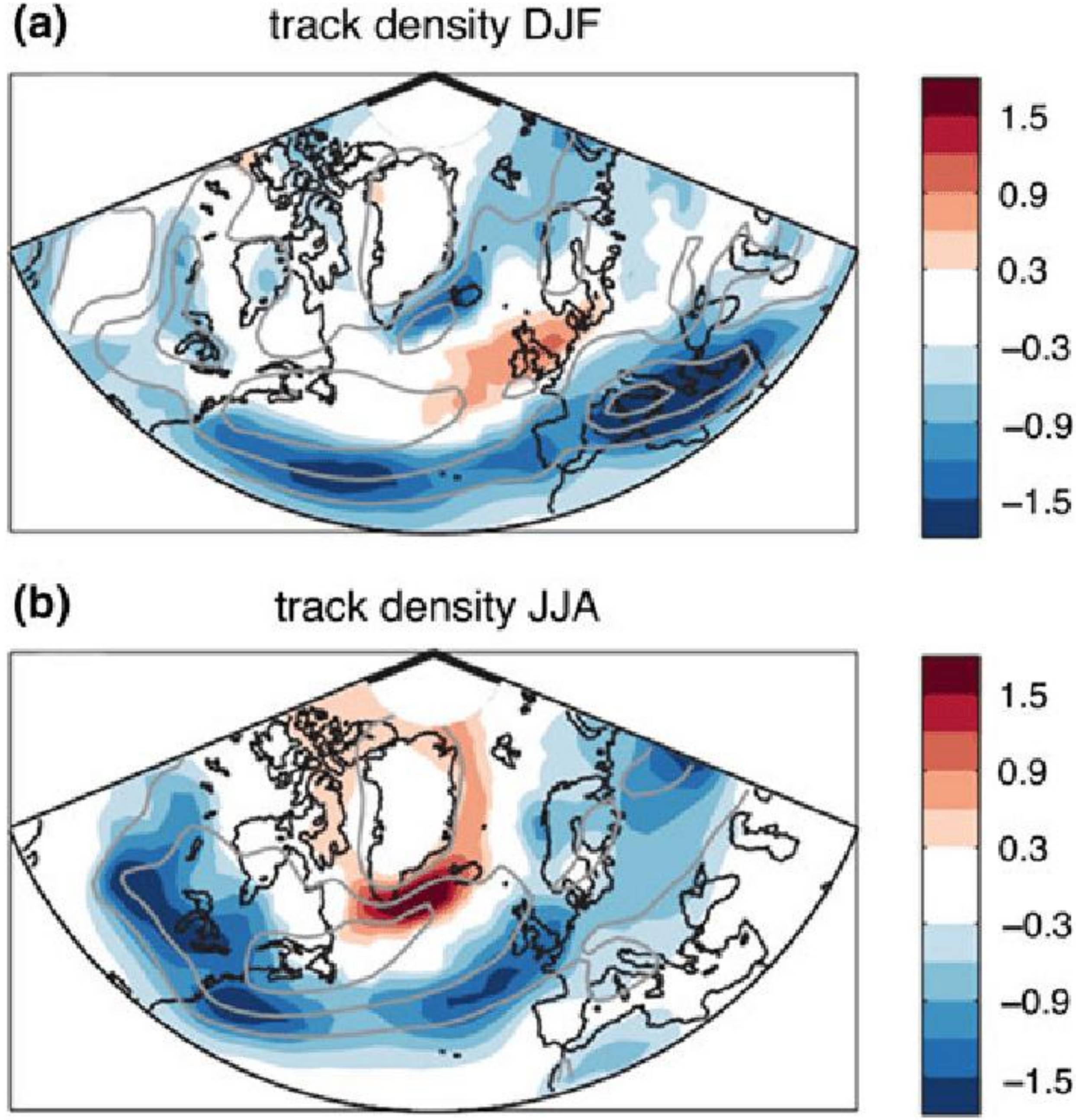
Seasonal Changes

2071-2100
vs
1971-2000



Soares et al. (2017)

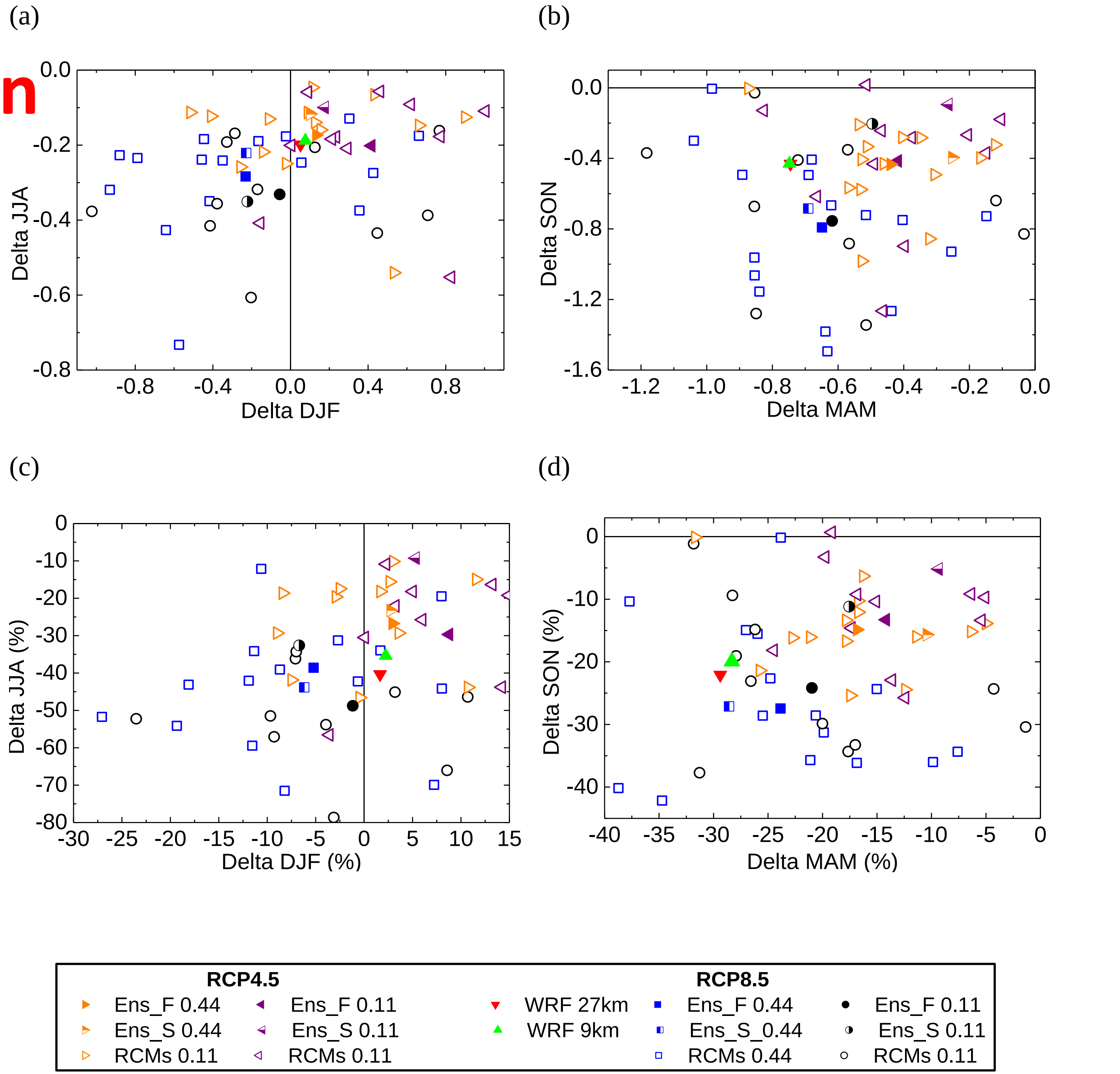
Projected change in mean track density for winter (December through February, DJF; upper panel) and summer (June through August, JJA; lower panel) based on the RCP8.5



May et al 2016

Precipitation

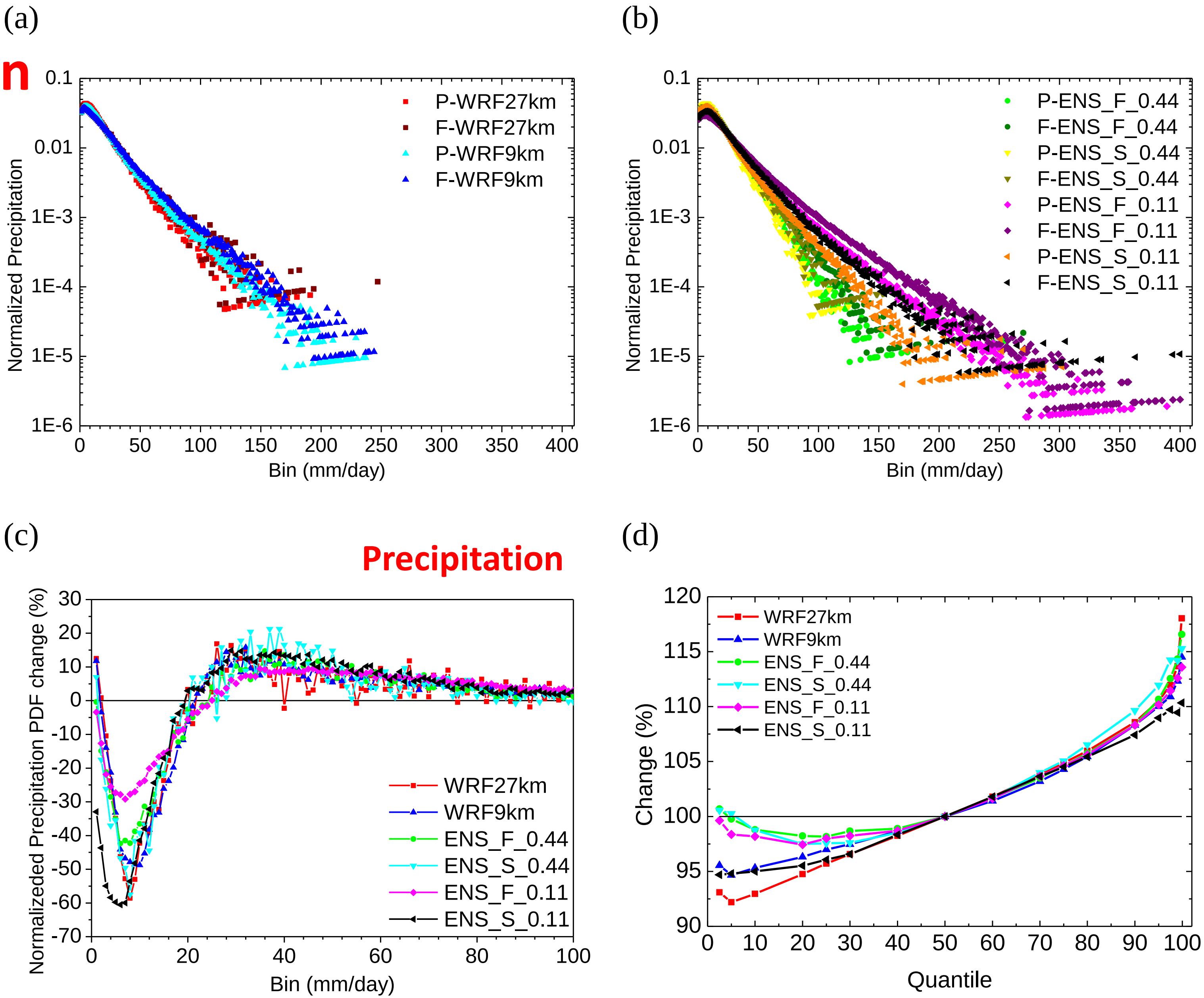
Delta changes



Soares et al. (2017)

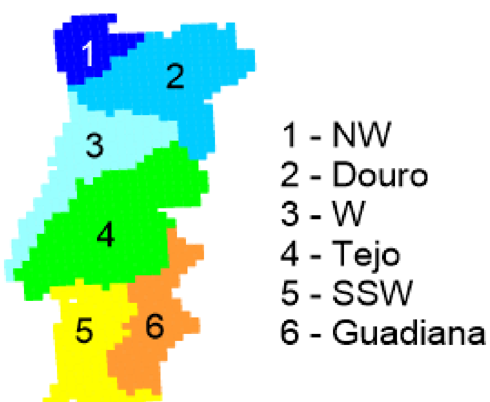
Precipitation

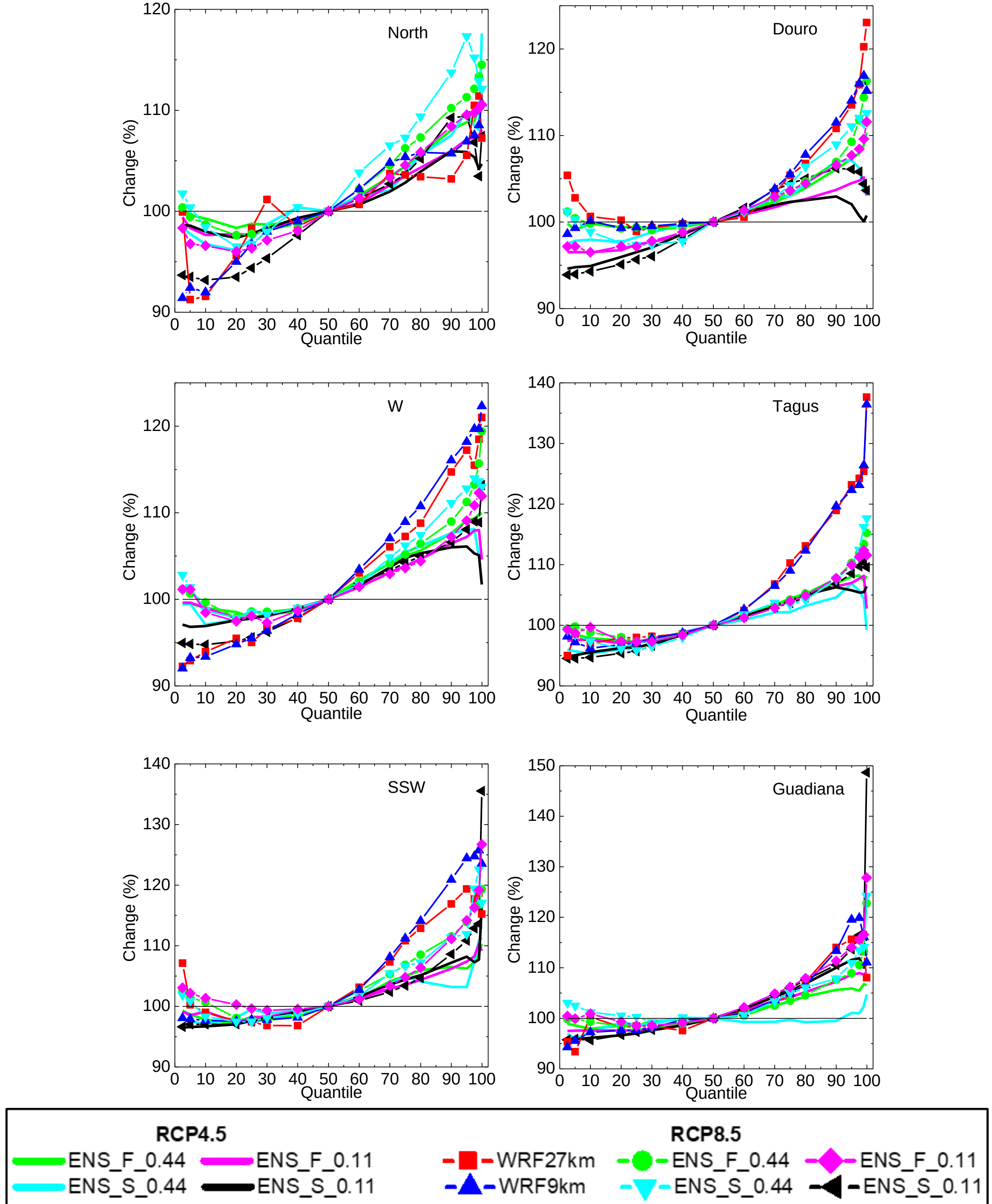
PDF Changes RCP8.5



Soares et al. (2017)

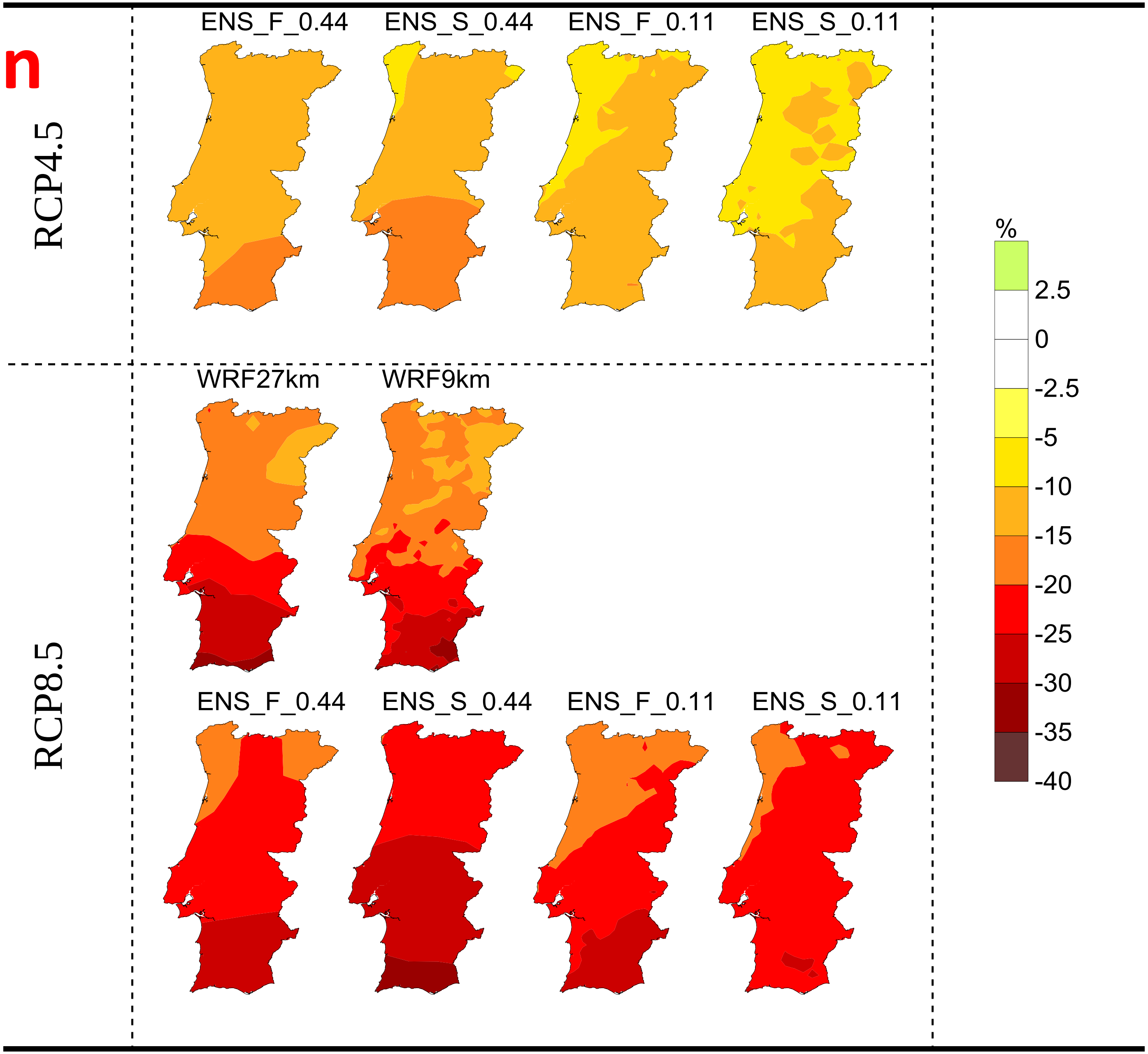
Precipitation
Quantile changes





Precipitation

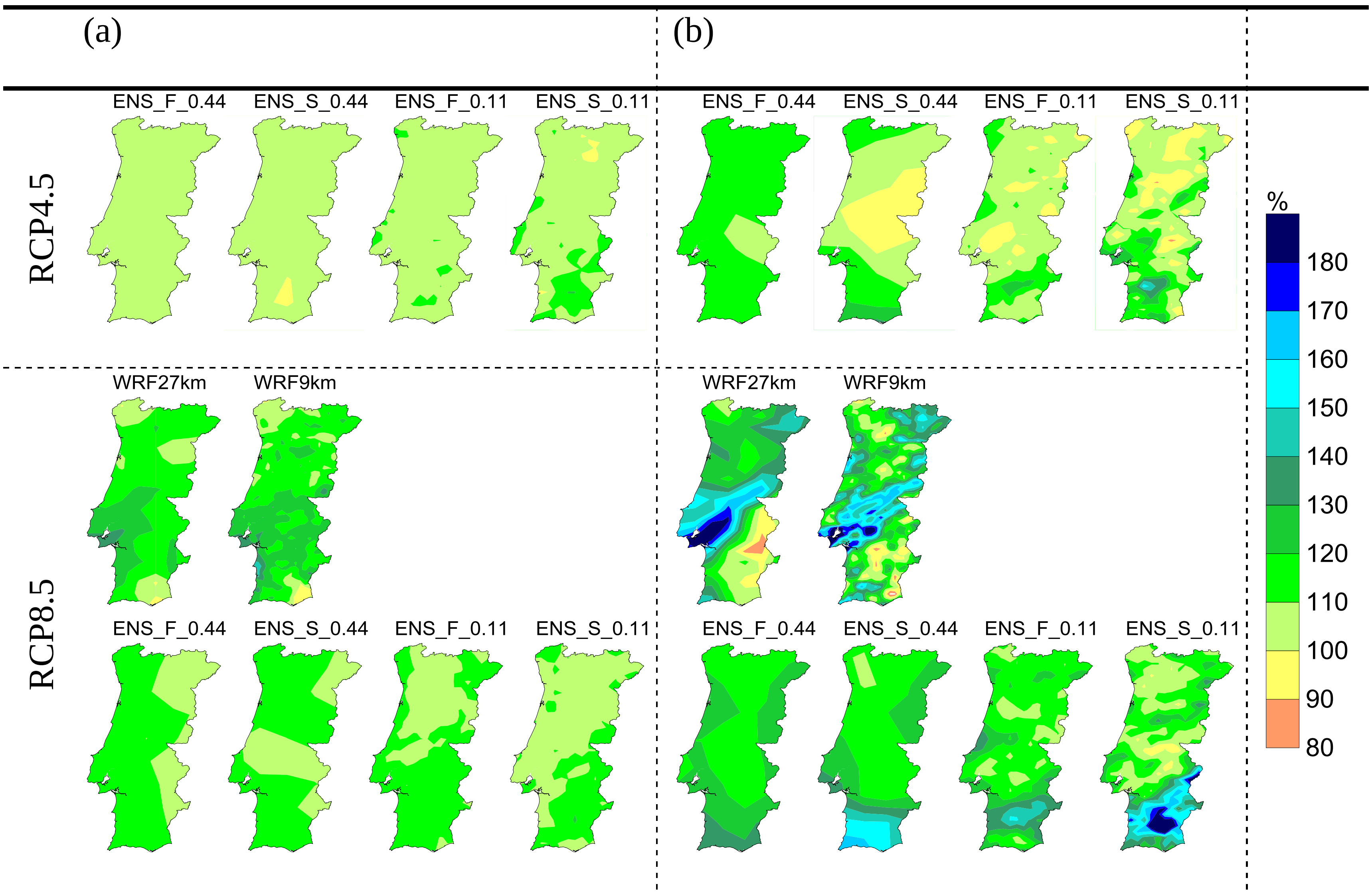
Wetdays relative changes



Soares et al. (2017)

Precipitation Extremes

Extreme Precipitation relative changes (p95, p99)

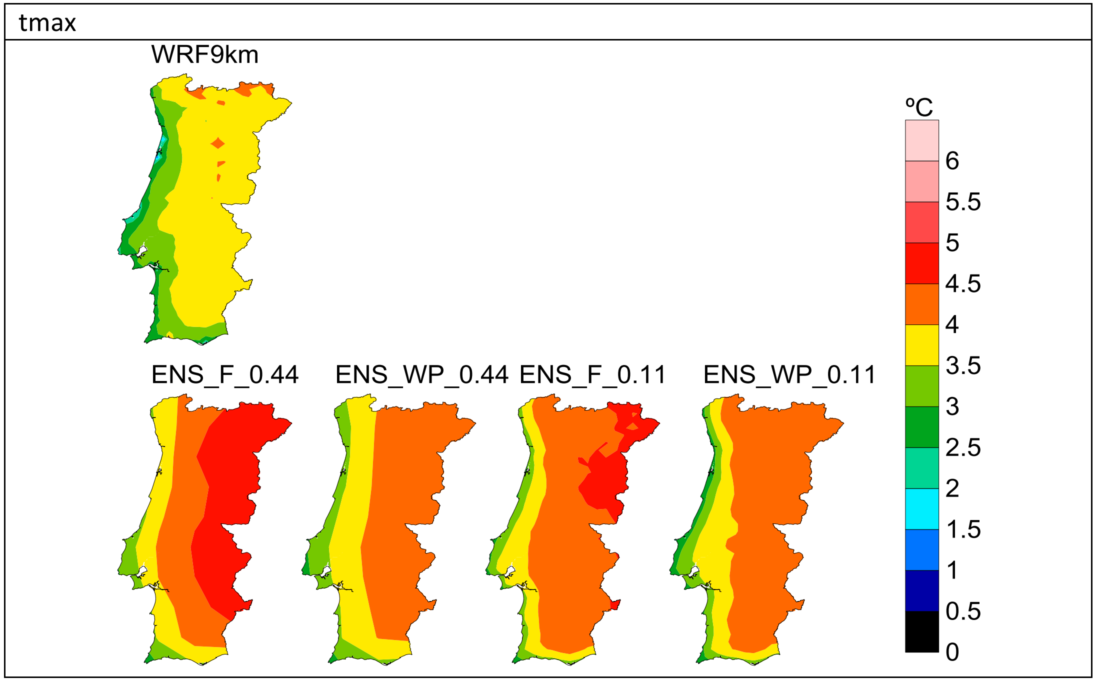


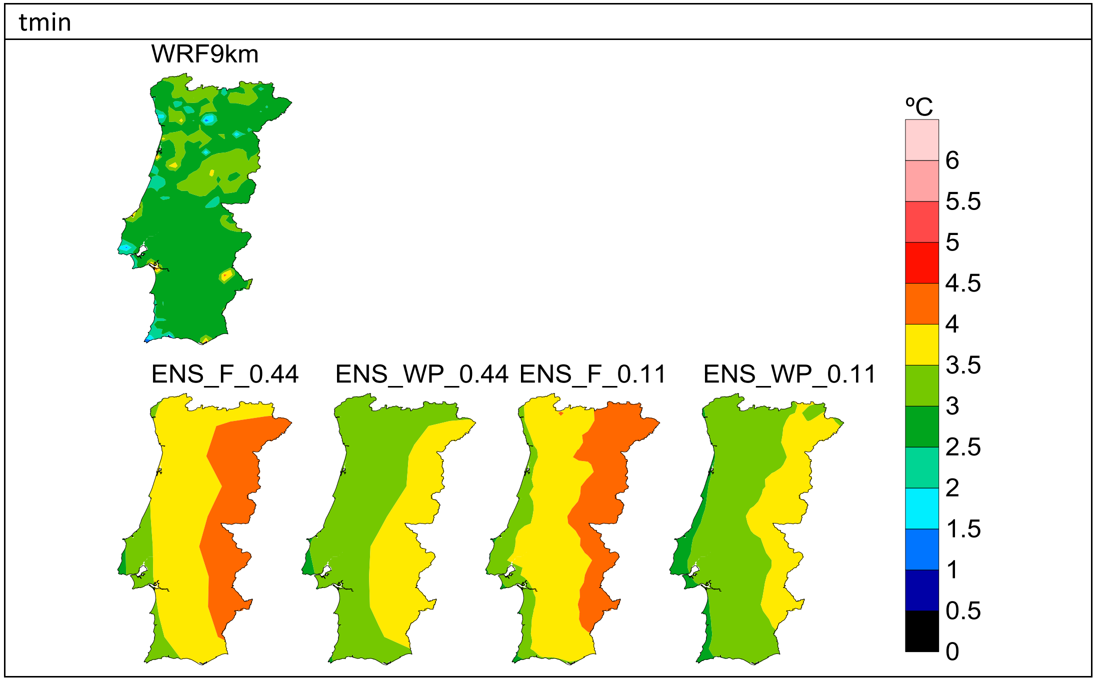
Soares et al. (2017)

Temperature

Temperature

2071-2100
vs
1971-2000



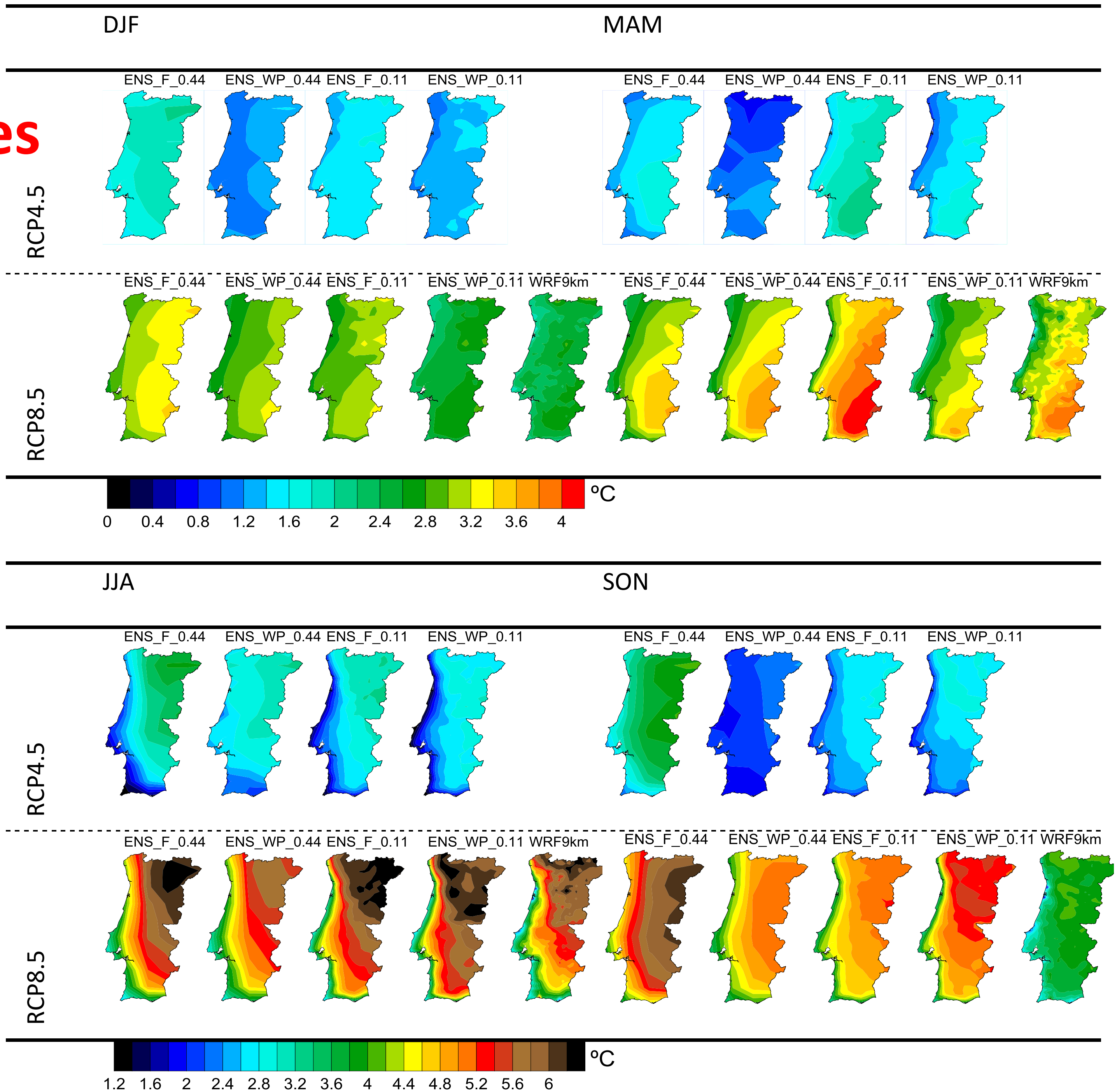


Anomalies of mean yearly temperature

Cardoso et al. (2018)

Seasonal Temperatures changes

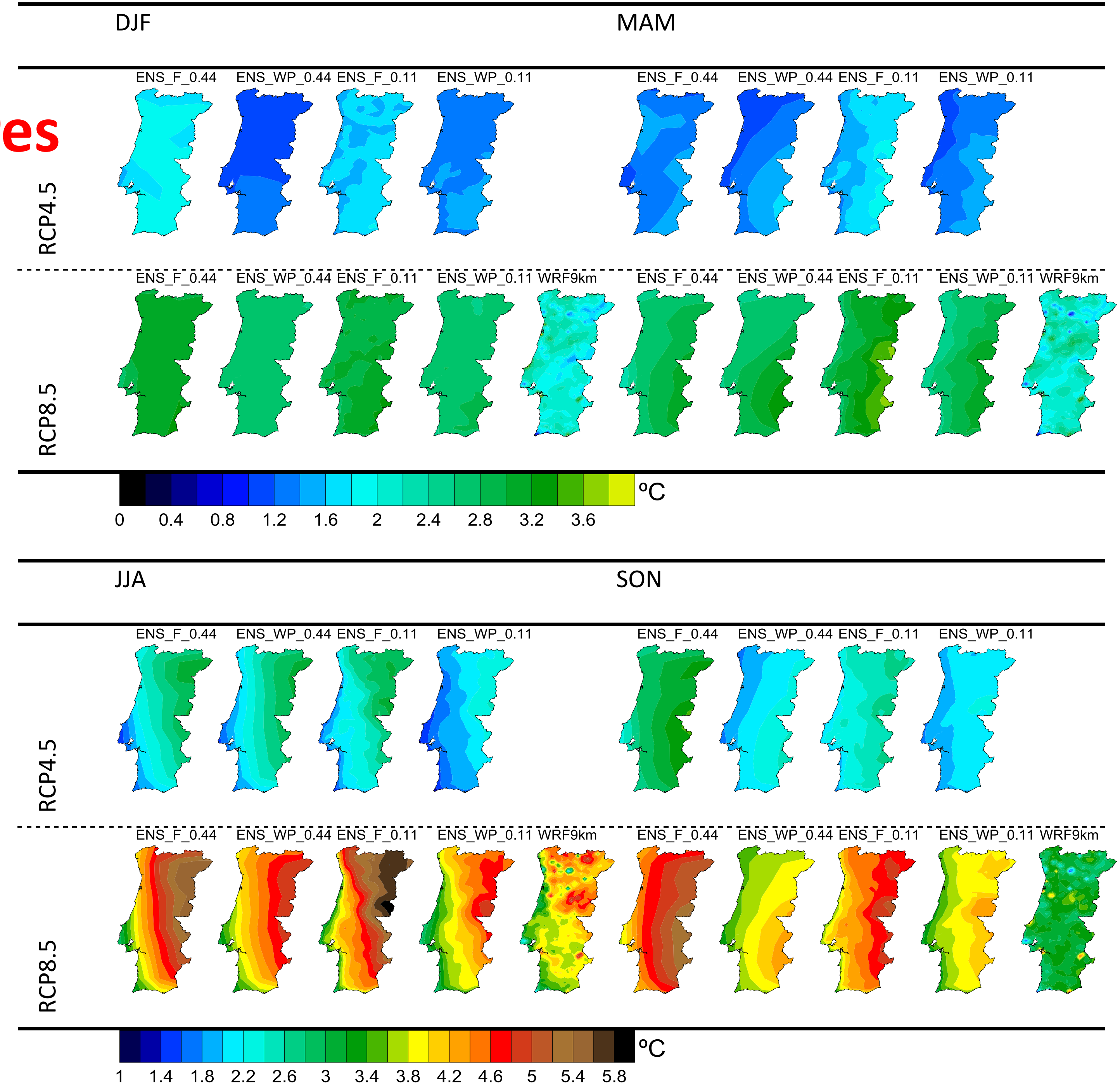
Tmax



Cardoso et al. (2018)

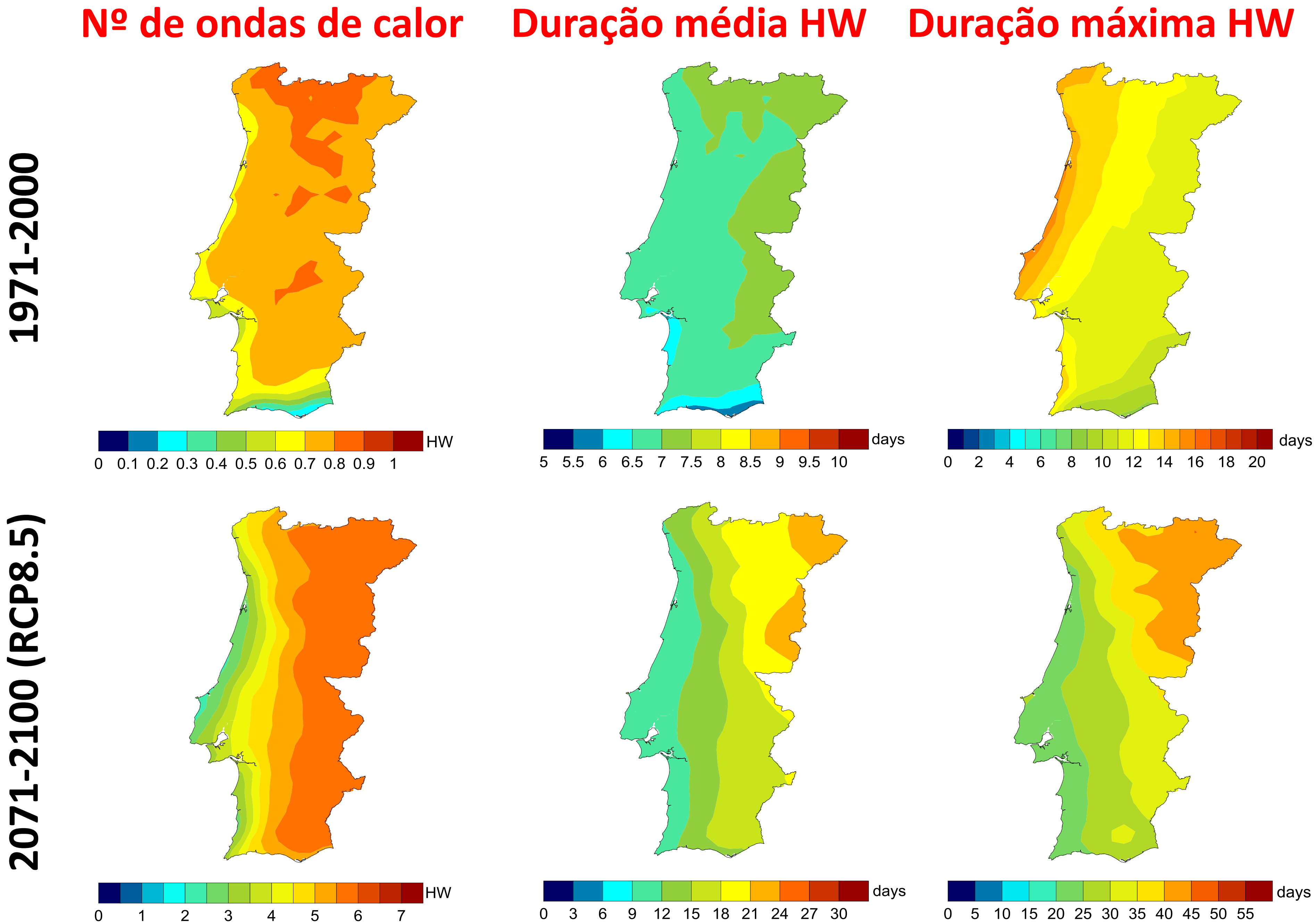
Seasonal Temperatures changes

Tmin



Cardoso et al. (2018)

Temperature Extremes



Cardoso et al. (2018)

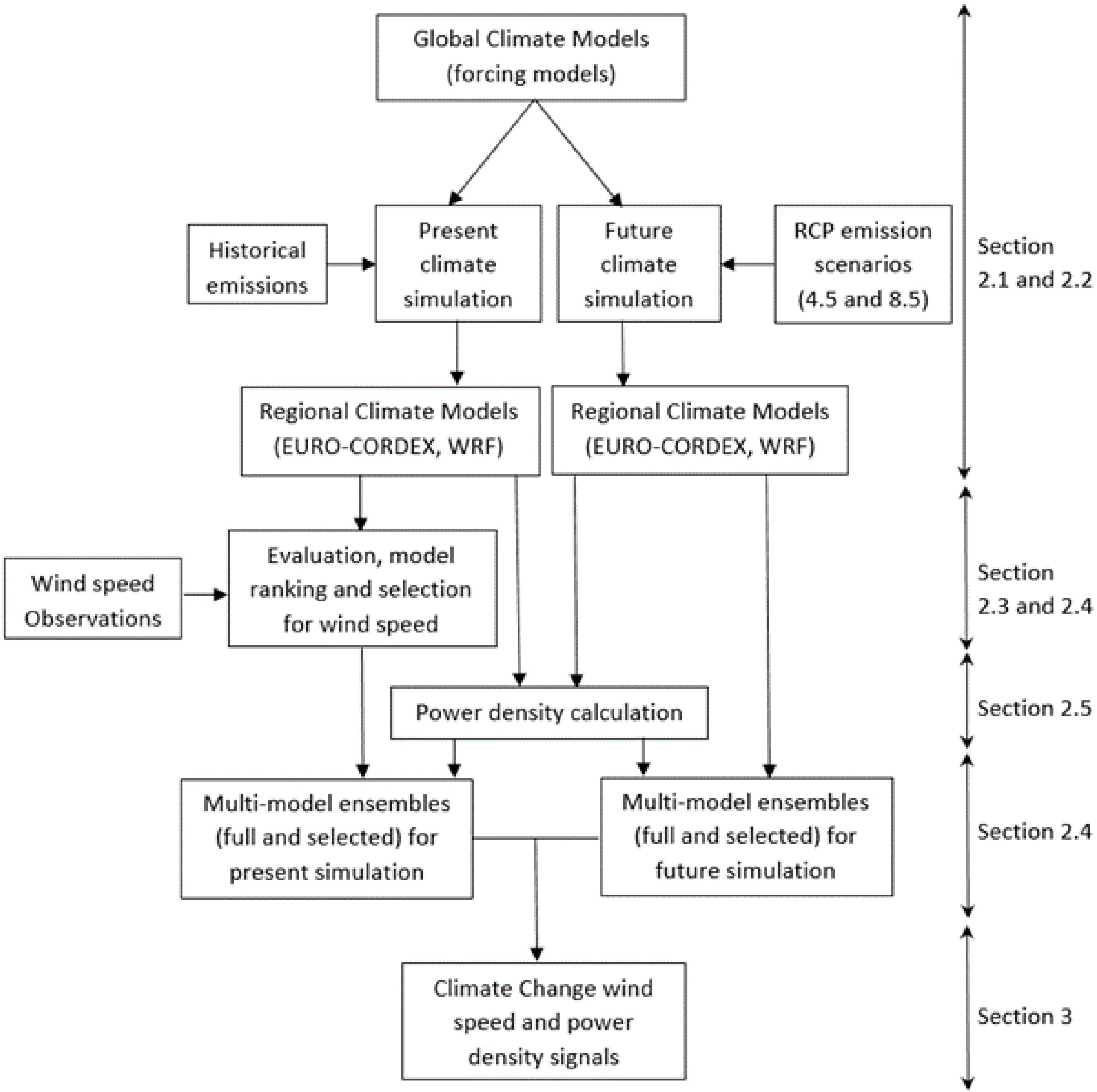
	Temperatura (°C)							
	RCP4.5				RCP8.5			
Região	+ 1.5 K	+ 2 K	+ 3 K	Fim	+ 1.5 K	+ 2 K	+ 3 K	Fim
1-GUARDA	1.068	1.619	2.711	2.280	1.183	1.690	2.869	4.336
2-BEJA	0.979	1.506	2.576	2.125	1.116	1.578	2.635	4.037
3-BRAGANCA	1.060	1.607	2.678	2.288	1.185	1.697	2.872	4.336
4-LEIRIA	0.857	1.275	2.247	1.834	0.937	1.311	2.249	3.500
5-COIMBRA	0.922	1.404	2.403	1.982	1.036	1.459	2.498	3.803
6-LISBOA	0.845	1.250	2.218	1.841	0.922	1.289	2.207	3.483
7-VILA_REAL	1.030	1.560	2.613	2.216	1.157	1.647	2.787	4.206
8-BRAGA	0.947	1.467	2.480	2.102	1.104	1.558	2.653	4.001
9-EVORA	1.013	1.553	2.659	2.155	1.143	1.620	2.729	4.125
10-PORTALEGRE	1.031	1.578	2.694	2.191	1.162	1.652	2.794	4.193
11-FARO	0.914	1.392	2.408	2.001	1.050	1.478	2.438	3.781
12-VIANA_DO_CASTELO	0.920	1.421	2.443	2.034	1.065	1.505	2.576	3.885
13-SANTAREM	0.941	1.430	2.444	2.013	1.053	1.491	2.539	3.873
14-PORTO	0.923	1.420	2.399	2.037	1.059	1.489	2.553	3.878
15-SETUBAL	0.883	1.336	2.319	1.906	0.984	1.387	2.338	3.652
16-VISEU	1.004	1.541	2.589	2.175	1.142	1.621	2.757	4.155
17-AVEIRO	0.893	1.362	2.311	1.932	1.010	1.415	2.427	3.701
18-CASTELO_BRANCO	1.071	1.629	2.742	2.277	1.205	1.717	2.884	4.334
19-PORTUGAL	0.976	1.488	2.534	2.104	1.100	1.559	2.636	4.012

	Precipitação (%)							
	RCP4.5				RCP8.5			
Região	+ 1.5 K	+ 2 K	+ 3 K	Fim	+ 1.5 K	+ 2 K	+ 3 K	Fim
1-GUARDA	-3.267	-4.945	-10.117	-5.613	-2.762	-3.442	-7.480	-13.569
2-BEJA	-9.311	-11.350	-19.003	-8.358	-9.772	-12.951	-17.381	-17.301
3-BRAGANCA	-1.273	-3.110	0.080	-3.158	-1.164	-1.977	-5.805	-7.878
4-LEIRIA	-3.760	-7.154	-12.317	-5.513	-4.556	-6.198	-12.123	-11.447
5-COIMBRA	-2.633	-6.531	-13.676	-5.442	-4.271	-5.574	-10.982	-11.793
6-LISBOA	-5.708	-8.219	-9.539	-5.584	-5.345	-8.053	-12.988	-14.035
7-VILA_REAL	-1.487	-3.514	-3.539	-5.160	-1.252	-3.135	-7.434	-11.597
8-BRAGA	-0.373	-4.342	-0.109	-3.994	-1.169	-3.407	-8.361	-6.777
9-EVORA	-7.354	-8.806	-15.794	-6.516	-6.571	-8.824	-13.426	-15.013
10-PORTALEGRE	-5.691	-7.749	-12.404	-5.659	-5.877	-6.731	-12.163	-13.711
11-FARO	-10.672	-13.110	-14.665	-9.395	-11.883	-16.000	-20.023	-21.337
12-VIANA_DO_CASTELO	-0.447	-4.268	0.244	-4.102	-0.859	-3.633	-7.903	-5.455
13-SANTAREM	-5.817	-7.774	-10.847	-5.094	-5.651	-6.947	-12.359	-12.713
14-PORTO	-0.376	-4.721	-4.106	-4.472	-1.806	-3.781	-8.683	-7.474
15-SETUBAL	-7.586	-10.533	-14.236	-7.653	-7.084	-10.361	-15.554	-15.610
16-VISEU	-2.460	-5.216	-9.753	-5.689	-2.702	-4.029	-8.680	-12.715
17-AVEIRO	-1.418	-5.647	-7.549	-4.604	-2.986	-4.755	-9.785	-8.324
18-CASTELO_BRANCO	-5.343	-7.155	-8.916	-4.665	-5.469	-6.388	-12.092	-13.350
19-PORTUGAL	-4.986	-7.425	-10.525	-5.860	-5.204	-7.132	-11.939	-13.137

Renewables

Wind Offshore

Methods


Global Climate Models
(forcing models)
Historical emissions
Present climate simulation
Future climate simulation
RCP emission scenarios (4.5 and 8.5)
Regional Climate Models (EURO-CORDEX, WRF)
Regional Climate Models (EURO-CORDEX, WRF)
Wind speed Observations
Evaluation, model ranking and selection for wind speed
Power density calculation
Multi-model ensembles (full and selected) for present simulation
Multi-model ensembles (full and selected) for future simulation
Climate Change wind speed and power density signals
Section 2.1 and 2.2
Section 2.3 and 2.4
Section 2.5
Section 2.4
Section 3

RCM simulations

- WRF at 9km
- EURO-CORDEX at 0.11º ~ 12km

Observations

- Offshore: SeaWind dataset and buoys
- Onshore : IPMA local stations

Error measures

- Bias, MAE, MAPE, RMSE, PDF skill scores, Correlarion, Starndard deviation, Anderson and Darling, Yule and Kendall, etc.

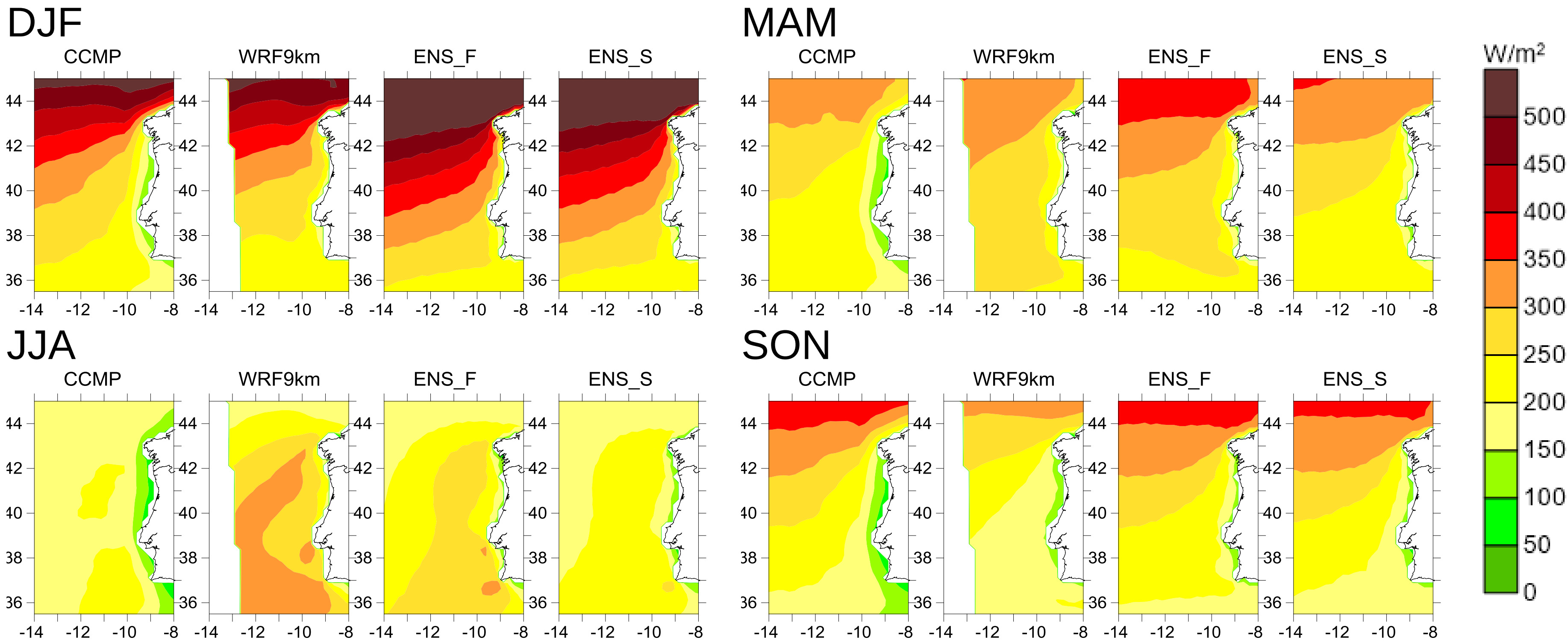
Ranking and Multi-model ensemble

- Ranking normalizing the errors
- Full, selected and weighted multi-model ensemble

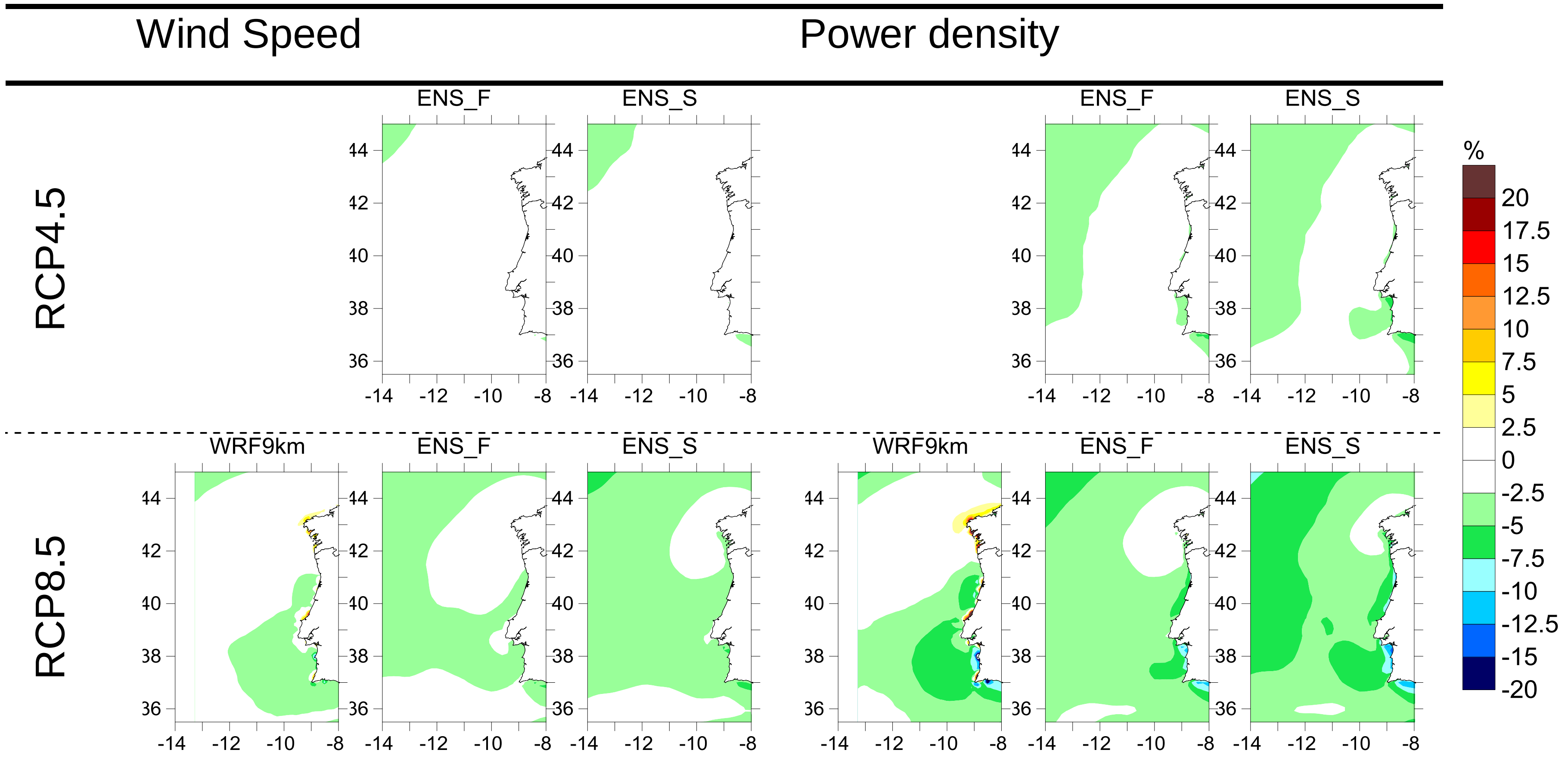
energy density: offshore hub height 90 m; onshore hub height 80m

$$\frac{P}{A} = \frac{1}{2} C \rho {v_{\mathrm{hh}}}^{3}$$

Seasonal mean power density (Wm^{-2}) at 90m height

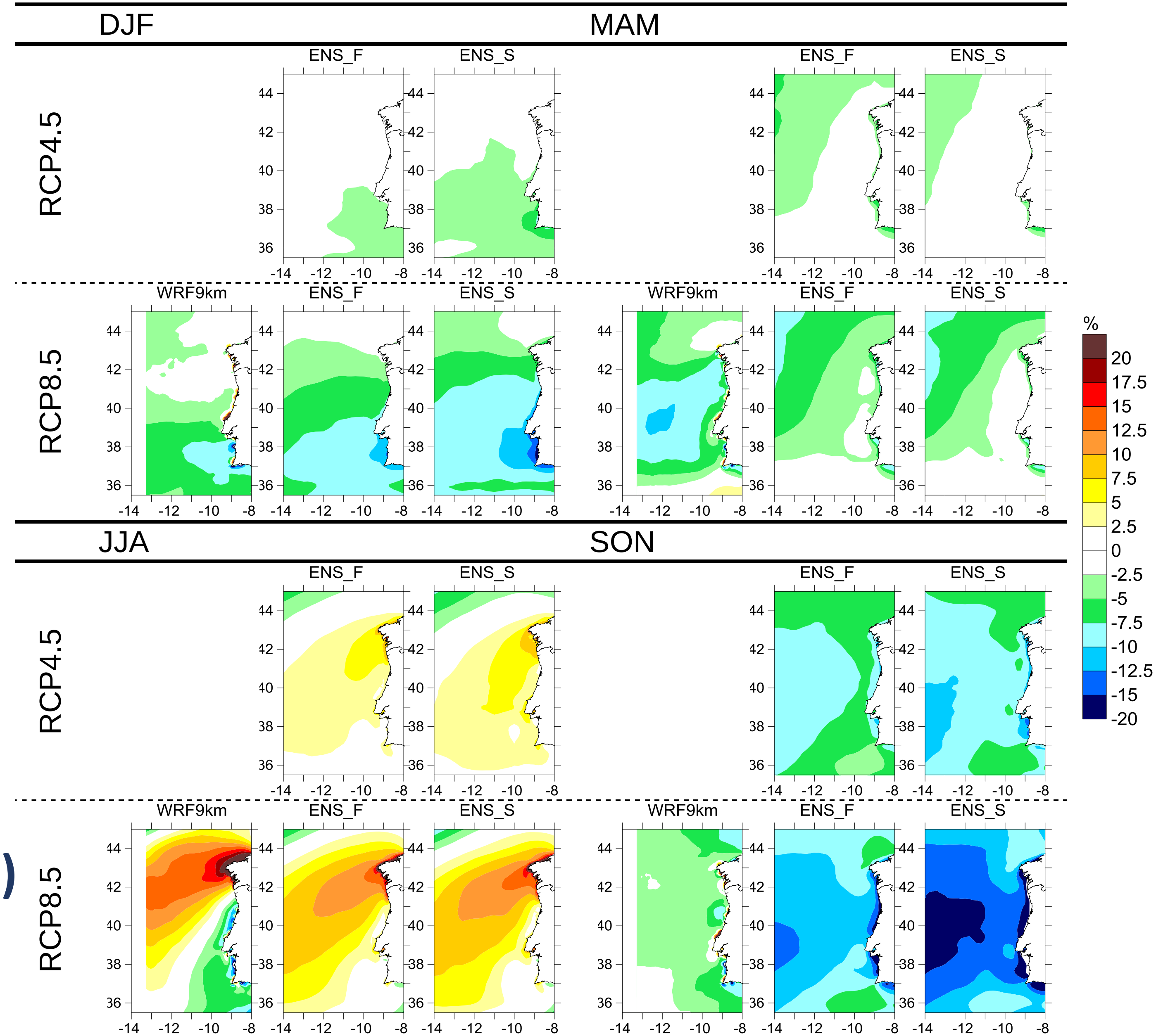


Yearly wind and power density relative changes



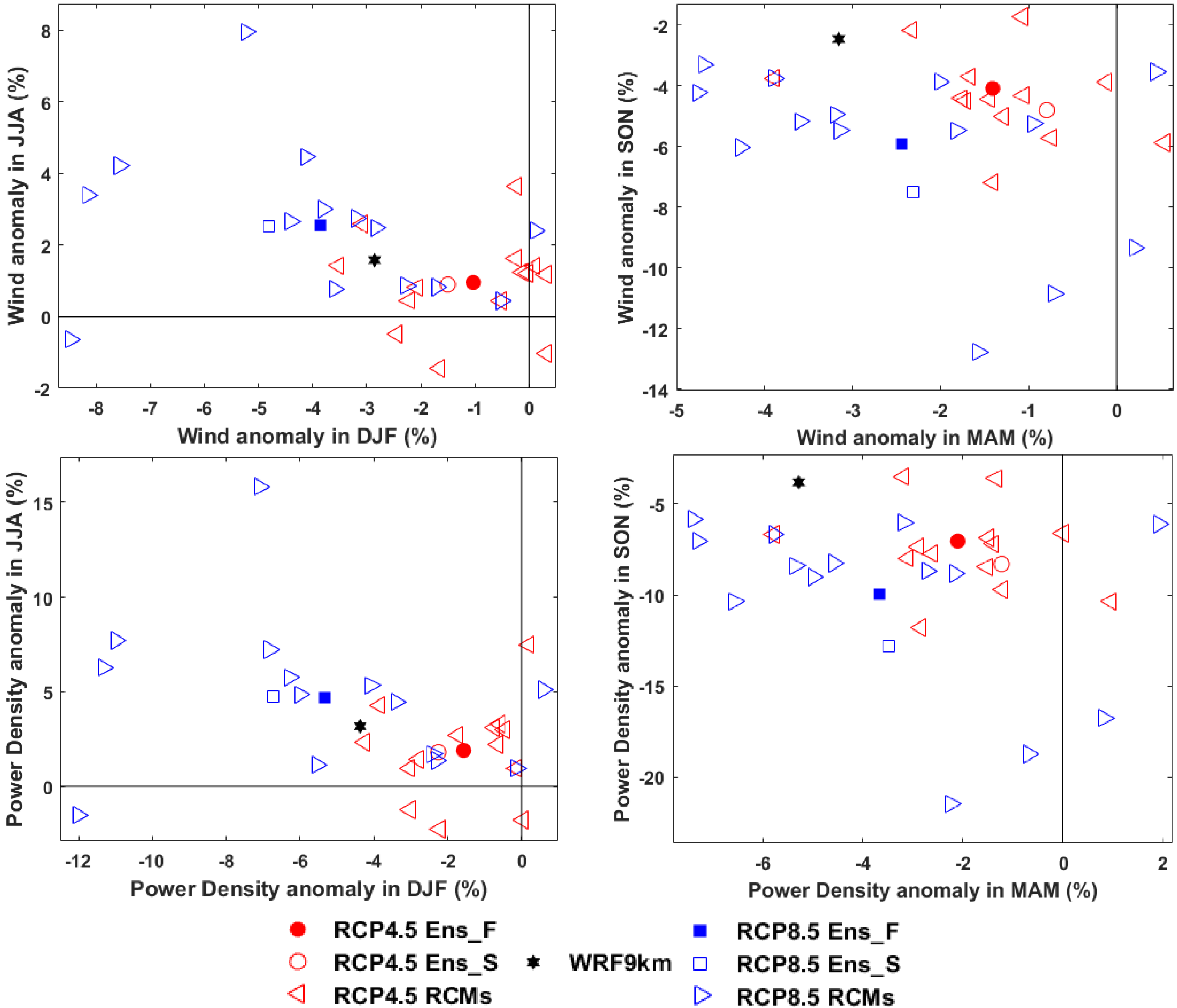
(2071-2100 minus 1971-2000)/1971-2000

Seasonal power density relative changes

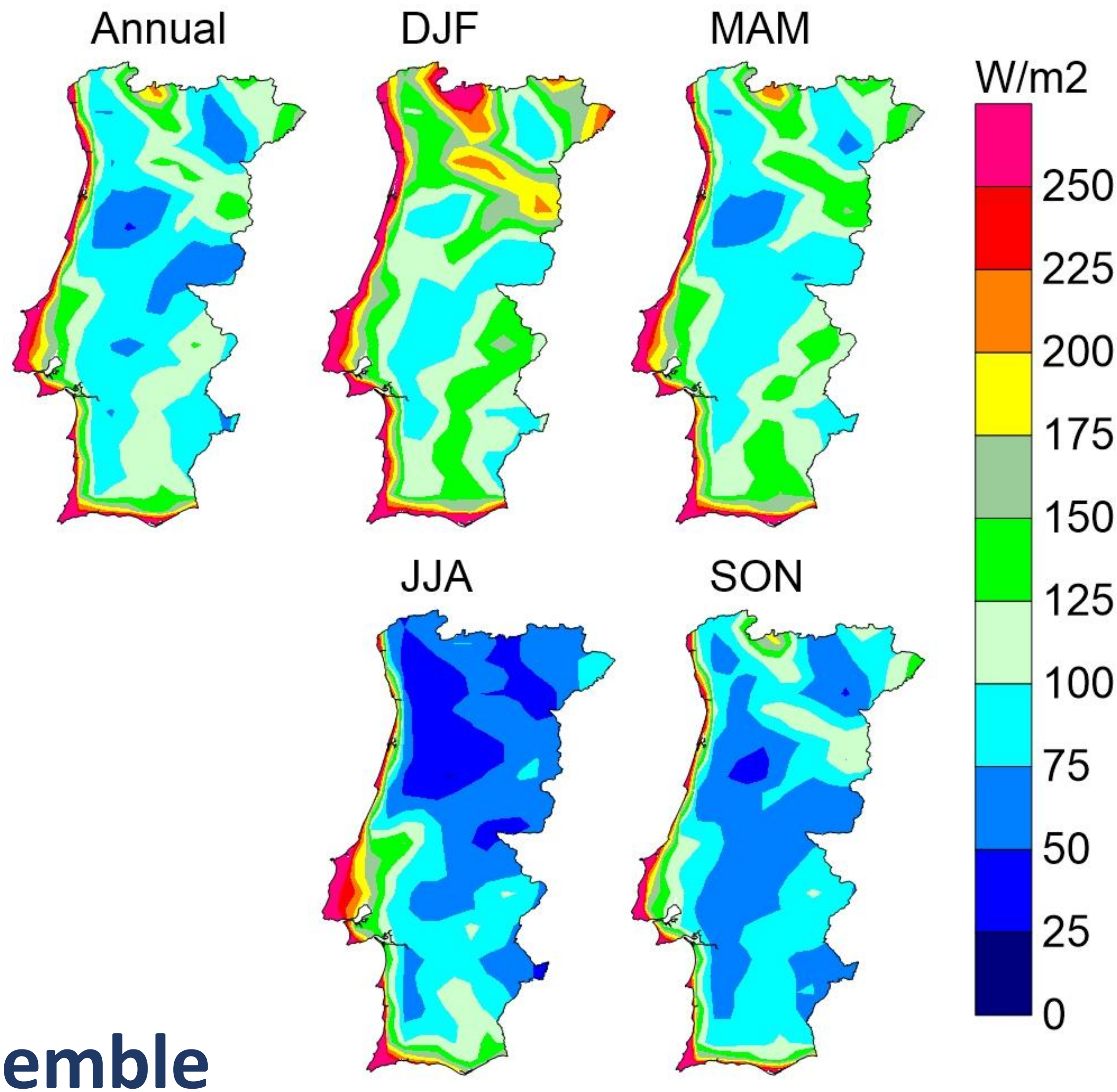


(2071-2100 minus 1971-2000) /1971-2000

Delta changes



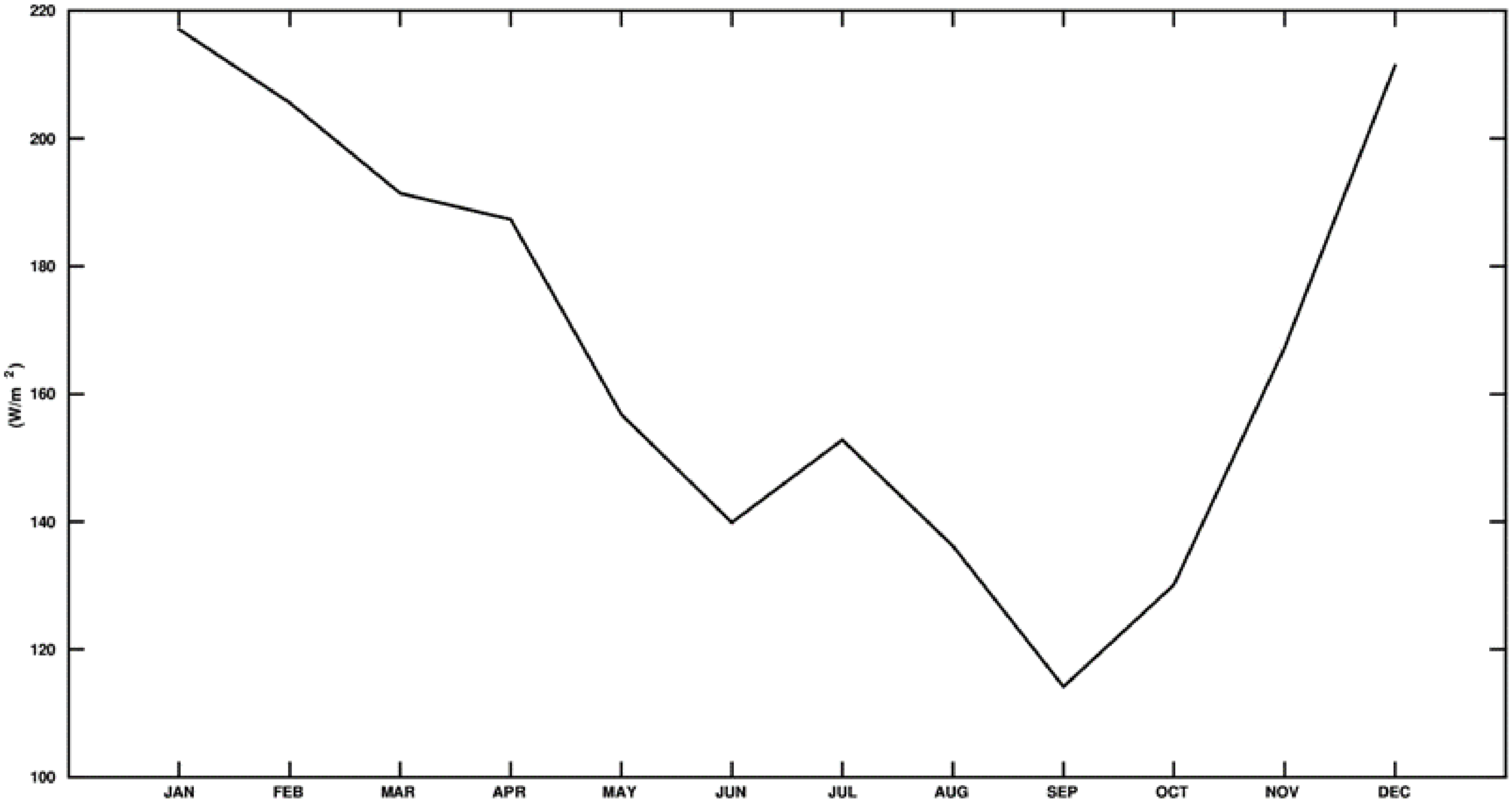
Wind Onshore



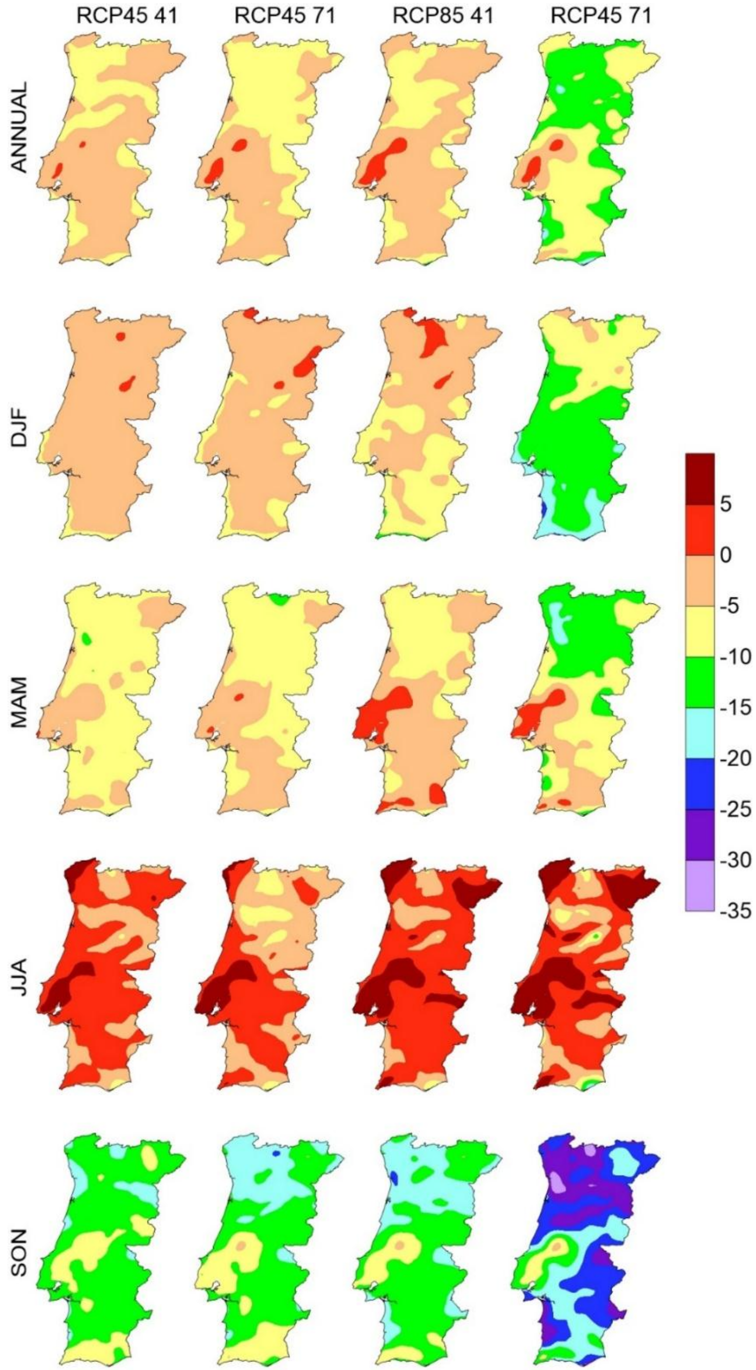
(1971-2000)

Annual and Seasonal Multi-model ensemble wind power density

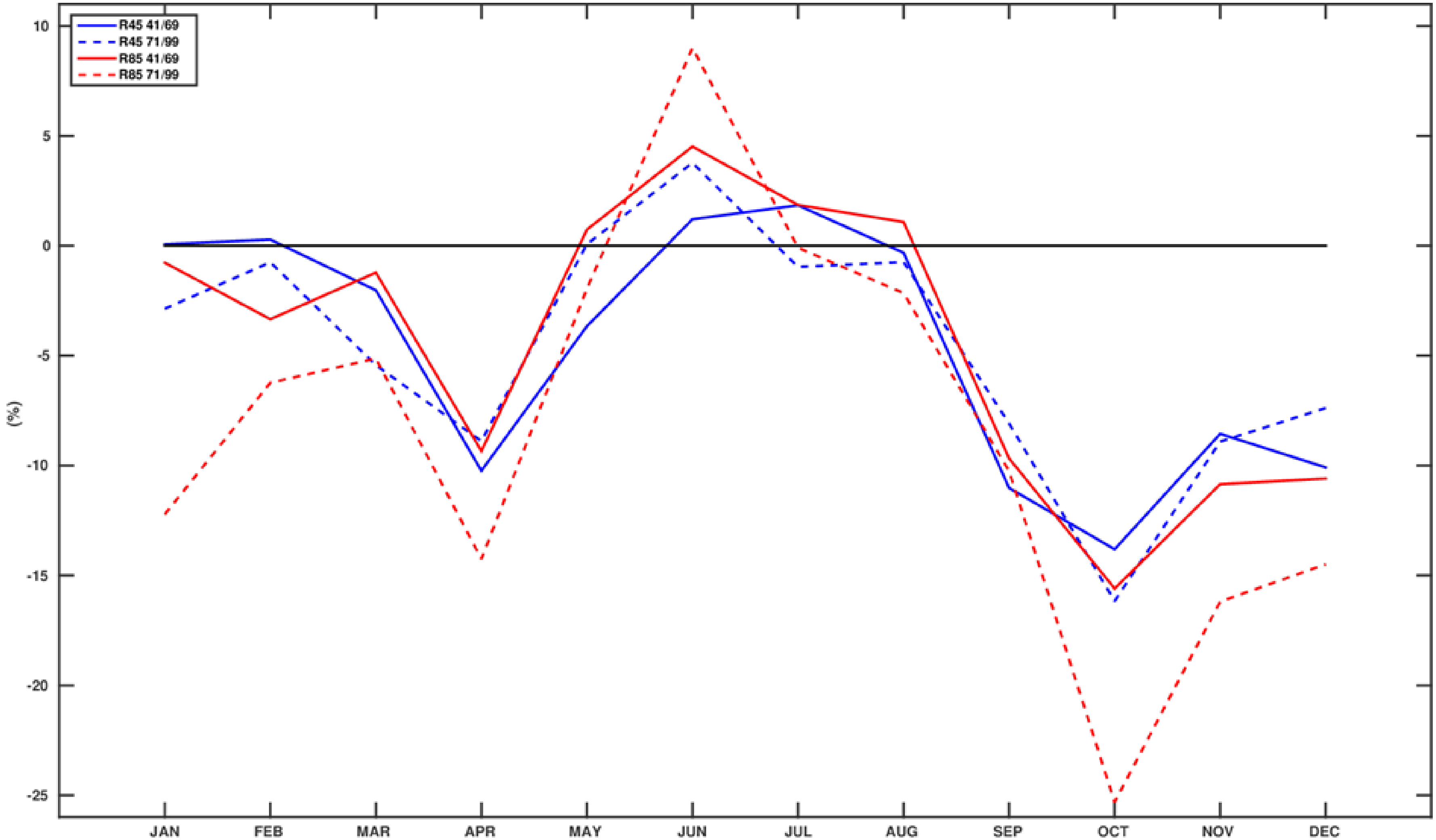
Wind power density annual cycles at the monthly scale from the weighted multi-model ensemble historical run (1971-2000) averaged for Portugal

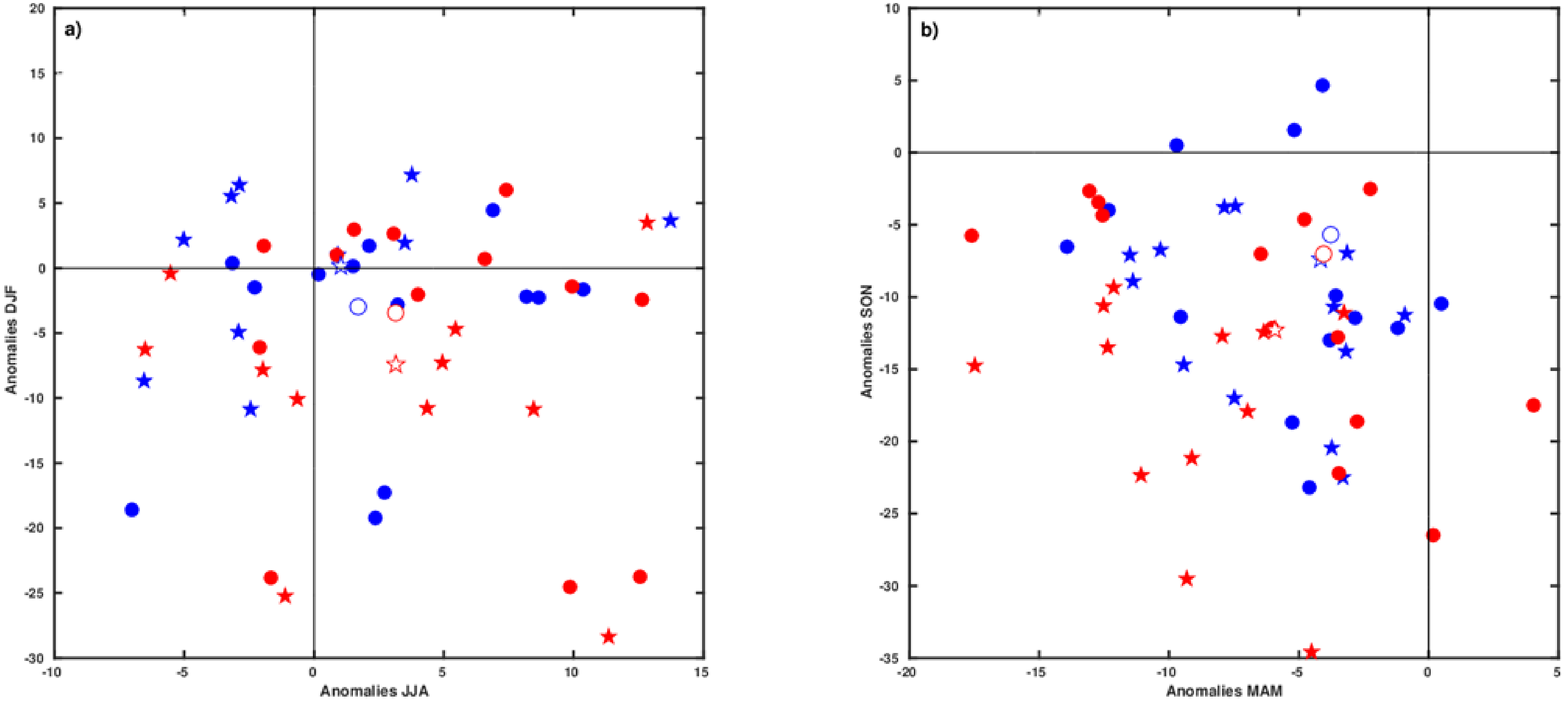


Maps of wind power anomalies [%]



Annual cycle of monthly wind power density anomalies [%]




a)
Anomalies DJF
Anomalies JJA
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-10
-5
0
5
10
15
b)
Anomalies SON
Anomalies MAM
10
5
0
-5
-10
-15
-20
-25
-30
-35
-20
-15
-10
-5
0
5

Solar resource

solar radiation

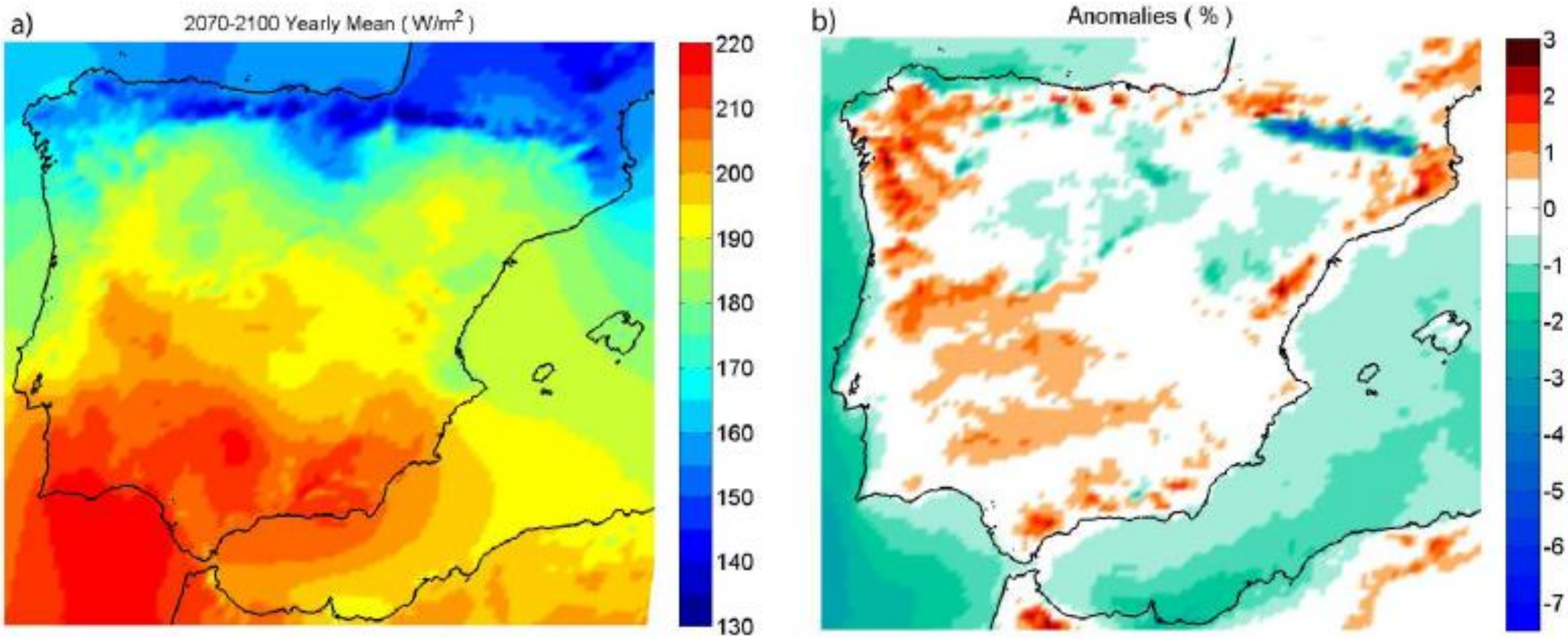


Figure 5.4 (a) Yearly mean map of projected WRF solar radiation for the end of the century (2070-2100) with interpolated probability-dependent correction function and (b) respective anomalies considering historical climate run (1970-2000) as baseline.

Muito Obrigado

Climate cooling potential

Climate cooling potential

$$CCP = c \cdot \rho \cdot v \cdot (T_{bld} - T_{vnt}) - c \cdot \rho \cdot v_{ref}(T_{bld} - T_{ext})$$

$$v = \begin{cases} v_{vnt} & if \;\; T_{vnt} < T_{bld} \\ v_{ref} & if \;\; T_{vnt} \geq T_{bld} \end{cases}$$

"CCP" is the Climatic Cooling Potential in kW per m3 building (or kWh per m3 building when integrated over a certain period)

"c" is the heat capacity of air (kWh/K.kg),
"ρ" is the air density (kg/m3), Tset (instead of Tbld)
"v" is the air flow rate in air changes per hour (m3/h),
"Tvnt" is the ventilation temperature (K),
"Tbld" is the temperature inside the building (K) and
"Text" is the air outside temperature (K).

Tset (instead of Tbld)= 26ºC

Climate cooling potential - Direct Ventilation

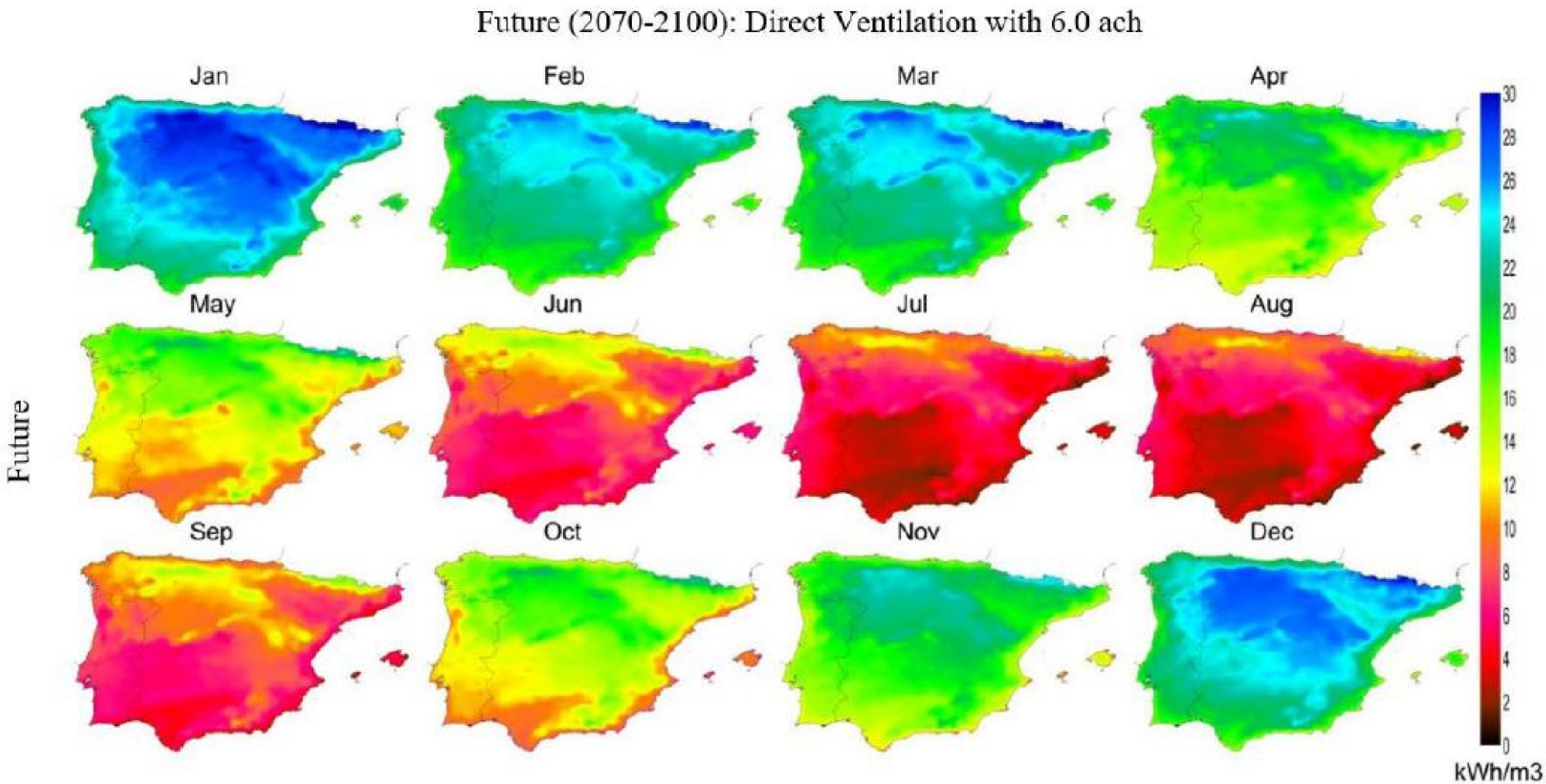


Figure 4.6. CCP Direct Ventilation, 6.0 ach, future climate (2070 to 2100), average monthly values: (a) future values.

$$(T_{vnt} = T_{ext})$$

"vref " of 1.5 ach (of 1.5 m3/h per m3 building) during daytime (7h – 19h), vref = 0 (night)

Climate cooling potential - Direct Ventilation

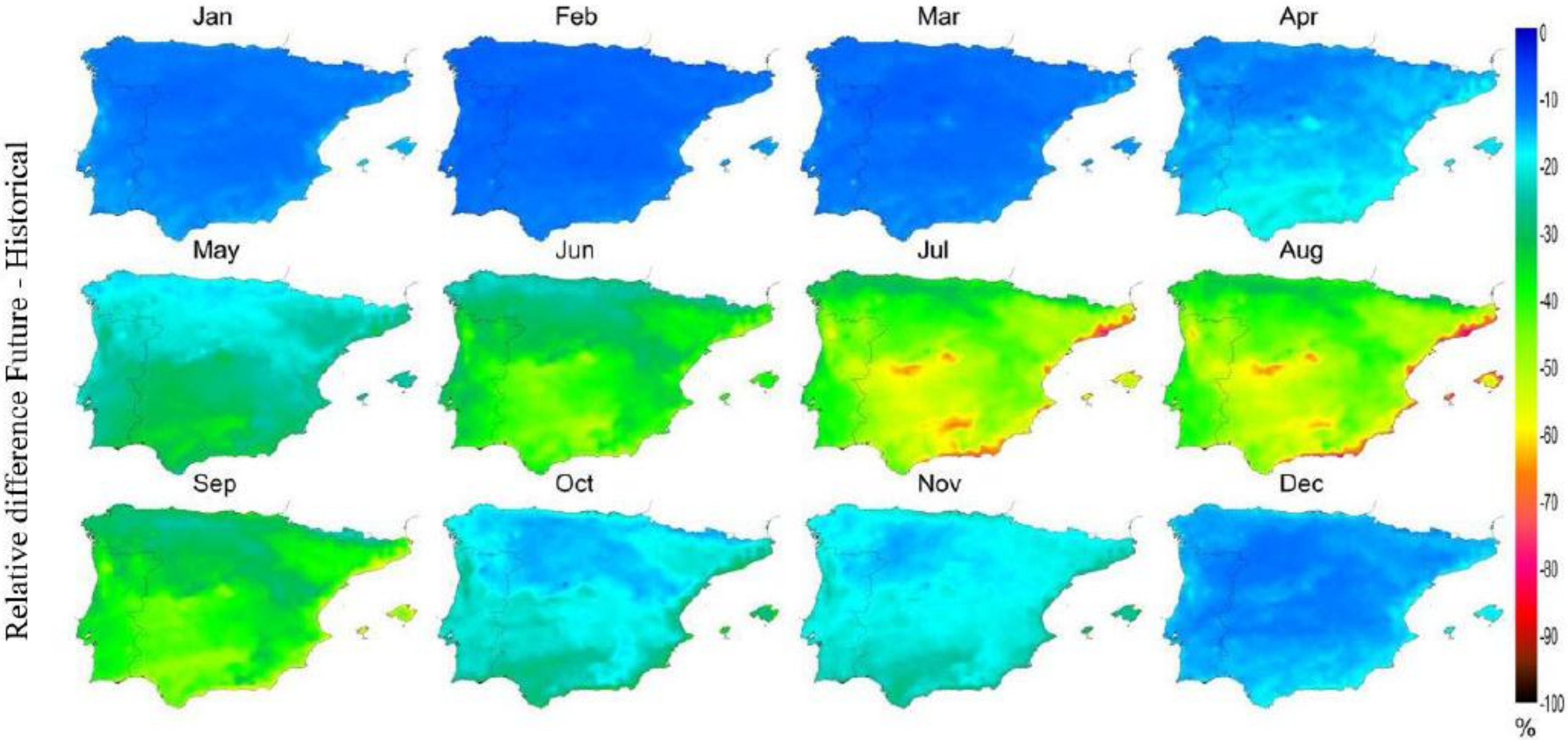


Figure 4.6. CCP Direct Ventilation, 6.0 ach, future climate (2070 to 2100), average monthly values: (b) relative difference between future and historical values: 100*(future - historical)/historical.

Climate cooling potential - Evaporative Cooling

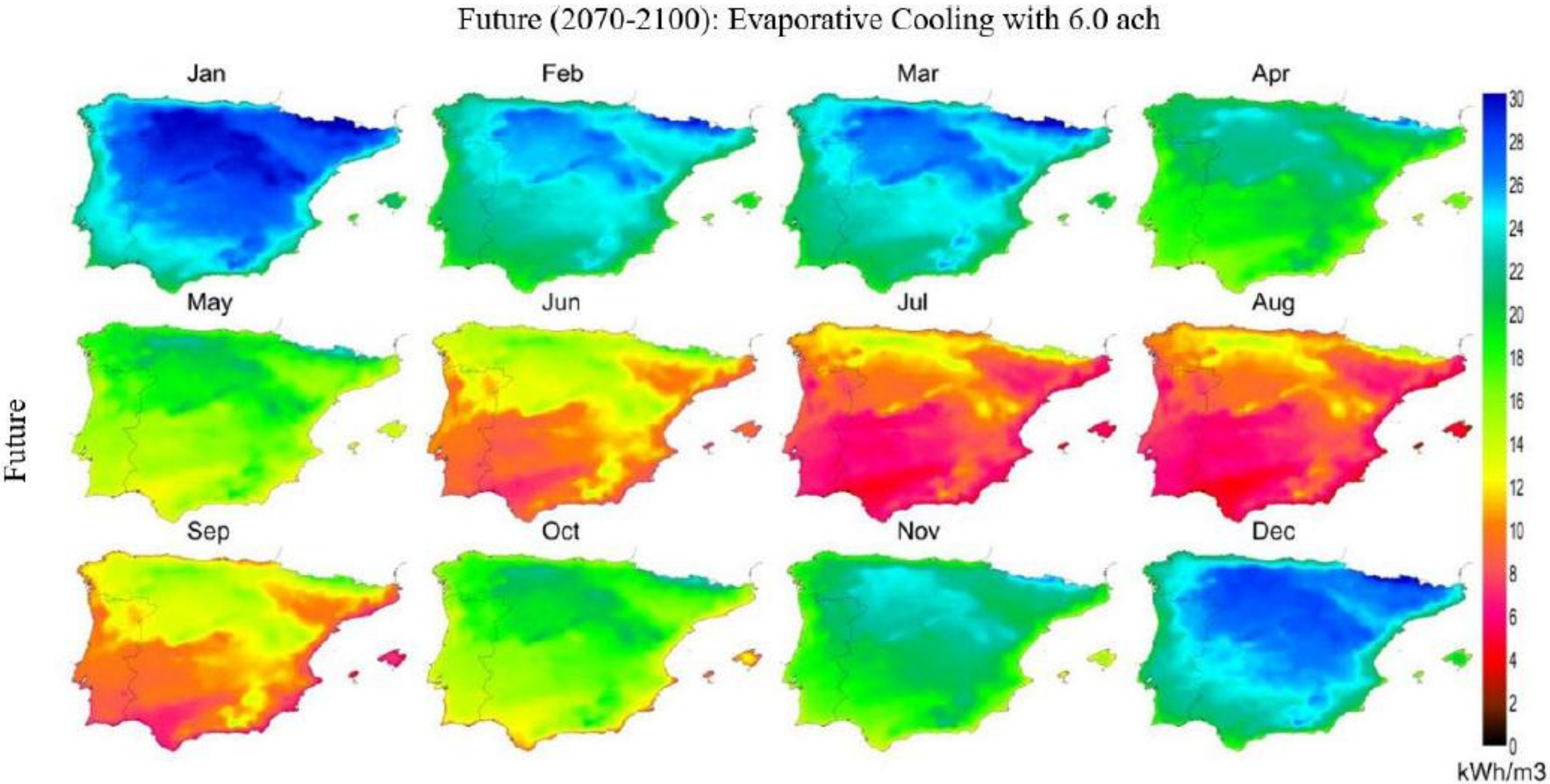


Figure 4.8. CCP Evaporative Cooling, 6.0 ach, future climate (2070 to 2100), average monthly values: (a) future values

$$T_{vnt} = T_{ext} + \eta(T_{wb} - T_{ext})$$

Climate cooling potential - Evaporative Cooling

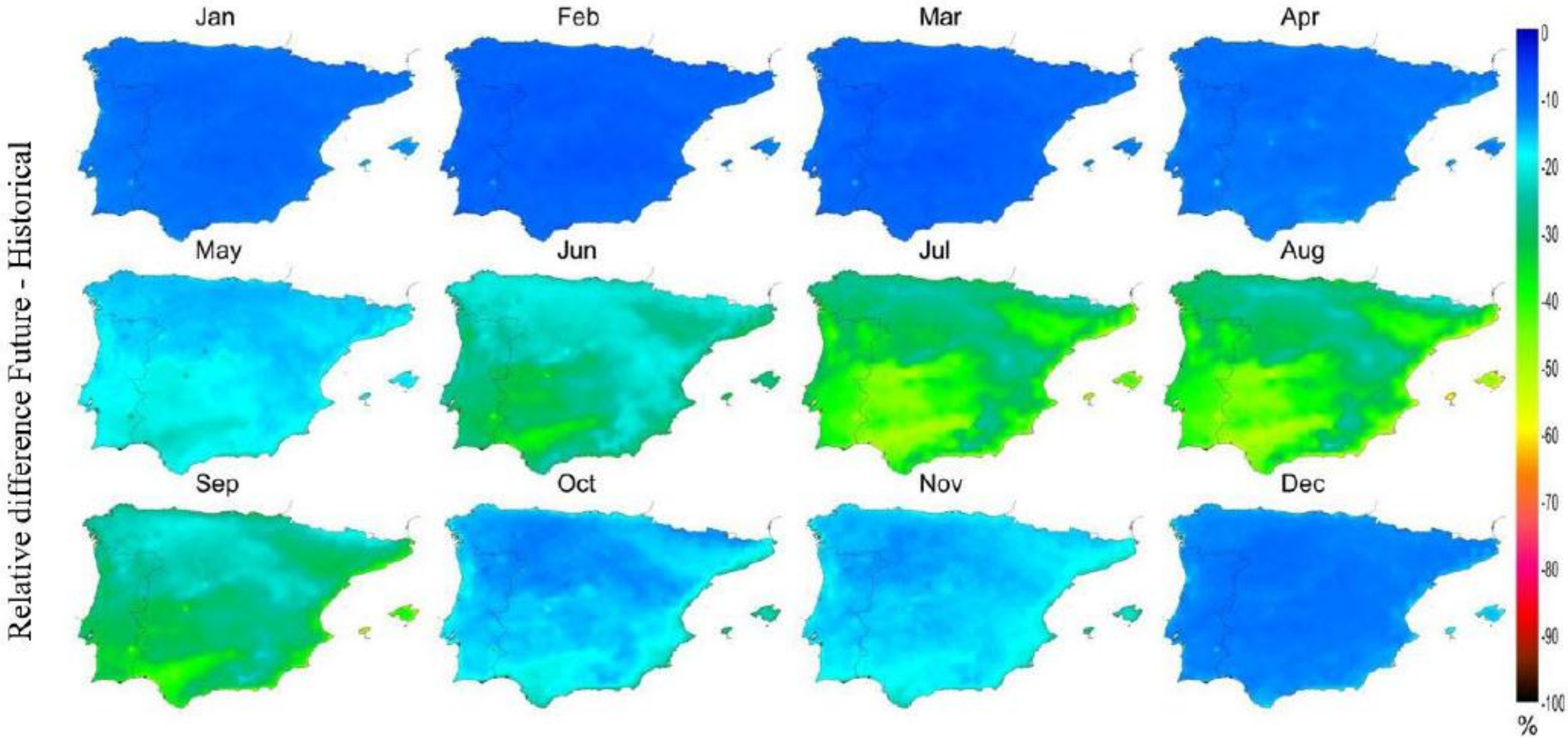


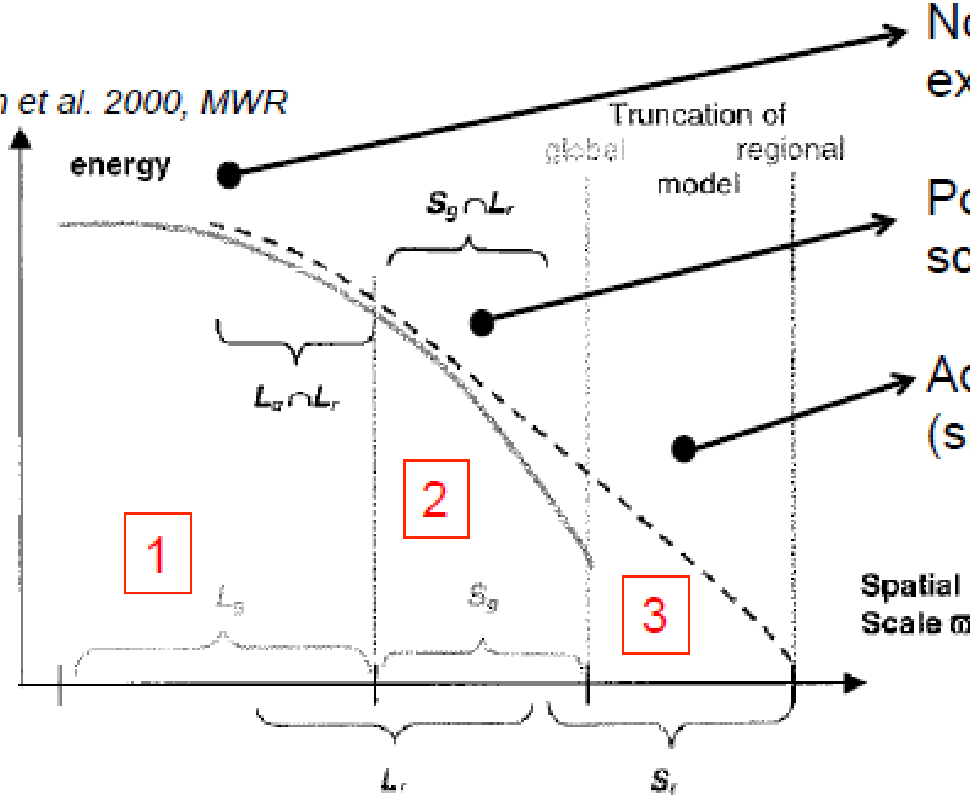
Figure 4.8. CCP Evaporative Cooling, 6.0 ach, future climate (2070 to 2100), average monthly values: (b) relative difference between future and historical values: 100*(future - historical)/historical.

The added-value: question of scales

What are the relative scales of GCM and RCM ?

- 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