Introduction to Convection-Permitting Climate Modelling

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27 August 2025

12th Workshop on the Theory and Use of Regional Climate Models

ICTP, Trieste

OGS

The Abdus Salam International Centre for Theoretical Physics

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Why do we run (regional) climate simulations?

- **Investigate the Earth System:**
  Studying how relevant climate parameters change in the (near) future
- **Provide information to impact researchers, stakeholders, and policy makers**
  Scale difference between available climate information provided by climate models (>100km) and information needed (~1km)

How do we bridge this gap?

RCMs as a suitable way to produce high-resolution climate information that is computationally affordable and suitable for end users.

Limitations of regional climate models

- **Important processes that are not resolved with grid spacings of climate models must be parameterised**
  - Deep Convection
  - Microphysics
  - Planetary Boundary Layer
  - Urban physics
  - Land surface – Atmosphere interactions
  - …
- **Parameterisations are a major source for model errors**
  Convection parameterisation schemes produce some of the largest uncertainties and model errors in future climate projections (*Sherwood et al.*, 2014)
- **Parameterising deep convection is challenging**
  - Interplay of processes acting at scales from the microscale to the synoptic scale
  - Convection parameterisation schemes interact with many other parameterisation schemes

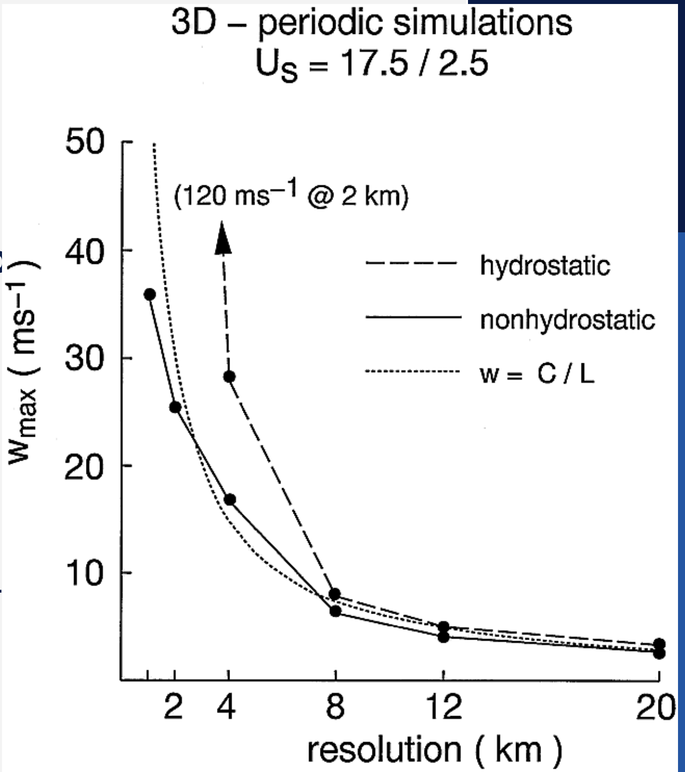
Why not just explicitly model deep convection instead?

At what scale can you resolve convection?

- **With increasing computer power, higher resolution simulations are possible.**

When we simulate with resolutions <4km, we can explicitly resolve deep convectio
Convective Permitting RCMs:

- CRCM5 (Zadra et al., 2008)
- WRF (Skamarock et al., 2019)
- COSMO-CLM (Rockel et al., 2008)
- Met Office Unified Model (Clark et al., 2016)
- AROME (Belušić et al., 2020; Seity et al., 2011)
- RegCM5 (Pichelli et al., 2021 , Coppola et al. 2021
- REMO (Jacob & Podzun, 1997)



Weisman et al. (1997)

Where do we see added value of CP models?

Interaction soil & atmosphere

Convective precipitation

Convection dominated environments

Cloud cover

radiation

Machine Learning (emulators)

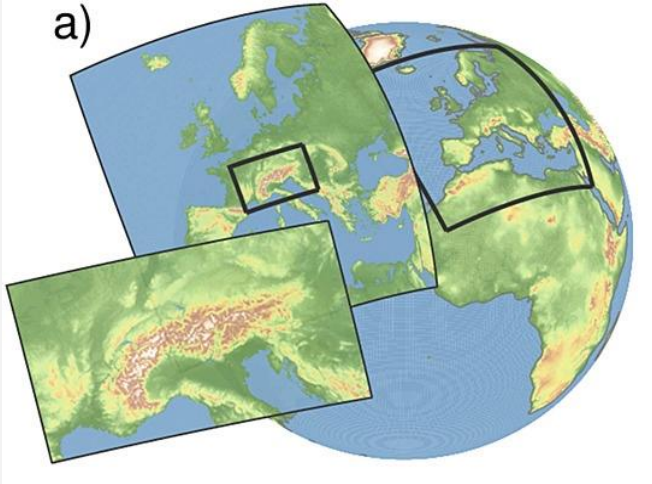
Orographic precipitation

Snow

Complex Terrain

Flow

temperature



Energy sector

Impact modelling

Hydrology

Urban modelling

Sea breeze

tropical & extratropical cyclones

Sting jets

lightning

Hailstorms

Small scale extremes

Flash floods

Urban Heat Islands

What do we need to perform CP climate model simulations?

What do we need for CP climate modelling?

- **Non-Hydrostatic Dynamical core**
  RegCM5 NH-MOLOCH core
  (Giorgi et al, 2023)

Horizontal momentum

$$\frac{du}{dt} = mc_{p_d}\Theta_v\frac{\partial\Pi}{\partial x} - mG(\zeta)\frac{\partial h}{\partial x}\left(g + \frac{dw}{dt}\right) + f_v + K_u$$

$$\frac{dv}{dt} = mc_{p_d}\Theta_v\frac{\partial\Pi}{\partial y} - mG(\zeta)\frac{\partial h}{\partial y}\left(g + \frac{dw}{dt}\right) - f_u + K_v$$

Vertical momentum

$$\frac{dw}{dt} = -F_z c_{p_d}\Theta_v\frac{\partial\Pi}{\partial z} - g + K_w$$

$$\Theta_v = \frac{T_v}{\Pi}$$

Temperature

$$\frac{d\Theta_v}{dt} \approx K_{\Theta_v}$$

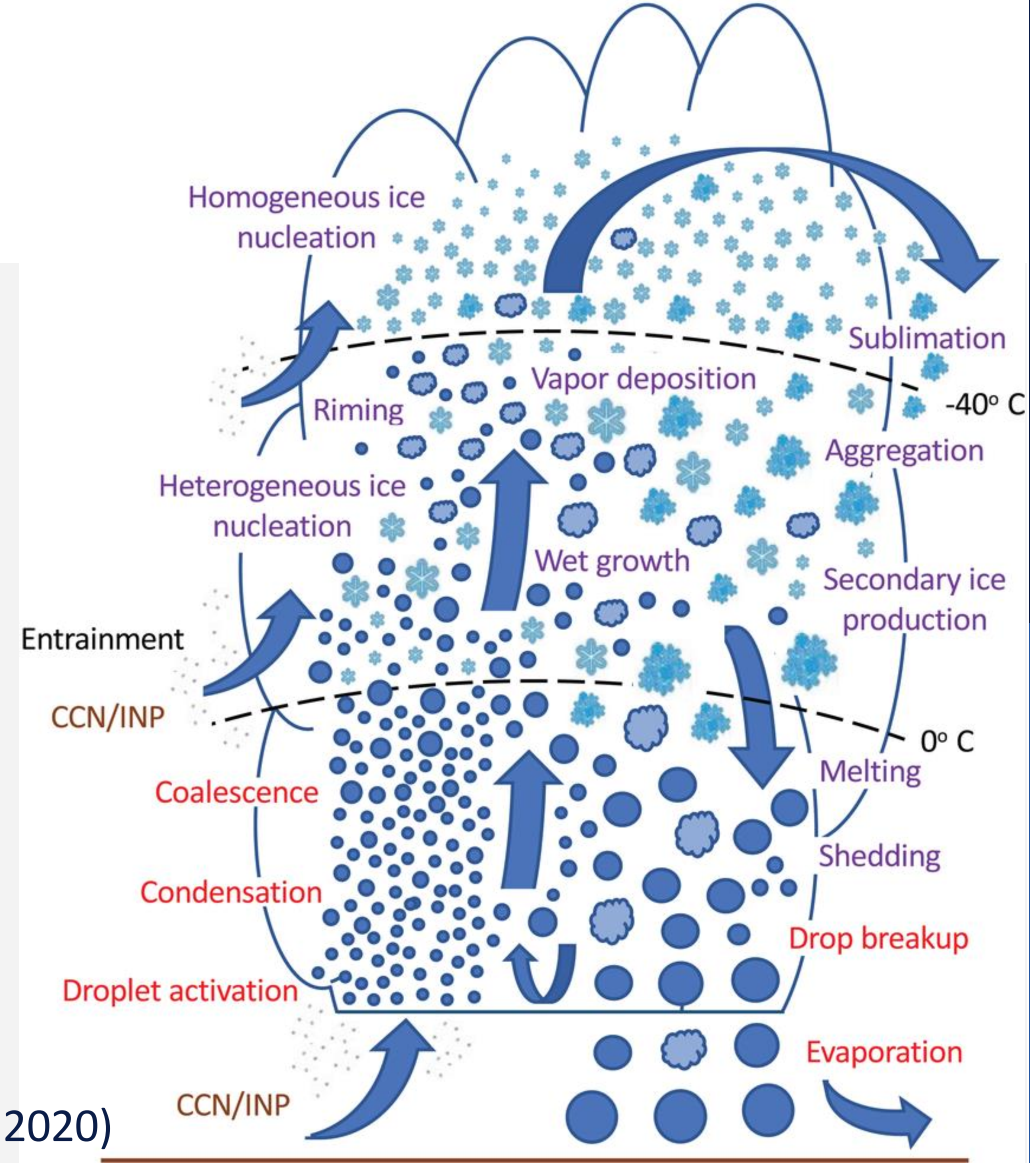
$$\Pi = \left(\frac{P}{P_0}\right)^{\frac{R_d}{C_{p_d}}}$$

Pressure

$$\frac{d\Pi}{dt} \approx -\Pi\frac{R_d}{C_{v_d}}m^2\left\{F_z\left[\frac{\partial\left(\frac{u}{mF_z}\right)}{\partial x} + \frac{\partial\left(\frac{v}{mF_z}\right)}{\partial y}\right] + \frac{\partial\left(\frac{s}{F_z}\right)}{\partial\zeta}\right\}$$

Things to consider when working with CPRCMs

- **Appropriate model physics and parameterisations**
  - tuning is important and region dependent
- **Clouds, Aerosols and radiation**
- Turbulence
- Soil-Vegetation-Atmosphere coupling

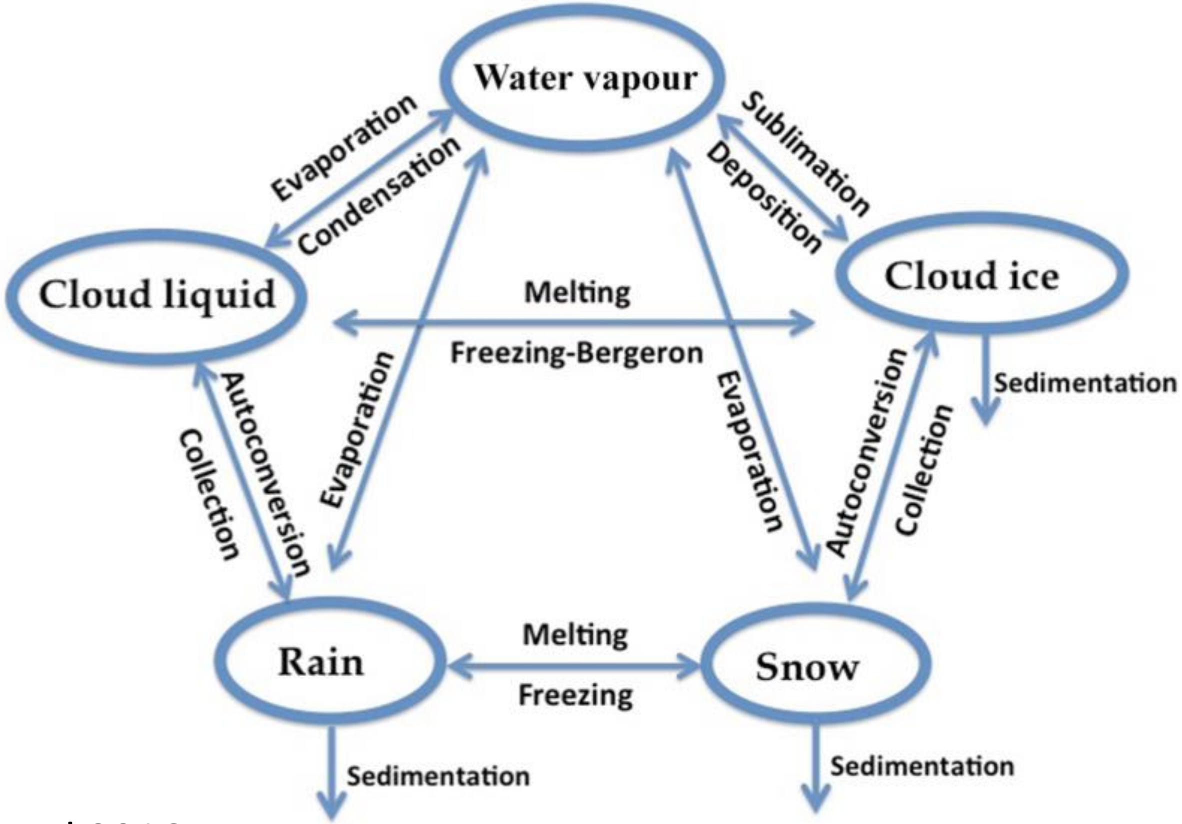


- Cloud microphysical processes and processes that contribute to the explicit triggering of deep convection are more important in CP simulations
- Cloud interactions with aerosols (and the effects on radiation) are not well understood

Morrison et al (2020)

Things to consider when working with CPRCMs

- **Microphysics schemes**
  - Nogherotto-Tompkins microphysics scheme
  - WSM7 microphysics scheme



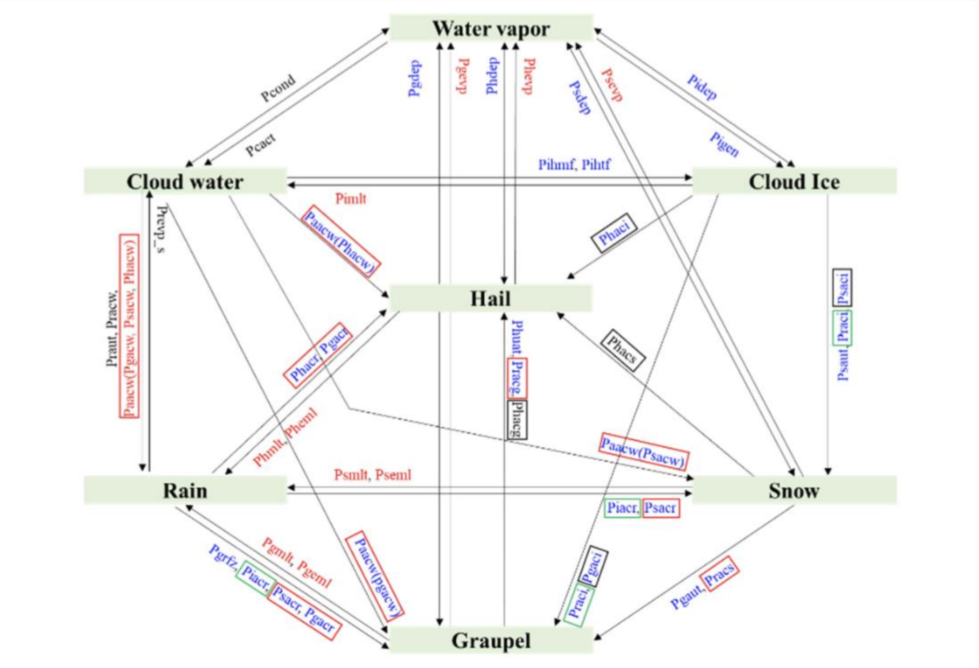
Nogherotto et al 2016

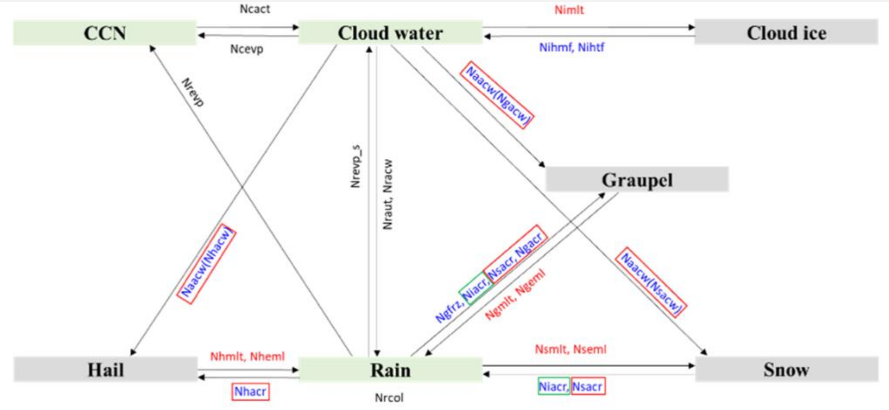
Things to consider when working with CPRCMs

- **Microphysics schemes**
  - Nogherotto-Tompkins microphysics scheme
  - WSM7 microphysics scheme (Jang et al. 2021)

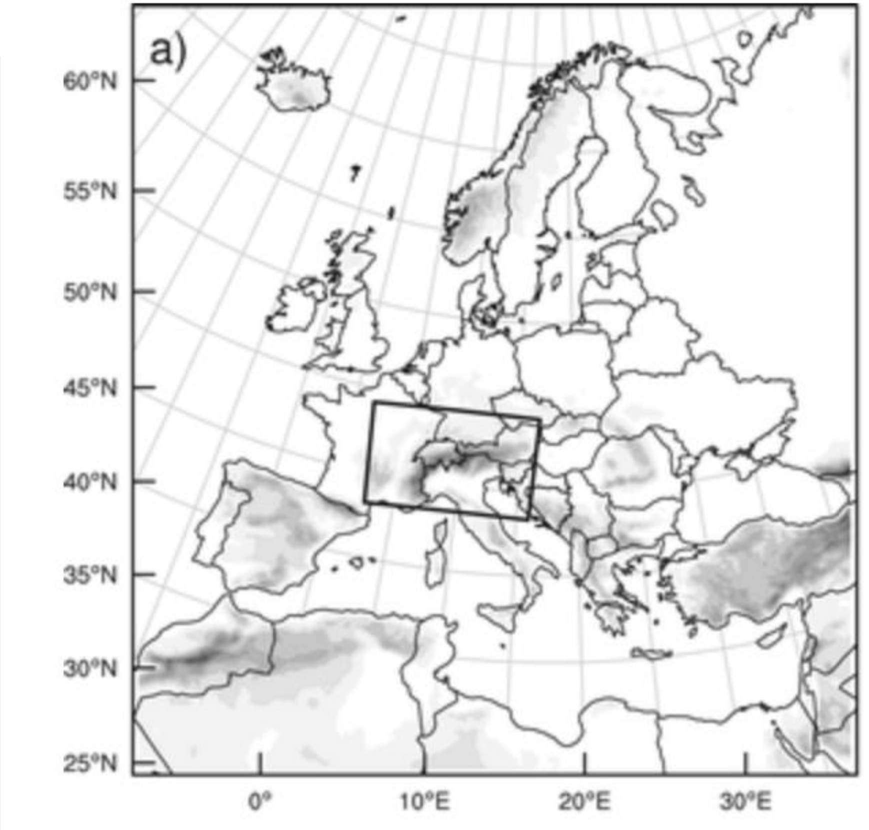
More complexity always better?

Not always (e.g. Van Weverberg et al., 2014). More complexity generally comes with more tunable parameters of not well-known processes.

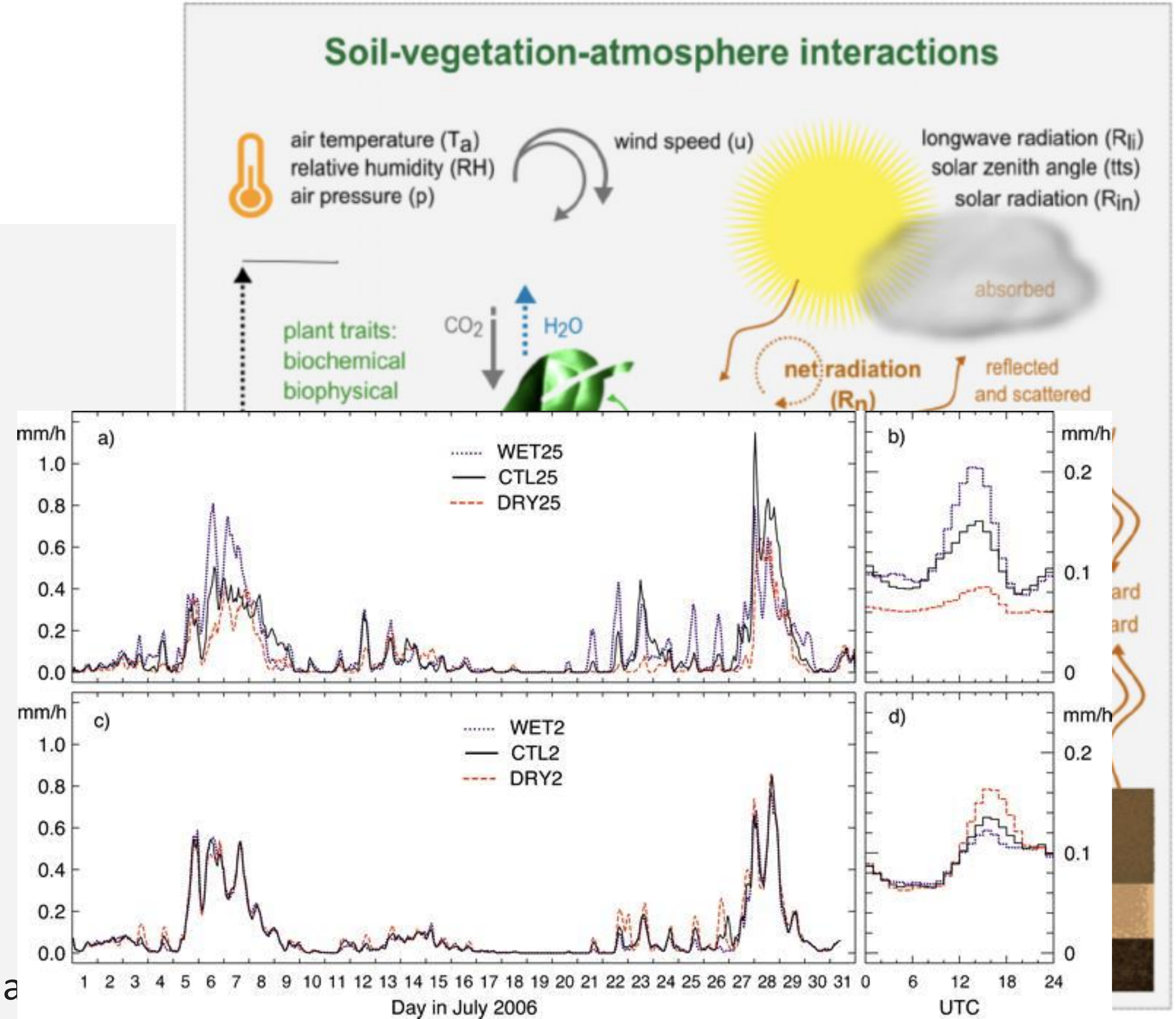




What do we need for CP climate modelling?



Hohenegger et al. (2009)



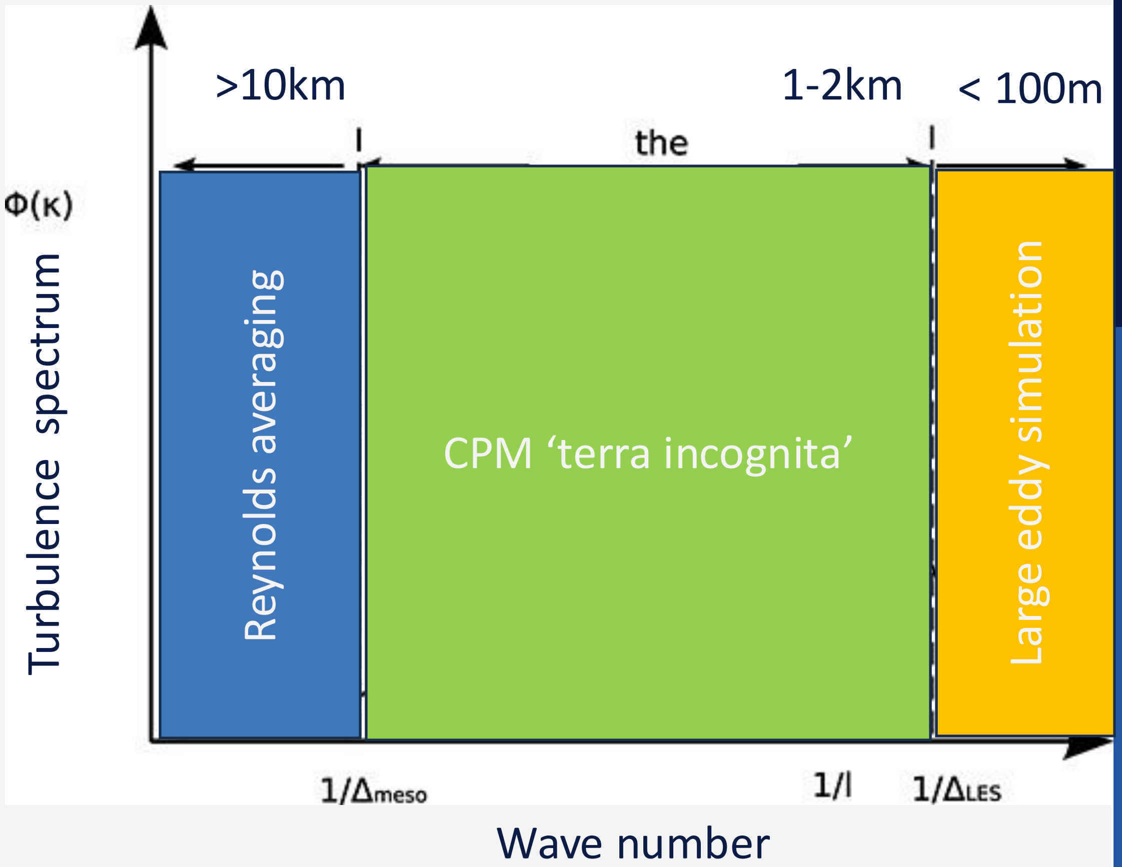
Rocha et a

Outstanding question for CPRCMs

- **Appropriate model physics**

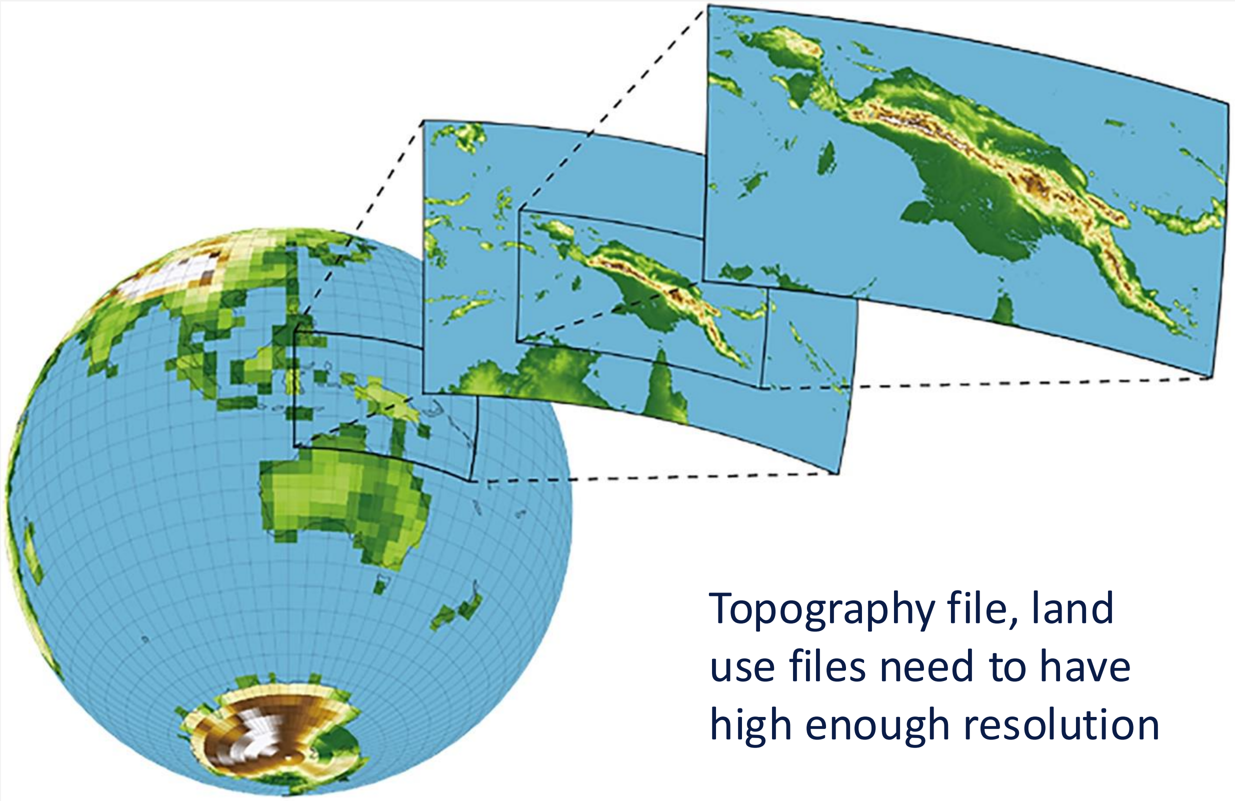
- Clouds, Aerosols and radiation
- **Turbulence**
- Soil-Vegetation-Atmosphere coupling

- models may benefit from 3D turbulence parameterisations. Chow et al. (2019)



Boundary conditions

Generally, the maximum step in resolution between nests should be <12 for CPRCMs (Berthou et al., 2020; Chawla et al., 2018).



Topography file, land use files need to have high enough resolution

Lucas-Picher et al. 2021

Telescopic nesting

Most common:
(two-step nesting strategy)

GCM (~100 km)
RCM (~12 km)
CPRCM (~ 3km)

Bigger resolution step is possible, but larger buffer zone at the boundaries is then essential

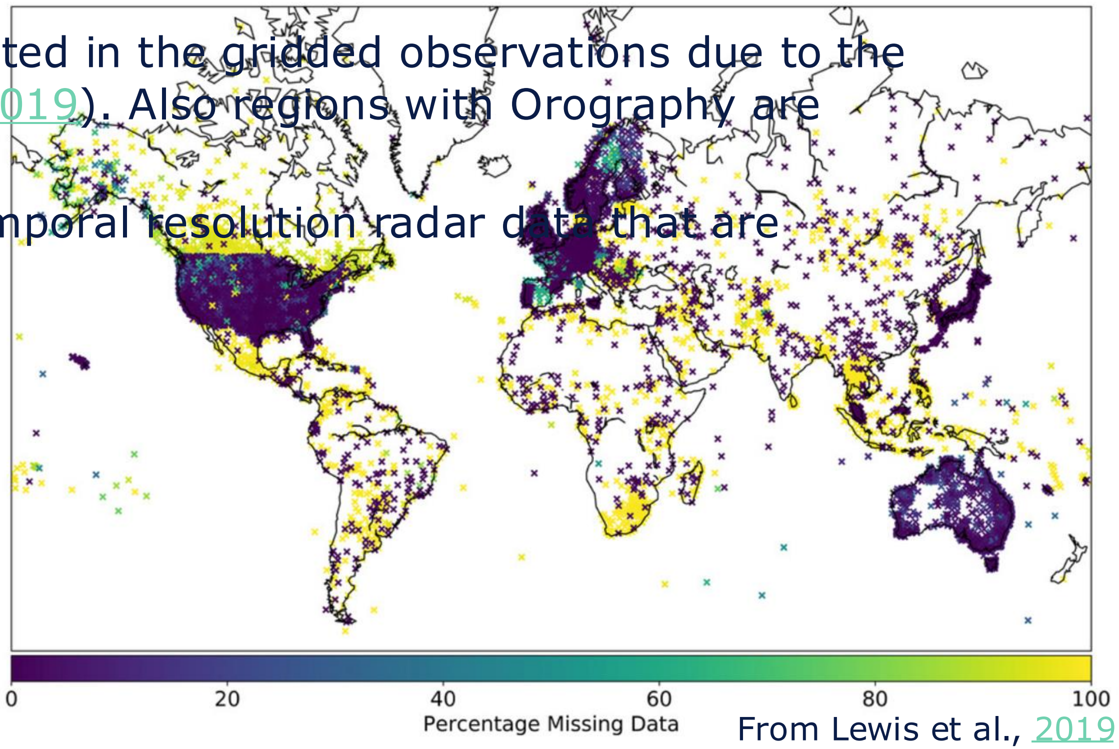
Observations

How to evaluate the results

- Evaluation of climate simulations becomes a challenge due to the lack of high-quality high-resolution observational gridded datasets (Piazza et al., 2019; Prein & Gobiet, 2017).
- Sub-daily data that is available only from a subset of weather stations (Lewis et al., 2019).

Observations are also not perfect!

- Precipitation extremes are possibly underestimated in the gridded observations due to the localized nature of these events (Piazza et al., 2019). Also regions with Orography are underpresented in gridded observations.
- Alternatively, some regions have high spatio-temporal resolution radar data that are adjusted with gauges from weather stations:
  - France (Tabary et al., 2012)
  - Germany (Winterrath et al., 2018)
  - the UK (Yu, Li, et al., 2020)
  - the United States (Lin & Mitchell, 2005)
  - Netherlands (Overeem et al., 2009)
  - Sweden (Berg et al., 2016)
  - Switzerland (Wüest et al., 2010).

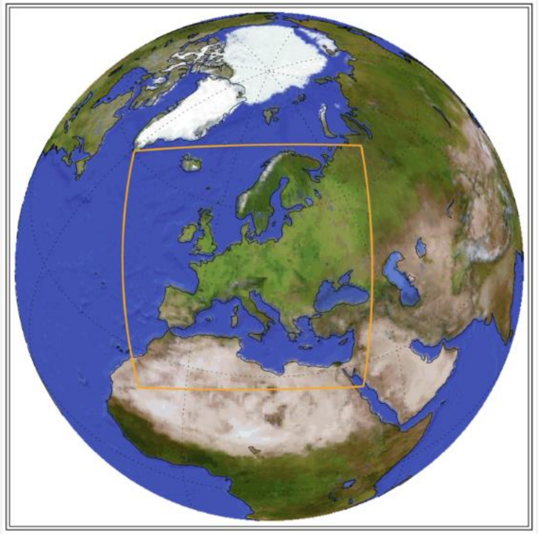


From Lewis et al., 2019

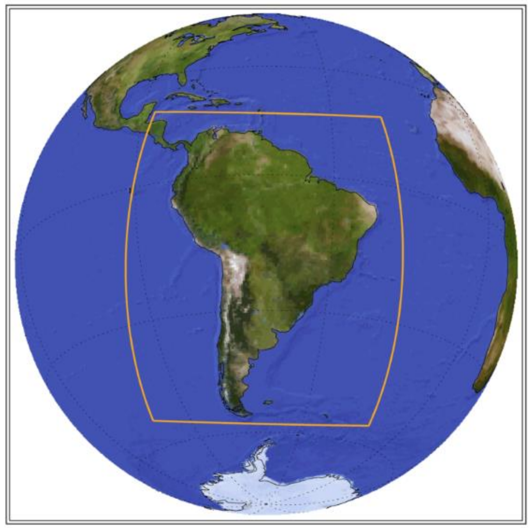
Computational Resources

Performing decadal-long CPRCM climate change projections is computationally demanding and also requires huge data storage capabilities (Schar et al 2020)

Transient climate simulation



EURO-CORDEX
12 km



South America-
CORDEX 12 km

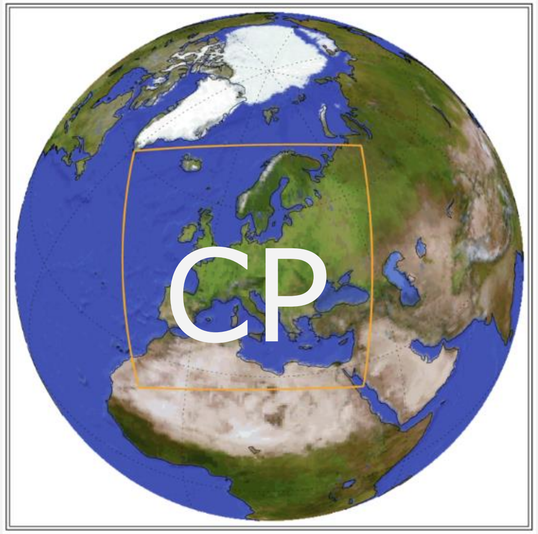
Time needed to run: Months
Storage needed: 1TB per year

https://cordex.org

Computational Resources

Performing decadal-long CPRCM climate change projections is computationally demanding and also requires huge data storage capabilities (Schar et al 2020)

Transient climate simulation



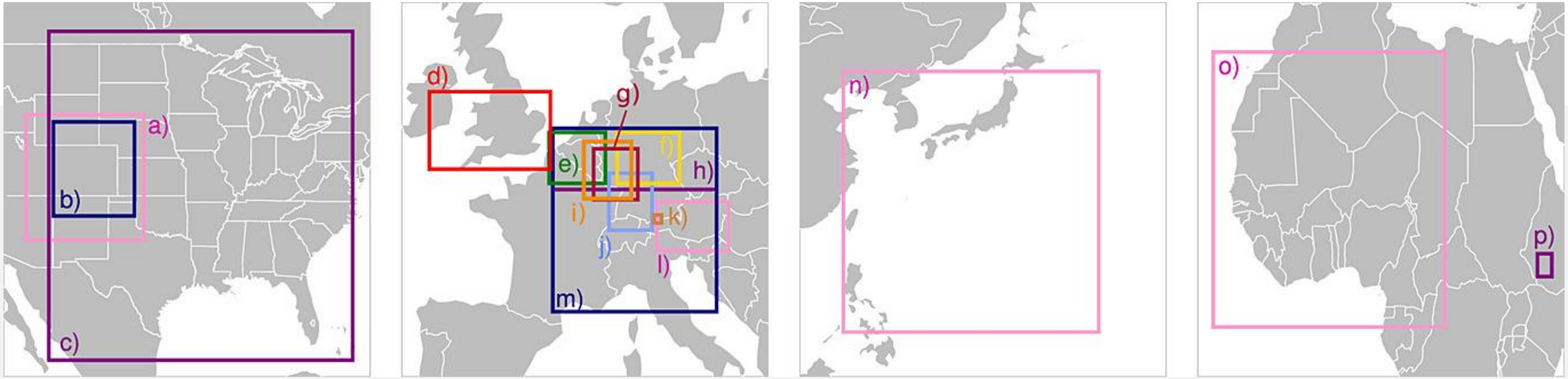
CP-CORDEX 3 km

Time needed to run: Years-Decades
Storage space needed: >10TB per year

So what can we simulate?

Where are we now?

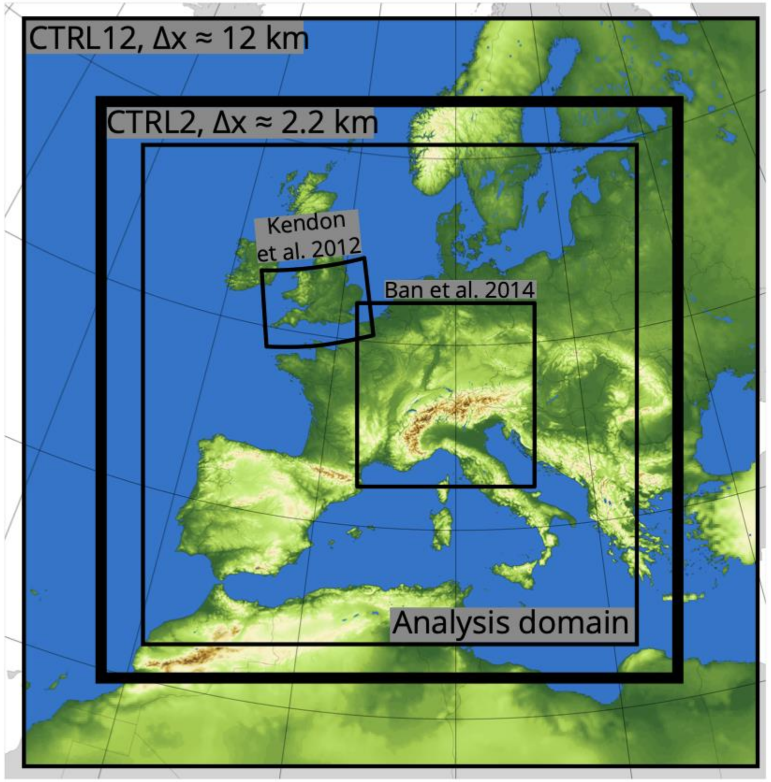
The history of CP simulation domains



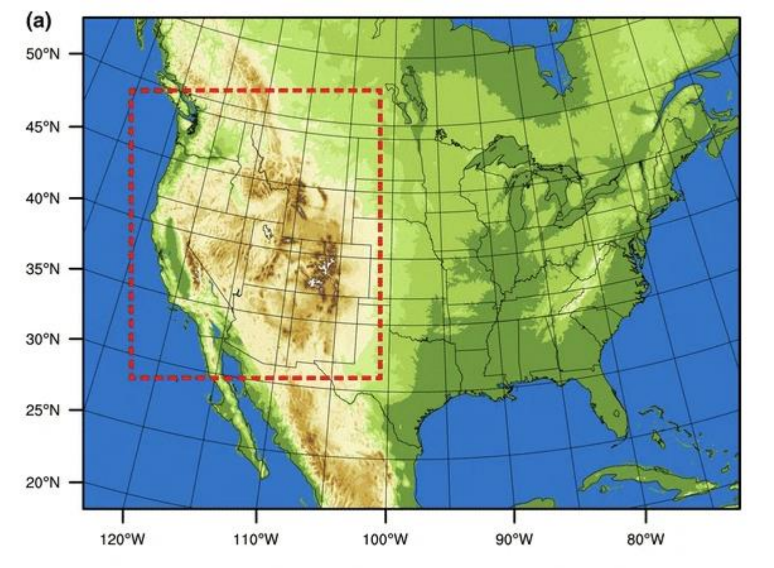
- CPRCMs were initially used for performing case studies and multi-seasonal simulations over small domains (Hohenegger et al., 2008; Knote et al., 2010; Rasmussen et al., 2011)
- Approximately 10 years ago, the first CPRCMs were used for decade-long and even longer climate simulations, still over small domains (Argüeso et al., 2014; Ban et al., 2014; Fosser et al., 2015; Kendon et al., 2012). For other examples, see review by Prein et al. (2015))

Where are we now?

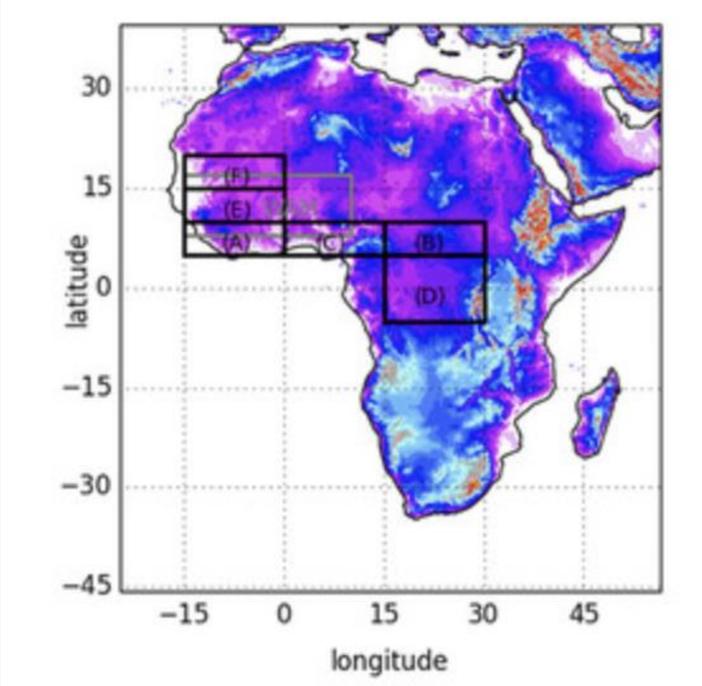
CPRCMs have been used widely over many regions of the globe over longer periods and larger domains, reaching even full continents (Europe: Leutwyler et al., 2016; North America: Liu et al., 2017; Africa: Stratton et al., 2018)



Leutwyler et al., 2016



Liu et al., 2017



Stratton et al., 2018

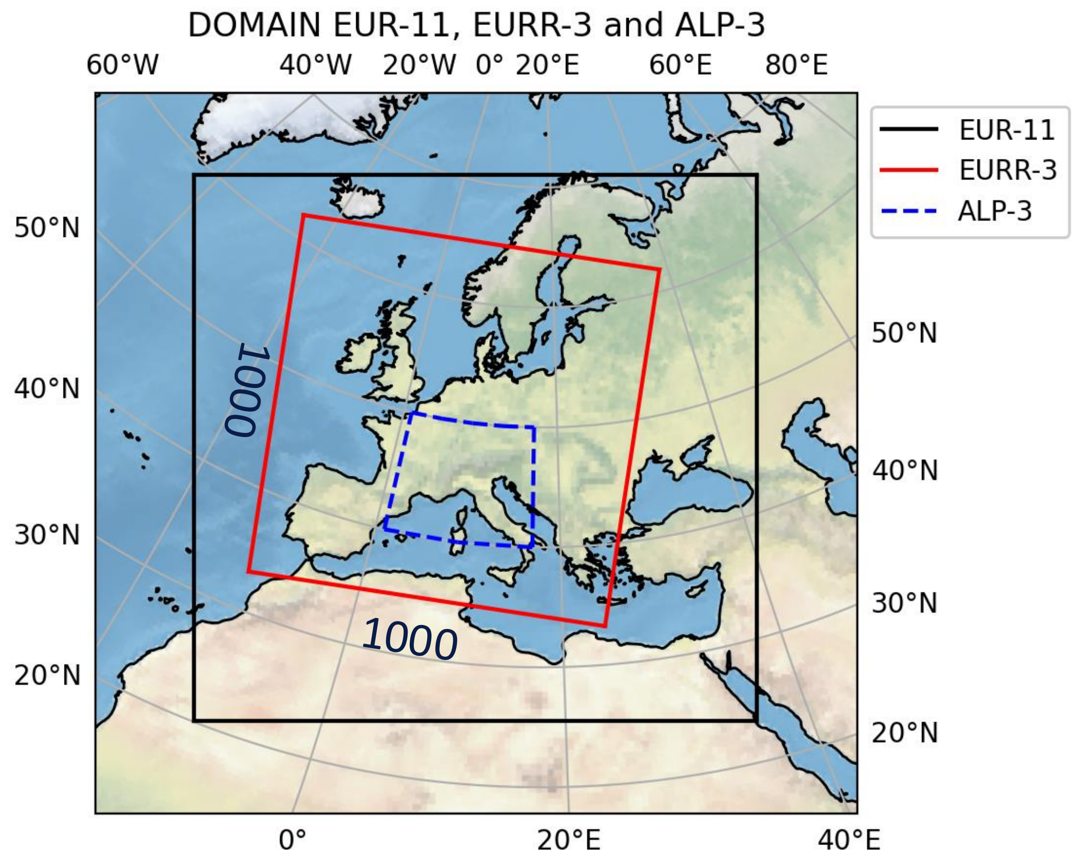
Still need very large supercomputers to run these simulations, which most of us don't have access to.

RegCM5 EURR-3 CP simulation
ICTP nesting strategy

The European **CP domain EURR-3** (red outline) has been simulated with RegCM5 using:

- **ERA5 boundary conditions** for the evaluation period **1999-2009**
- GW level scenarios by nesting the EURR-3 domain on the output from the EUR-12 simulations driven by **EC-Earth3-Veg GCM boundary conditions.**

Cost: (~200.000 CPU core hours/year)
Storage space needed: 9TB per year



Recent Climate Projects at CP scale

Due to the complexity, scientific projects were launched to better coordinate CPRCM research activities and increase the amount of CPRCM simulations with similar experimental configurations to explore uncertainties and robustness in CPRCM climate change projections.

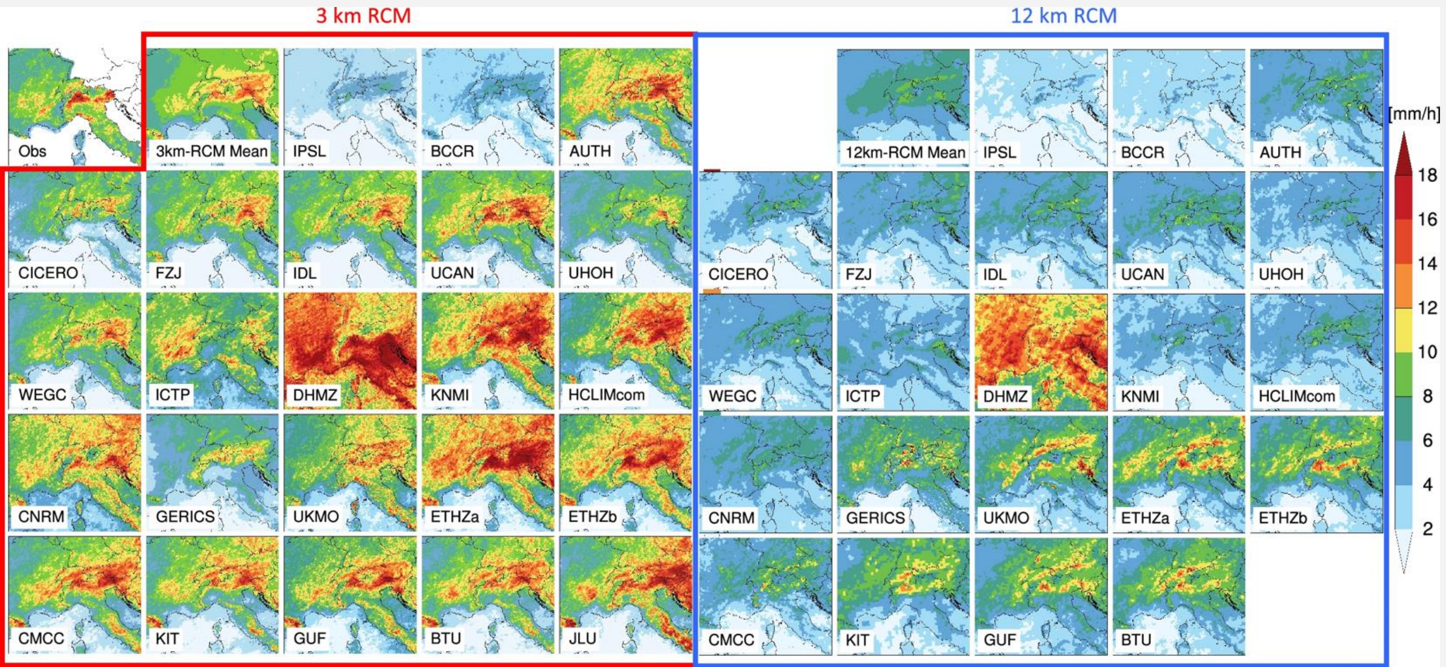
- **FPS-CPS** (**ELVIC** – Climate Extremes in the Lake Victoria Basin)
- **FPS-CPS** (Euro-Mediterranean)
- **FPS URB-RCC** (URBan environments and Regional Climate Change)
- **FPS-SESA** (Southeastern South America)

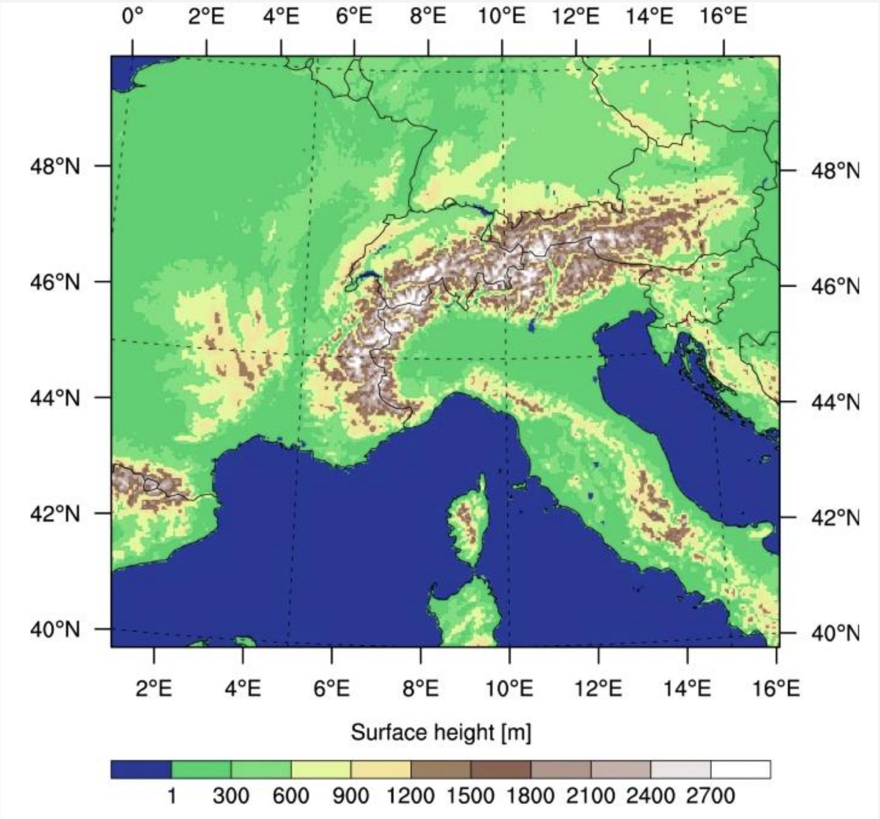
Recent Climate Projects at CP scale

- **FPS-Convection**

Ensembles are essential to get any robust signal from your CPRCM

Ban et al., 2021

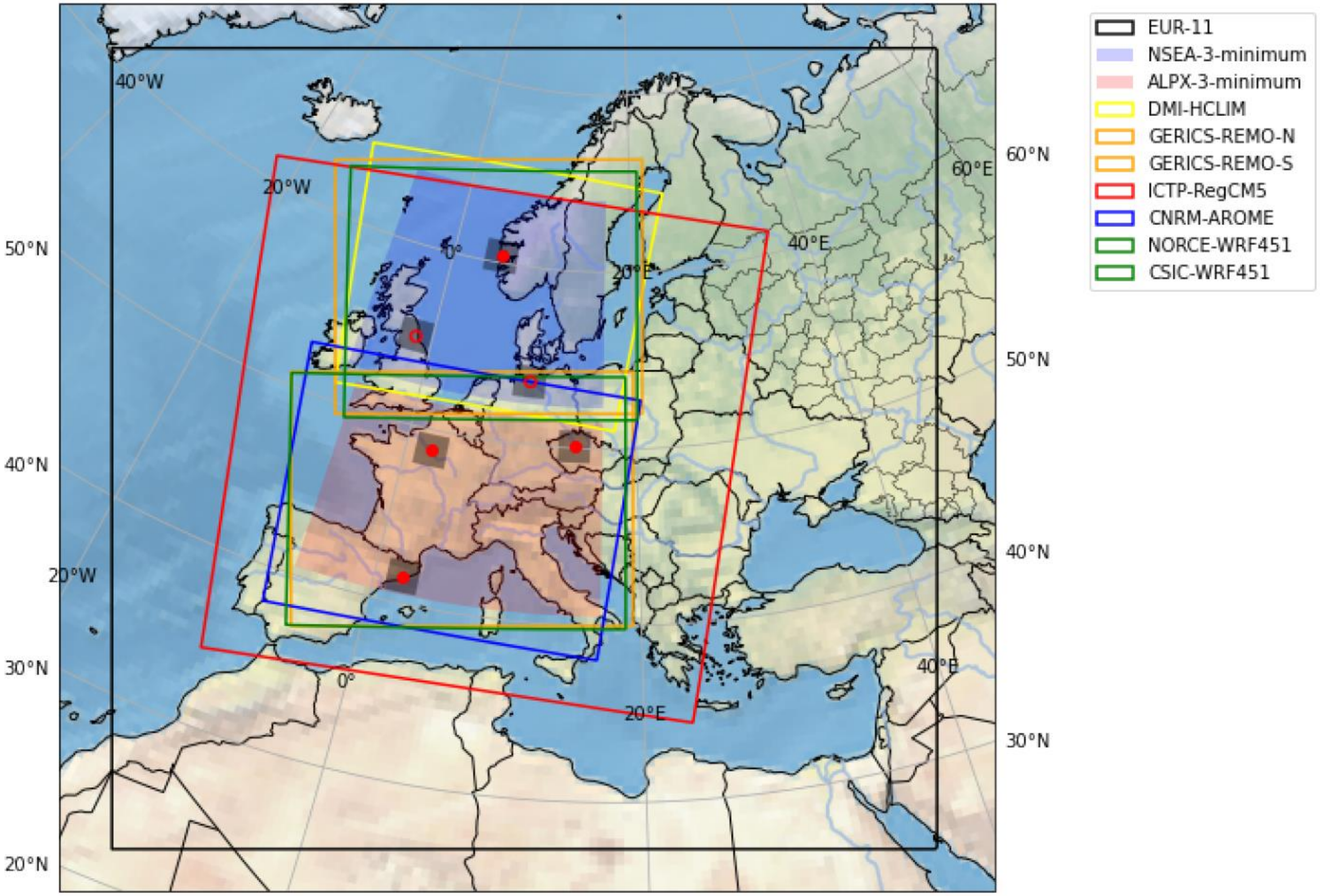




Domain size for CP simulations

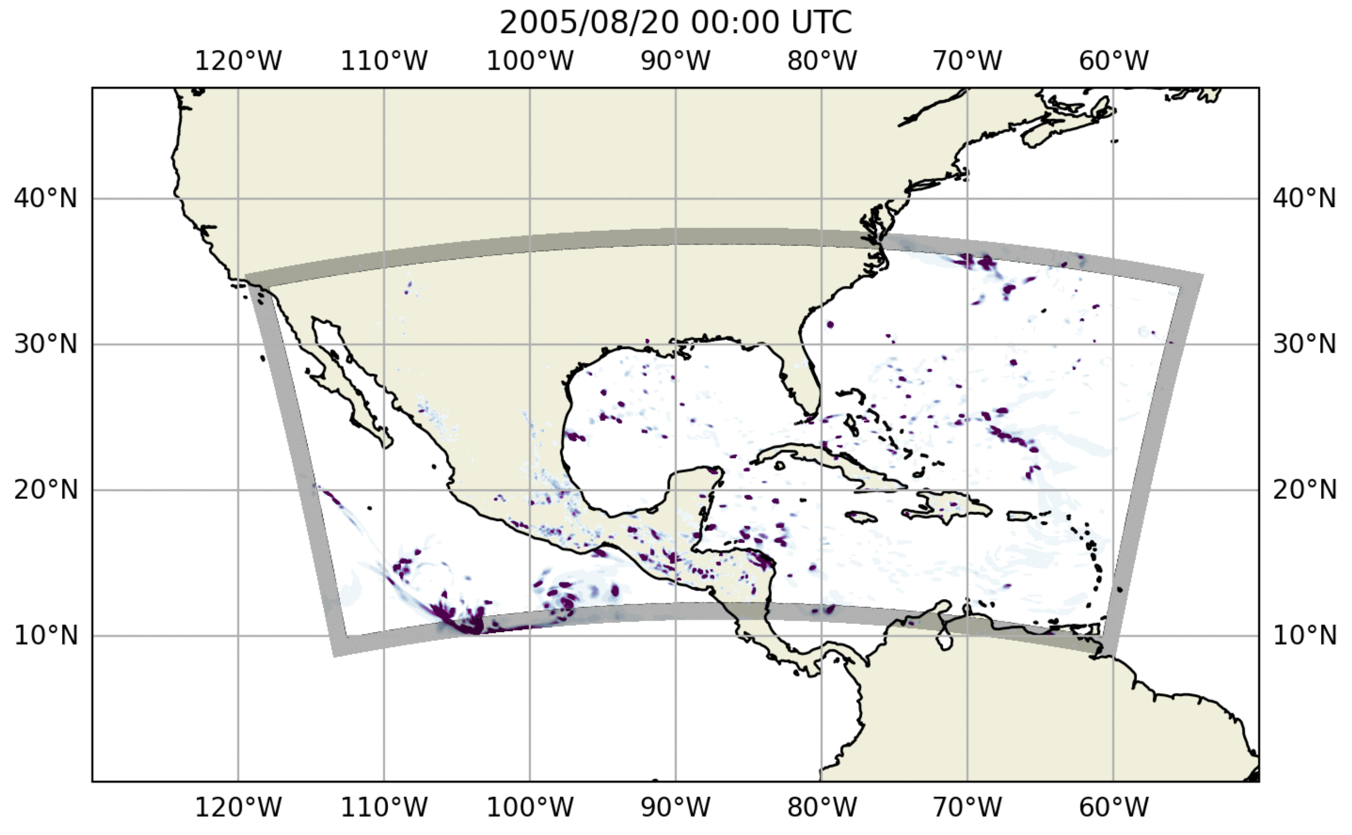
CPRCM I4C simulations

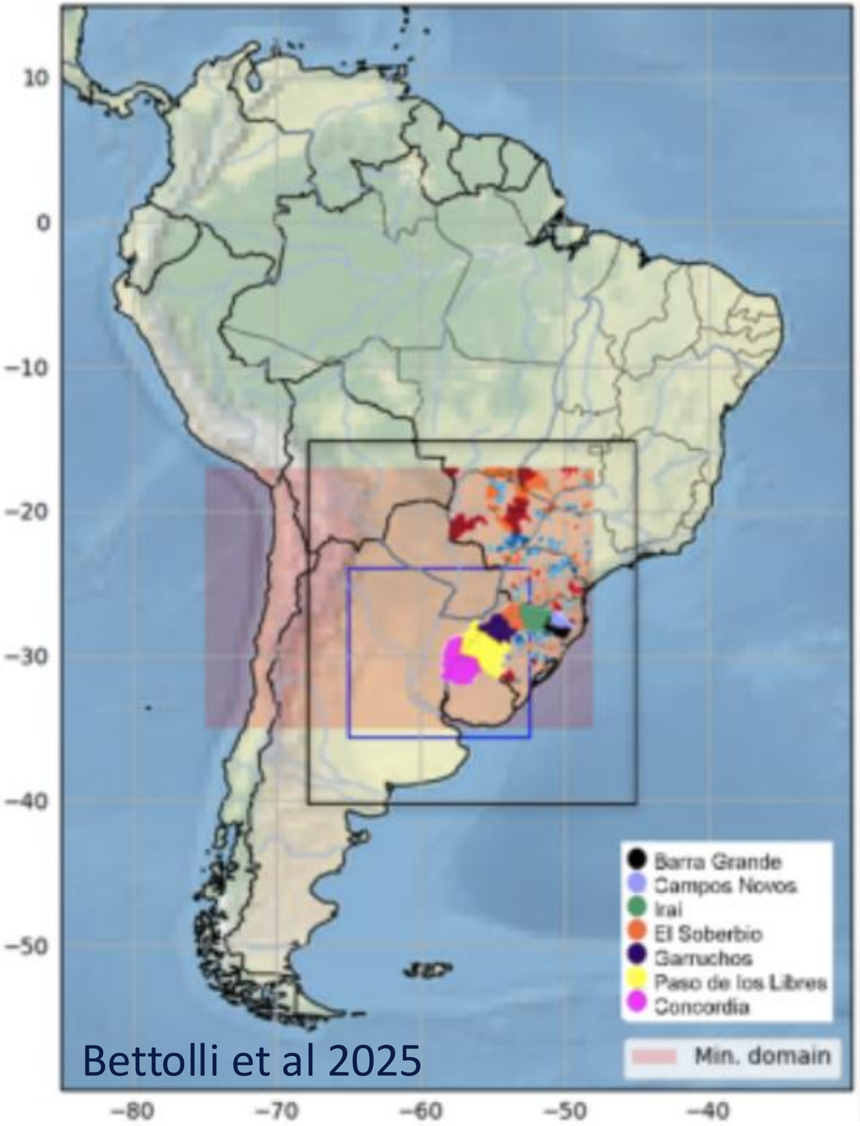
CPRCM (Group)	GCM CMIP6 scenarioMIP
CNRS-MF-AROME46t1	CNRM-ESM2-1, r1i1p1f2
UNESCO-ICTP-RegCM5 DMI-HCLIM43-AROME	EC-Earth3-Veg, r1i1p1f1
Hereon-GERICS-REMO2020	MPI-ESM1-2-HR, r1i1p1f1
CSIC-WRF451 NORCE-WRF451	NorESM2-MM, r1i1p1f1



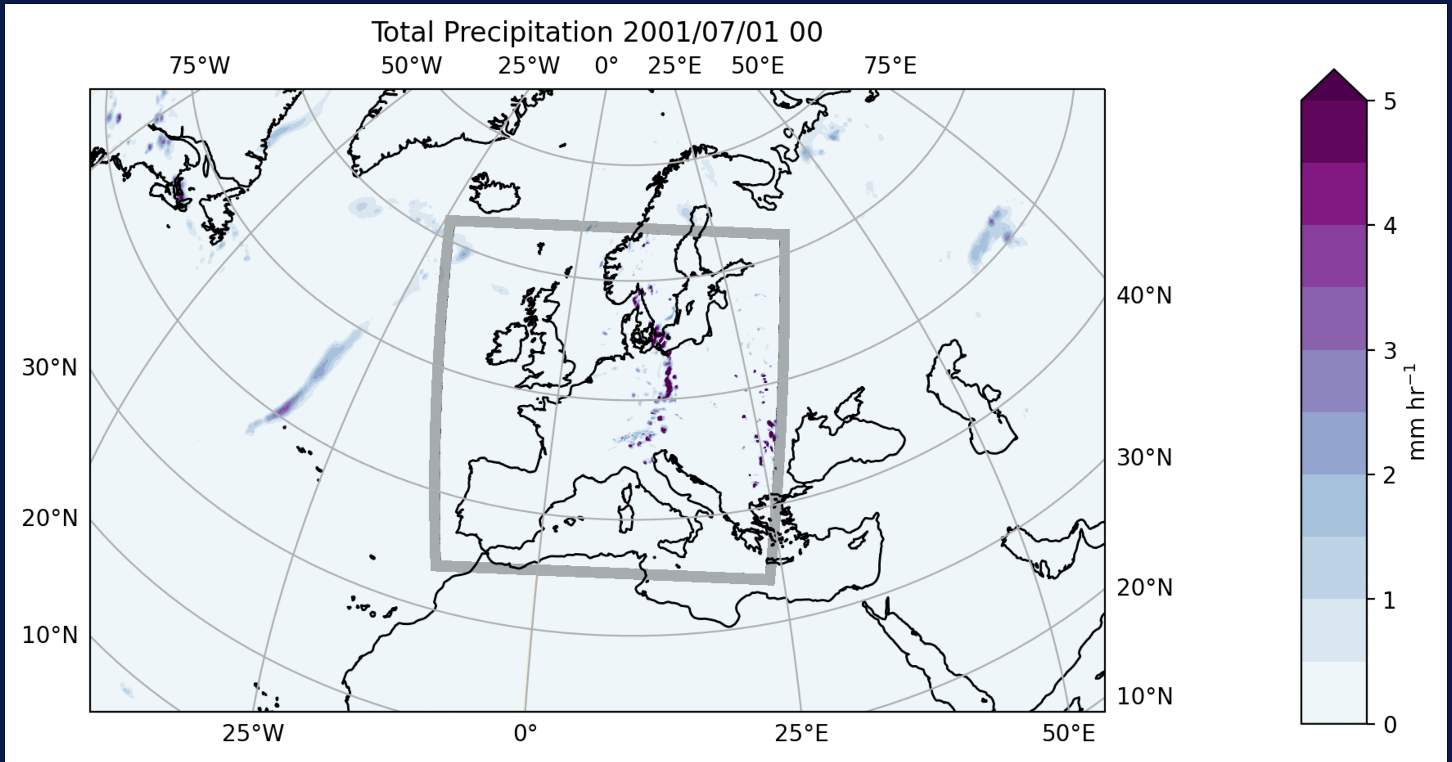
https://impetus4change.eu

Domain size for CP simulations



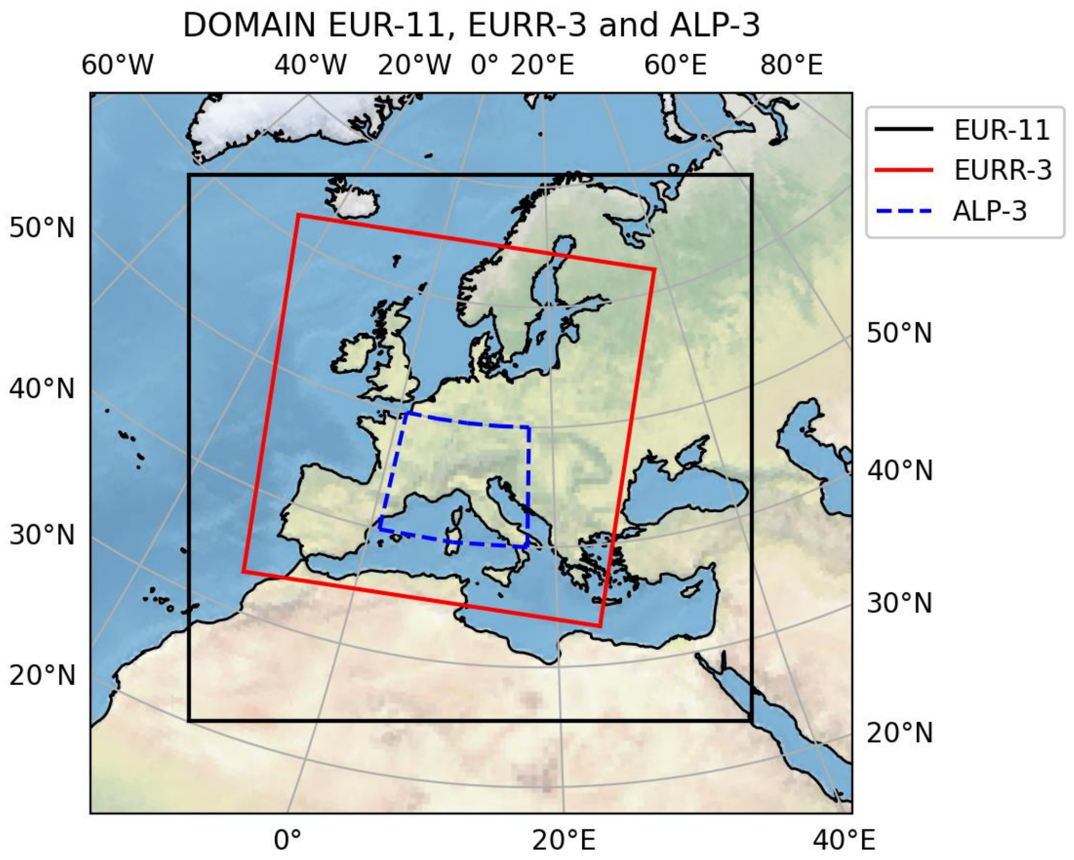


How to deal with the output of your model?



RegCM5 EURR-3 CP simulation
How to evaluate the results

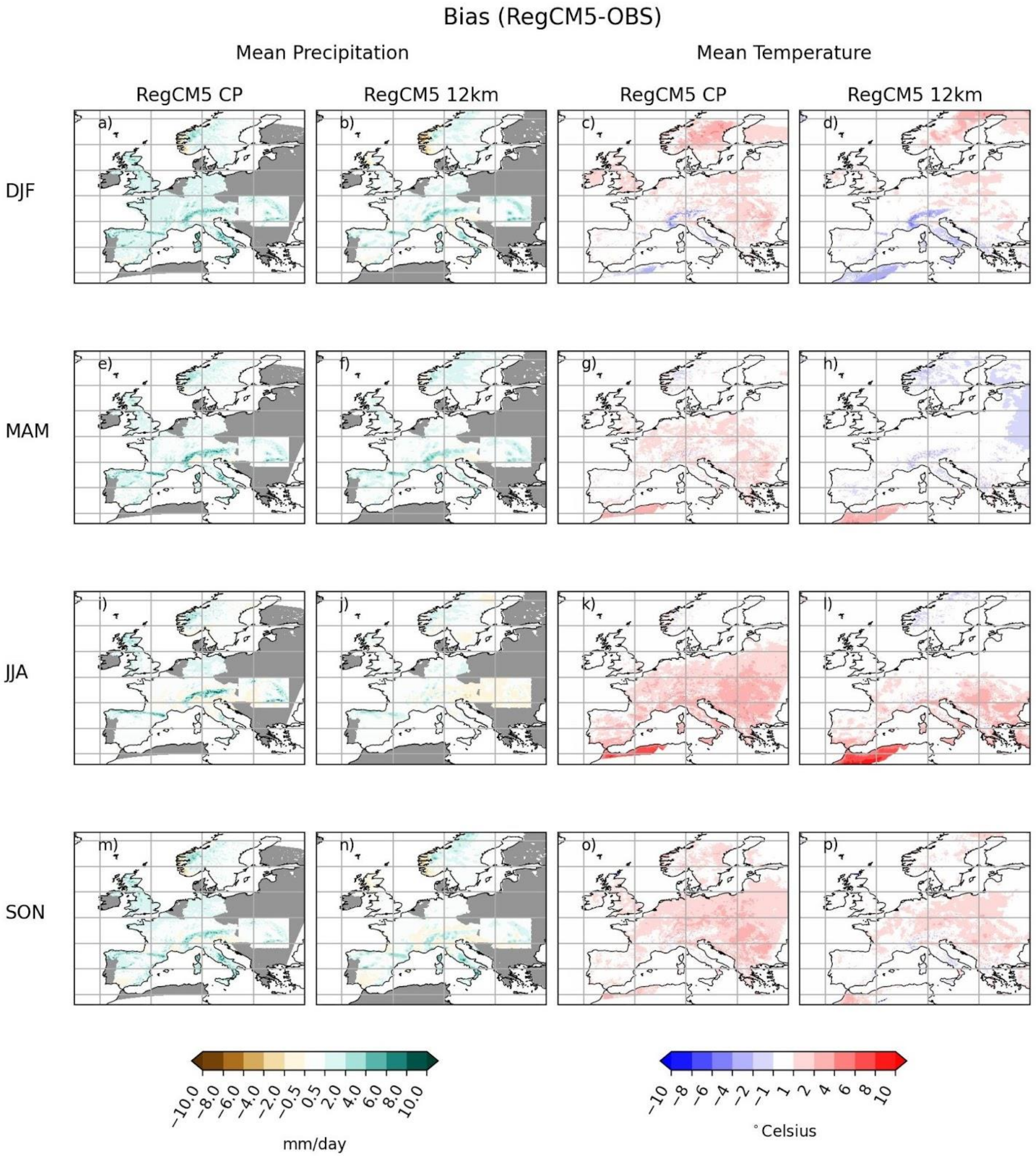
RADKLIM	Germany	PRECIP	Radar based (rain gauges calibration)	1 km	HOURLY	2001-2009	Kreklow et al. (2020)
SPAIN02	Spain	PRECIP	Station based	0.11 degrees	DAILY	1971-2010	Herrera et al. (2010)
CARPATCLIM	Carpatians	PRECIP	Station based	0.1 degrees	DAILY	1961-2010	Szalai et al. (2013)
ENG_REGR	Great Britain	PRECIP	Station based	5 km	DAILY	1990-2010	http://www.precisrcm.com/Erasmo/ncic.uk.11.tgz
COMEPHORE	France	PRECIP	Reanalysis based on radar and rain gauges	1 km	HOURLY	1997-2017	Tabary et al. (2012)
GRIPHO	Italy	PRECIP	Station based gridded dataset	3 km	HOURLY	2001-2016	Fantini (2019)
EURO4M	Alps	PRECIP	Station based gridded dataset	5 km	DAILY	1971-2008	Isotta et al. (2014a)
PTHBV	Sweden	PRECIP	Station based gridded dataset	4 km	DAILY	1961-2011	https://opendata-download-metanalys.smhi.se Johansson (2000)
METNO	Norway	PRECIP	Station based gridded dataset	1 km	DAILY	1980-2008	Mohr et al. (2009)
RdisaggH	Switzerland	PRECIP	Combination of rain-gauge data and radar measurements	1 km	HOURLY	2003-2010	Wüest et al. (2010)
CEH-GEAR	Great Britain	PRECIP	Rain-gauge based gridded dataset	1 km	HOURLY	1990-2016	Lewis et al. (2022)

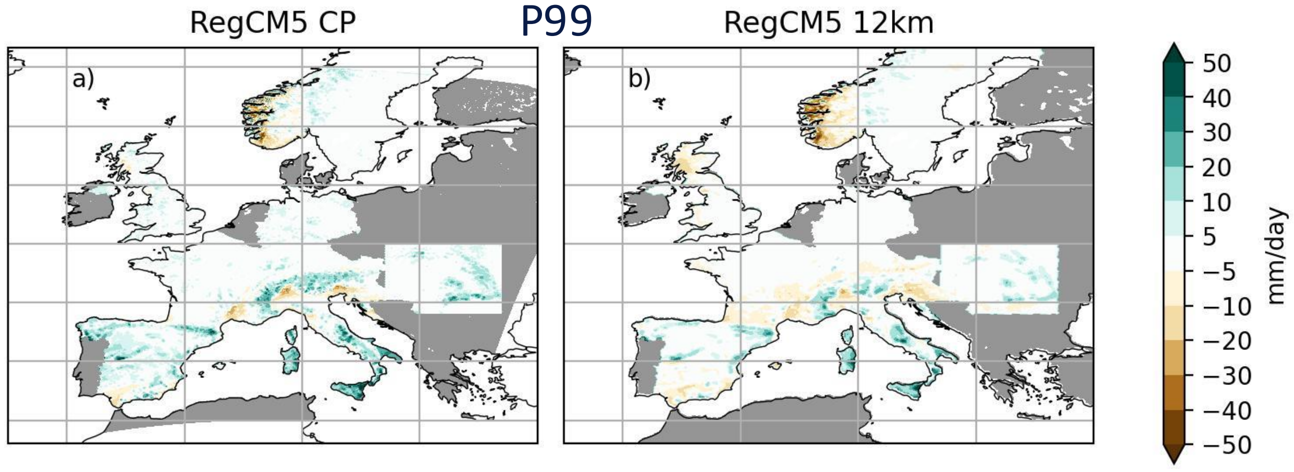


RegCM5 CP simulation
Latest results

Evaluation simulation results (2000-2009):

- Mean **daily** precipitation compares well with observations for all seasons. General results between the two datasets is similar for **mean precipitation, precipitation frequency and P99**

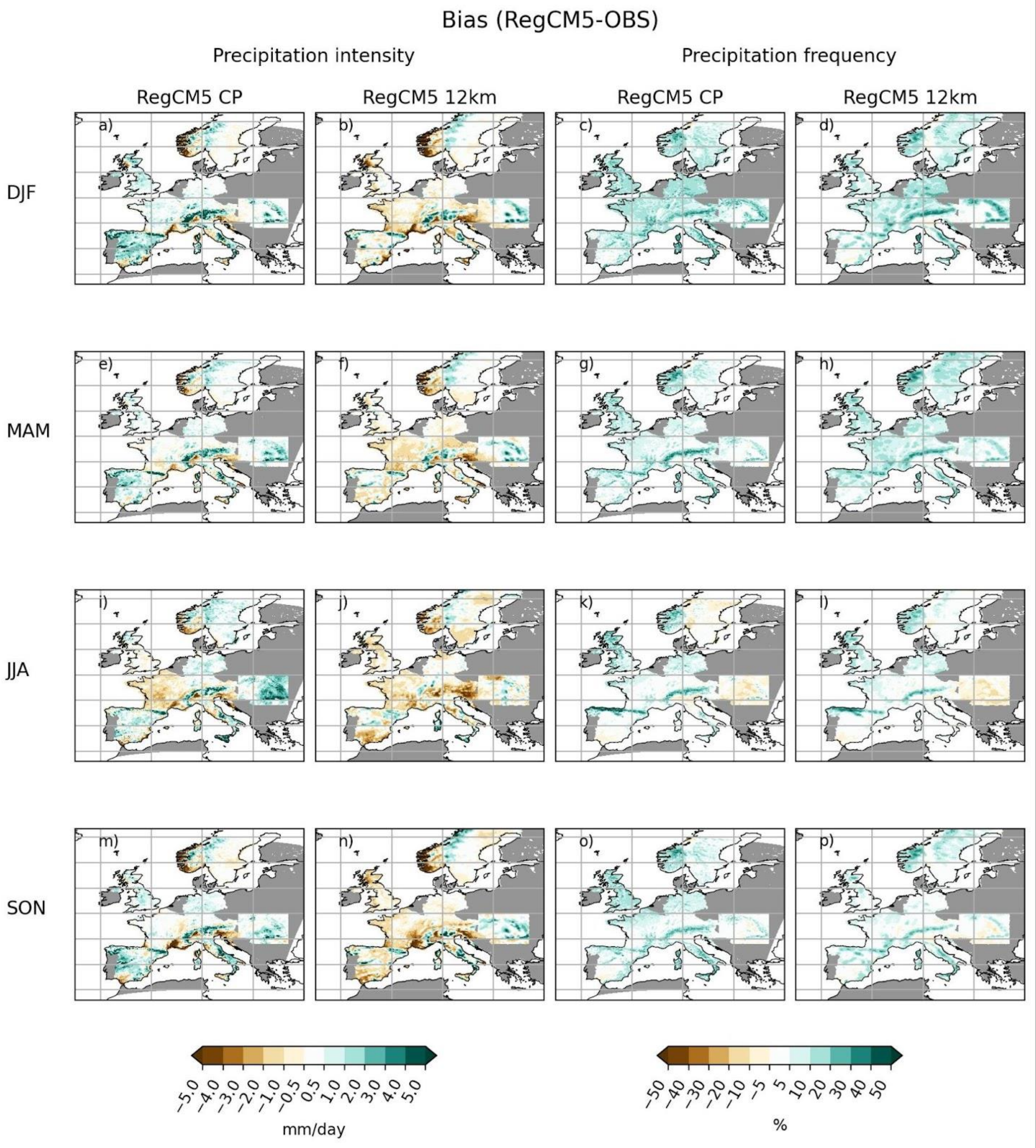




RegCM5 CP simulation
Latest results

Evaluation simulation results (2000-2009):

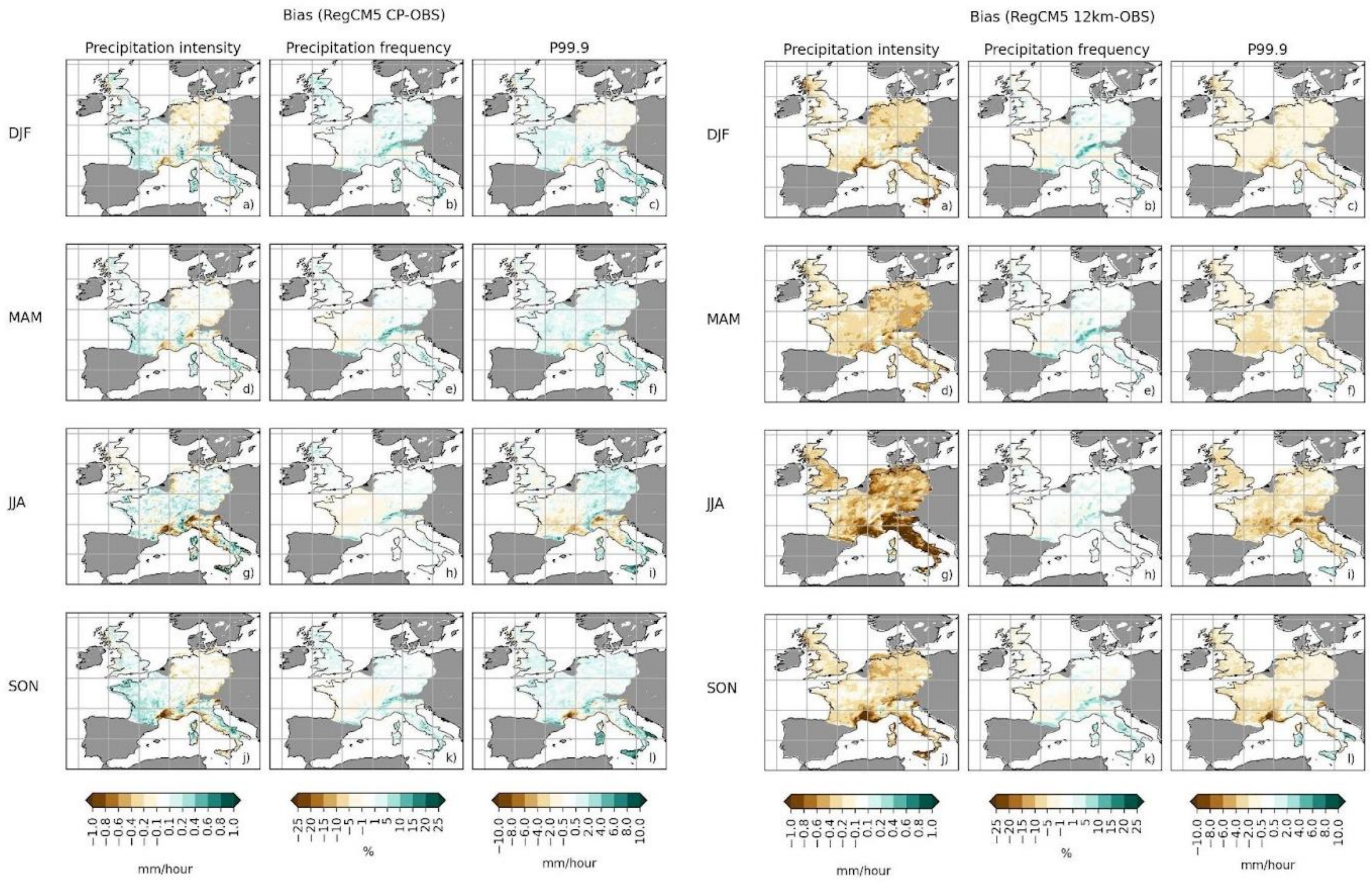
- Clear improvement in the daily precipitation intensity signal



RegCM5 CP simulation
Latest results

First evaluation simulation results (2000-2009):

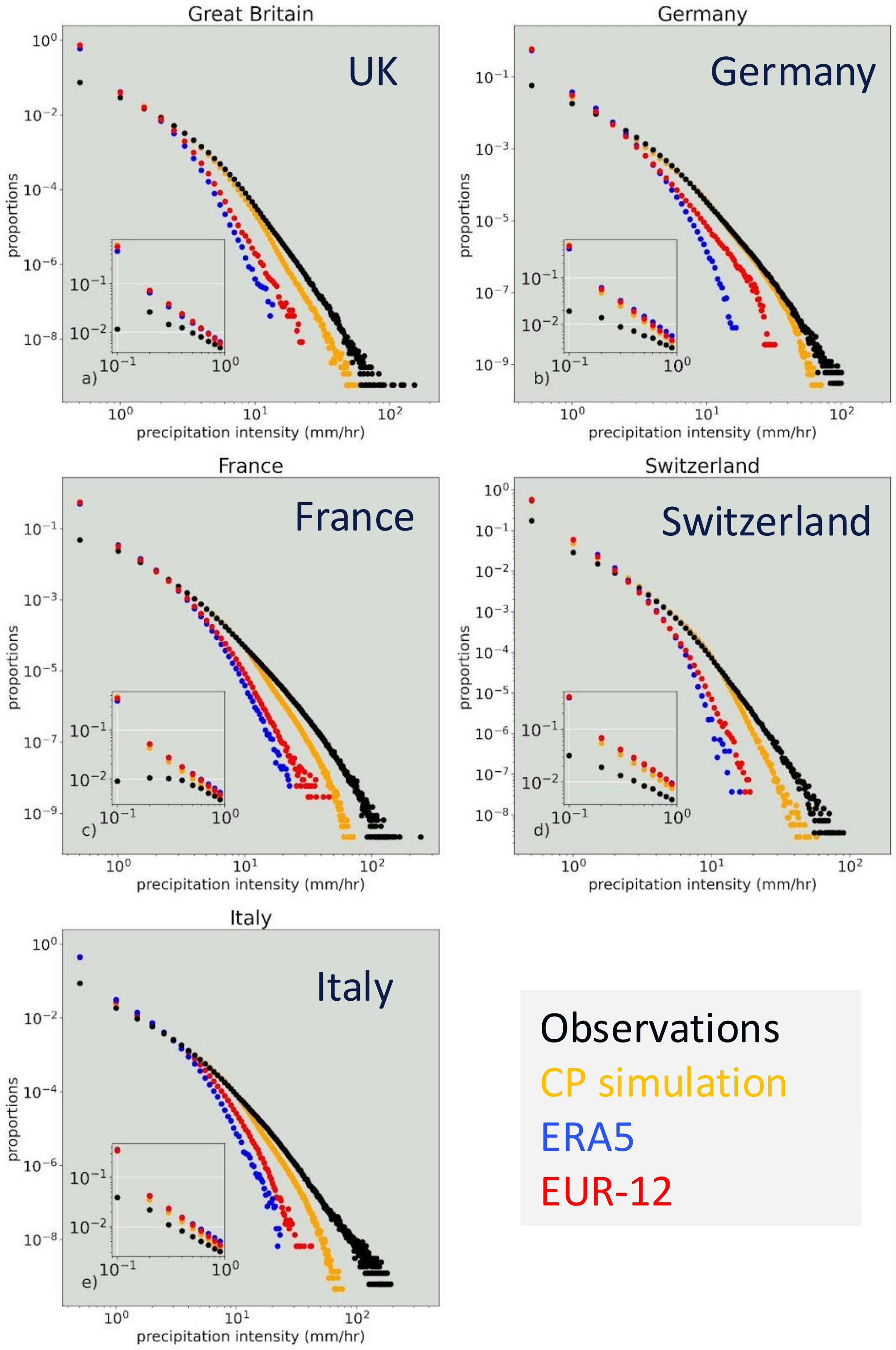
- **Hourly** Precipitation intensity, frequency and P99 compare well with high resolution observations over Europe for all seasons.
- Results are generally better than for the EUR-12 simulation (12km)



RegCM5 CP simulation
Latest results

First evaluation simulation results (2000-2009):

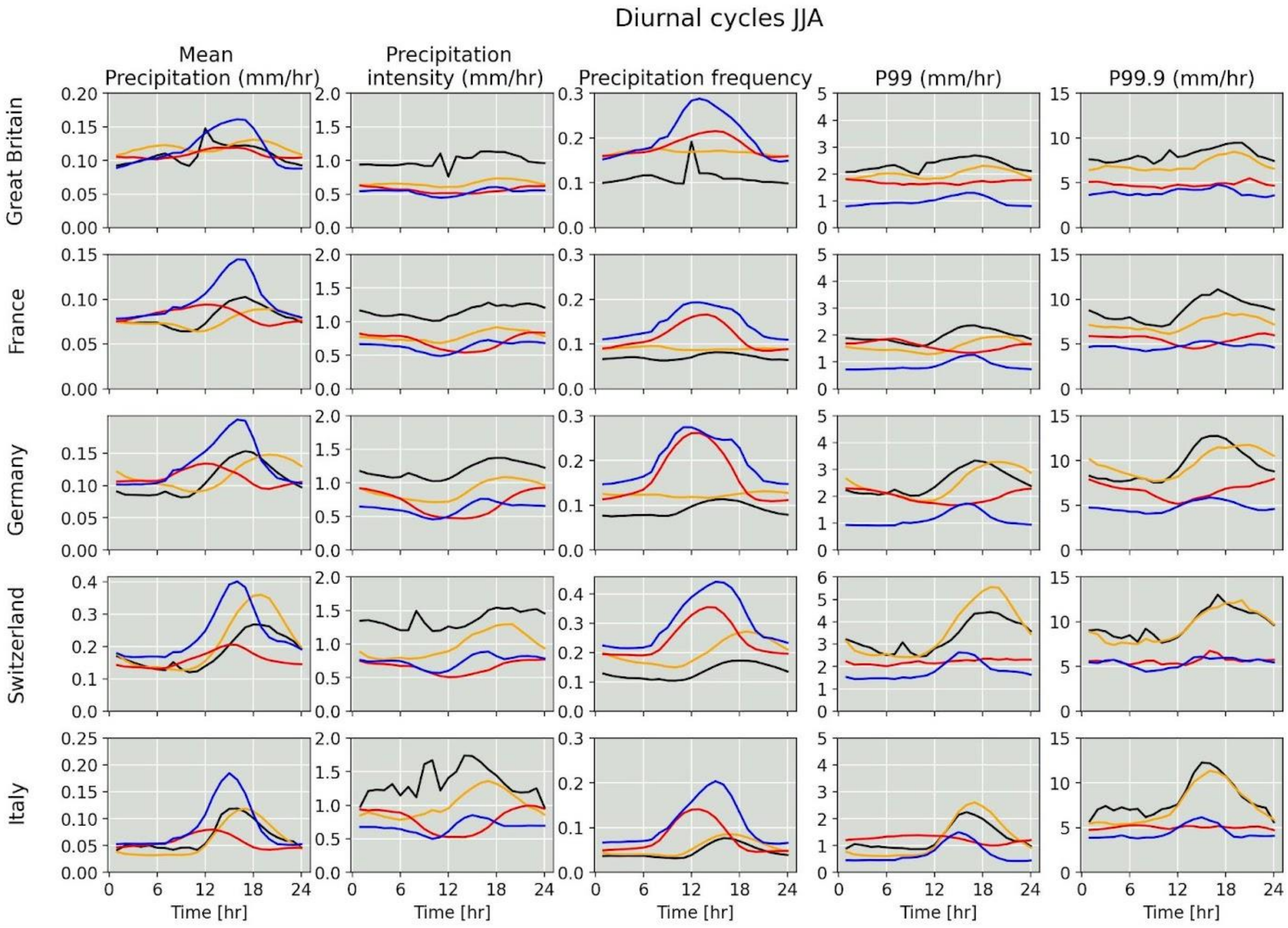
- Extreme **hourly** precipitation events are captured well by the simulation, as shown by the good comparison between the simulated precipitation PDF (orange points) and the hourly precipitation observations (black points) for 5 regions selected in the EURR-3 domain.



RegCM5 CP simulation
Latest results

First evaluation simulation results (2000-2009):

- Better representation of the diurnal cycle of precipitation variables

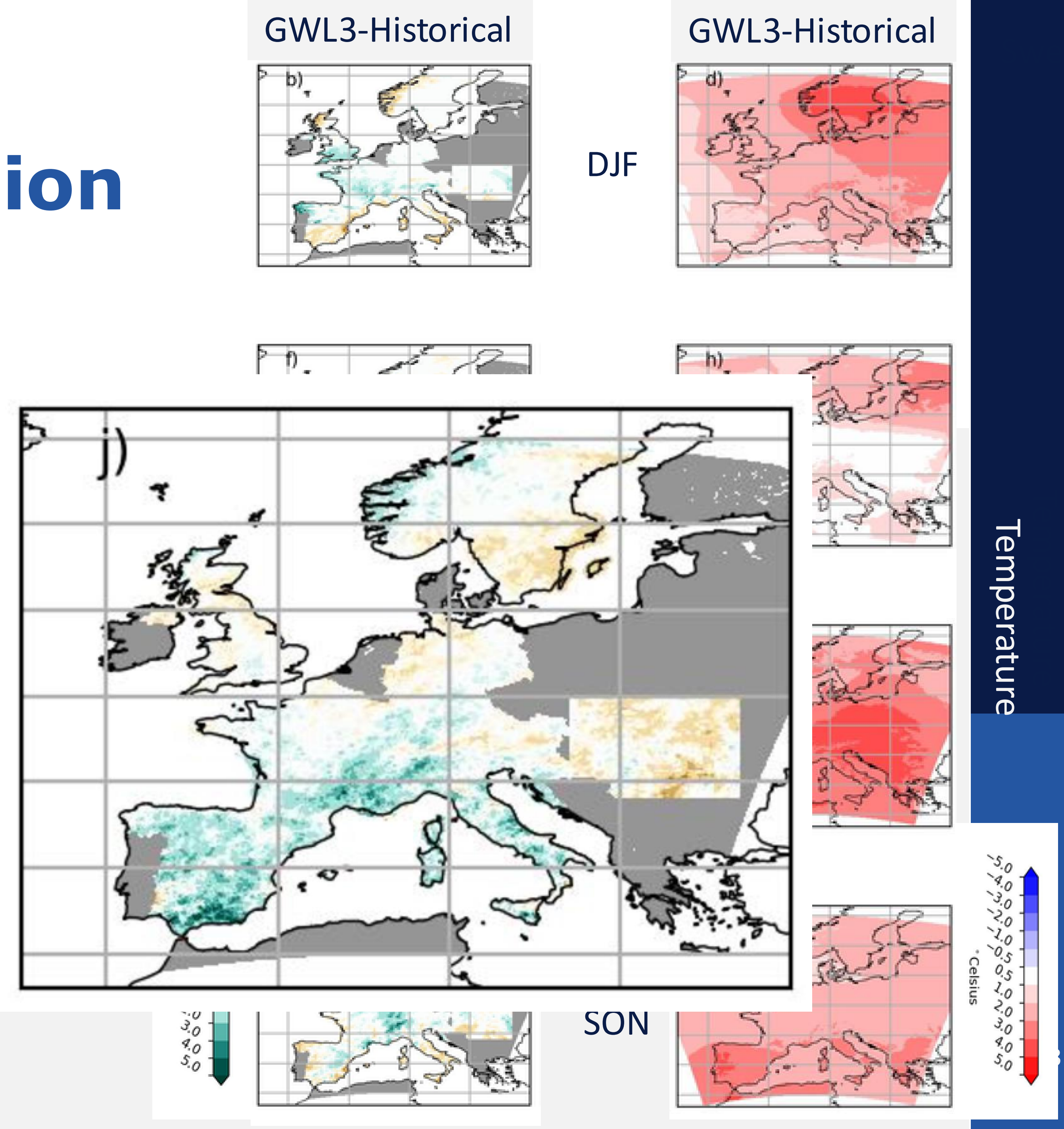


Observations
CP simulation
ERA5
EUR-12

RegCM5 CP simulation
Latest results

Simulation results for future climate scenarios.

Seasonal differences in daily precipitation intensity and surface temperature between the historical simulation (1995-2014) and the GWL3 simulation (2048-2062)

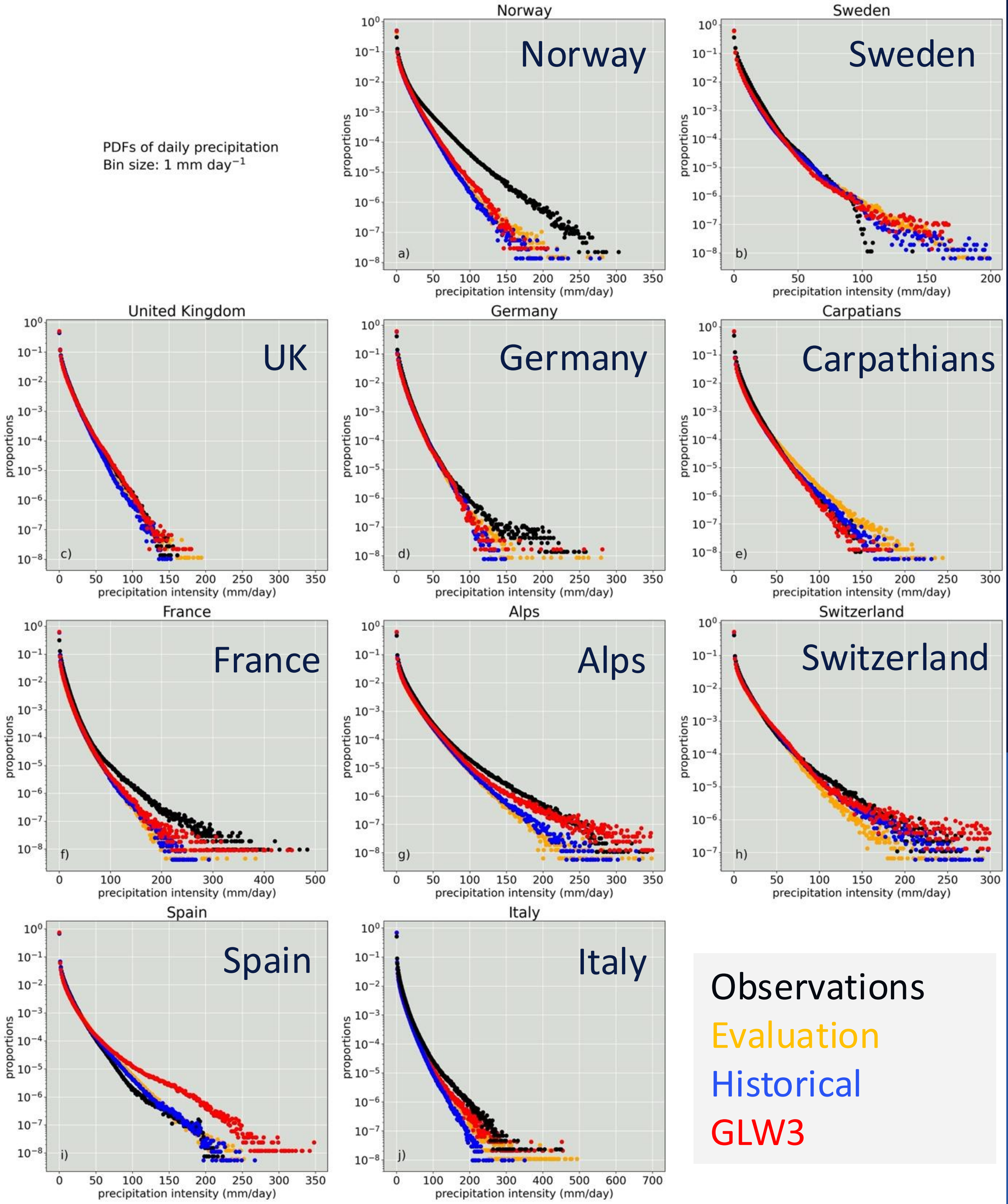


RegCM5 CP simulation
Latest results

Simulation results for future climate scenarios.

Daily precipitation PDFs for 10 regions within the simulated domain for:

1) Observations (2000-2009)
2) Evaluation period (2000-2009)
3) Historical simulation (1995-2005)
4) GLW3 scenario (2048-2057)



Thank you

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