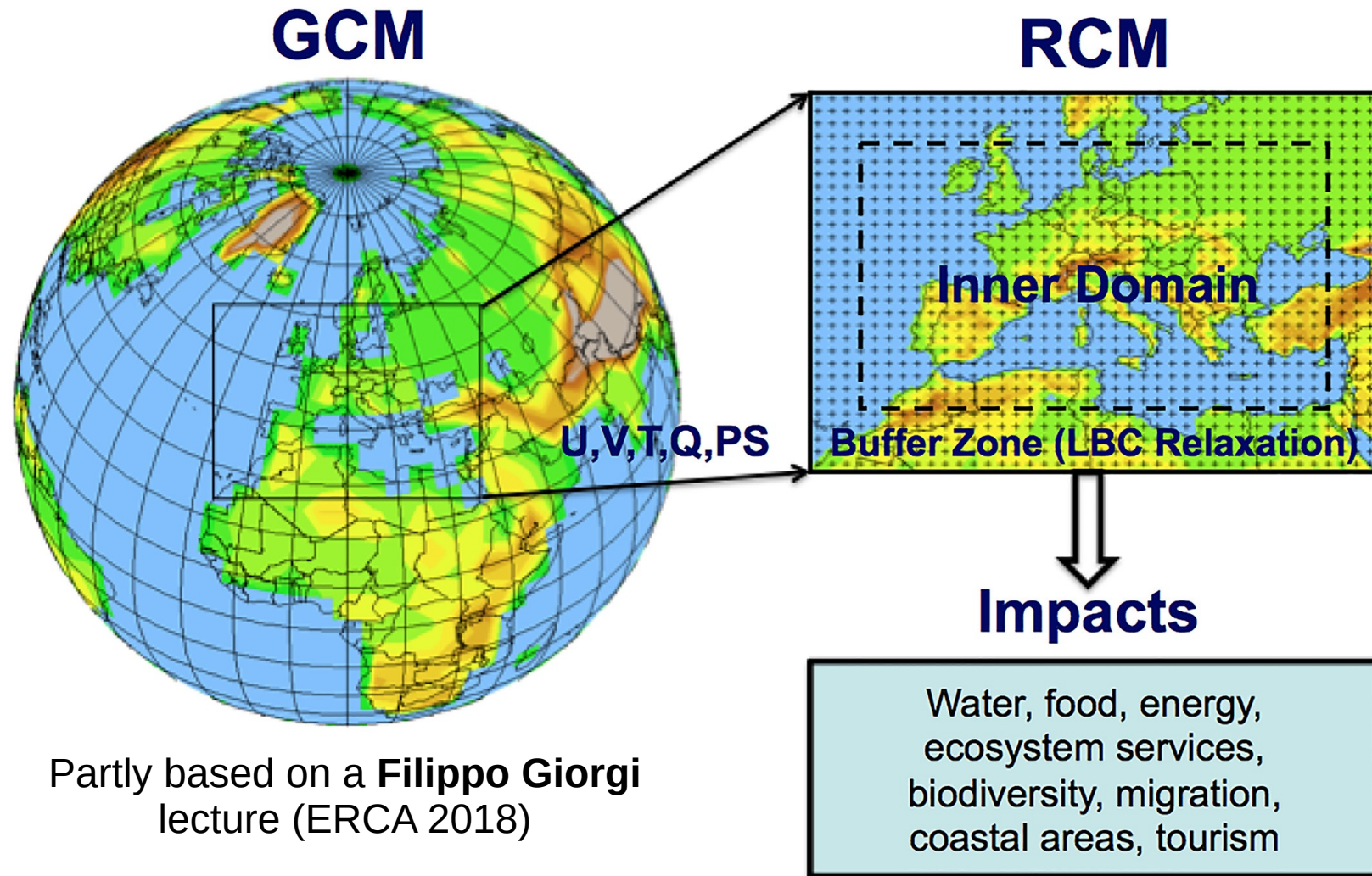
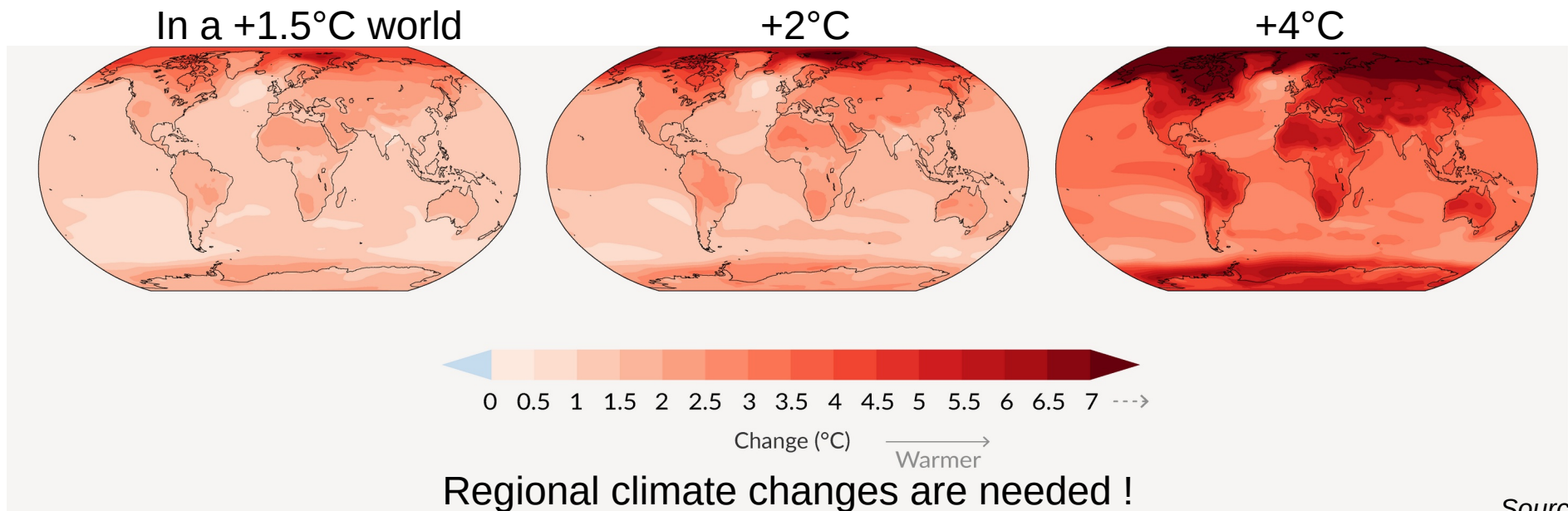
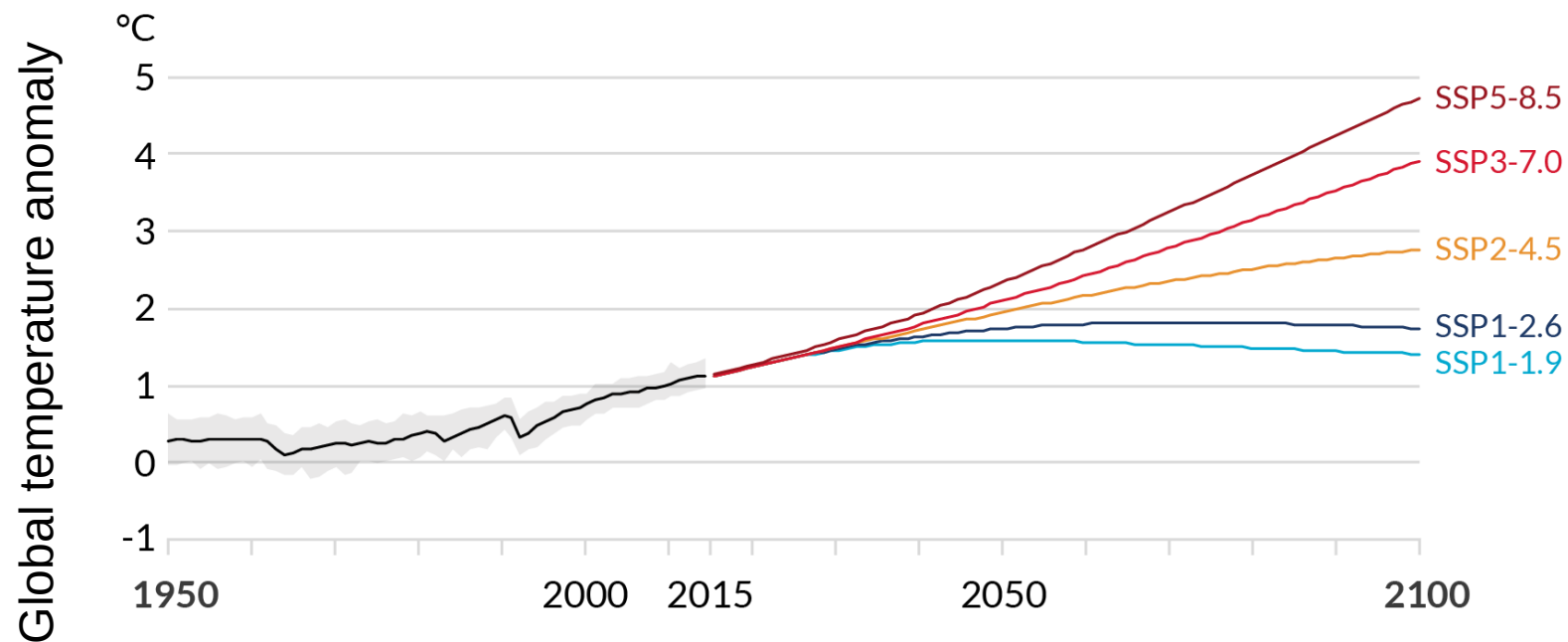


Regional climate modelling



Partly based on a **Filippo Giorgi** lecture (ERCA 2018)

1. Introduction

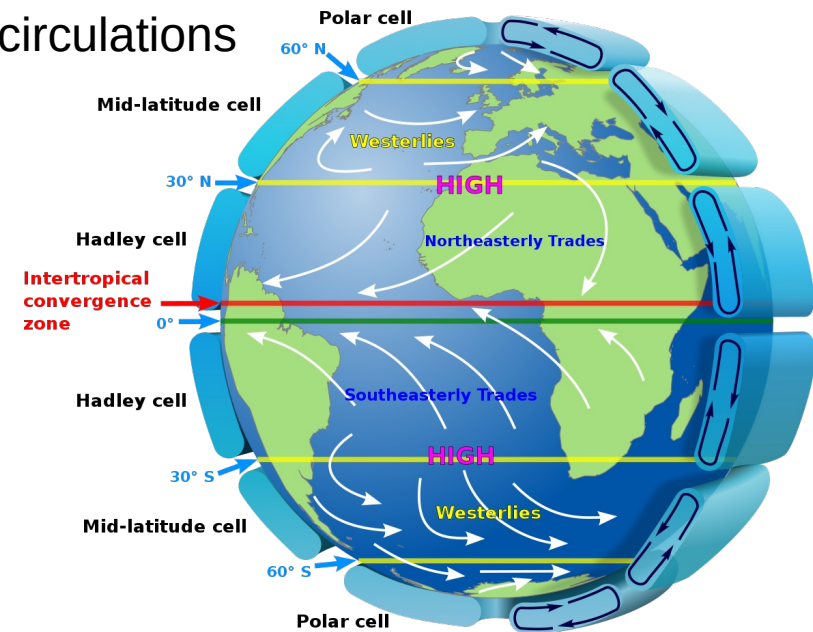
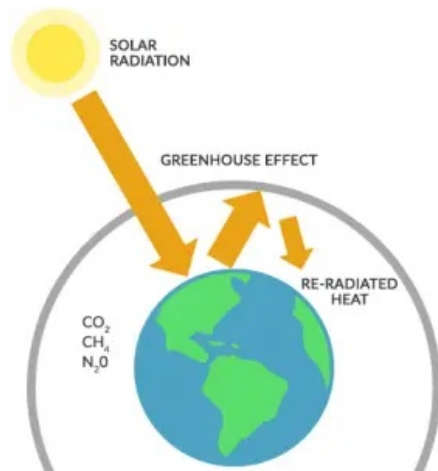


Source: AR6

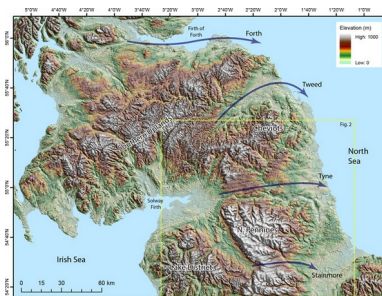
1. Introduction

Regional climates (variabilities) are determined by

1. planetary and large scale forcings and circulations

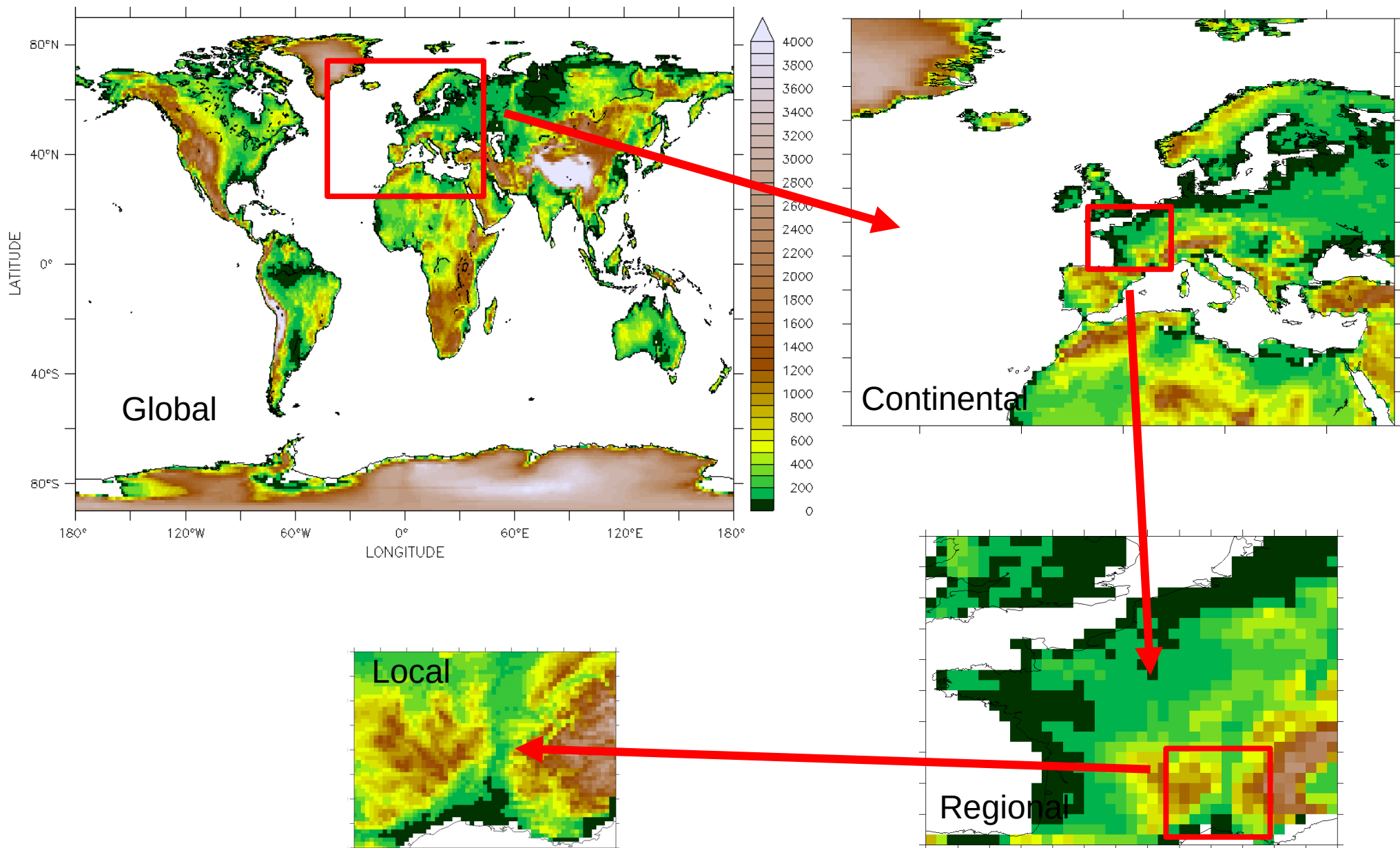


2. regional and local forcings modulate regional climate change + possible feedbacks to large scale



We need to simulate processes at a wide range of spatio-temporal scales.

1. Introduction



Climate changes needs to be simulated at multiple spatial scales!

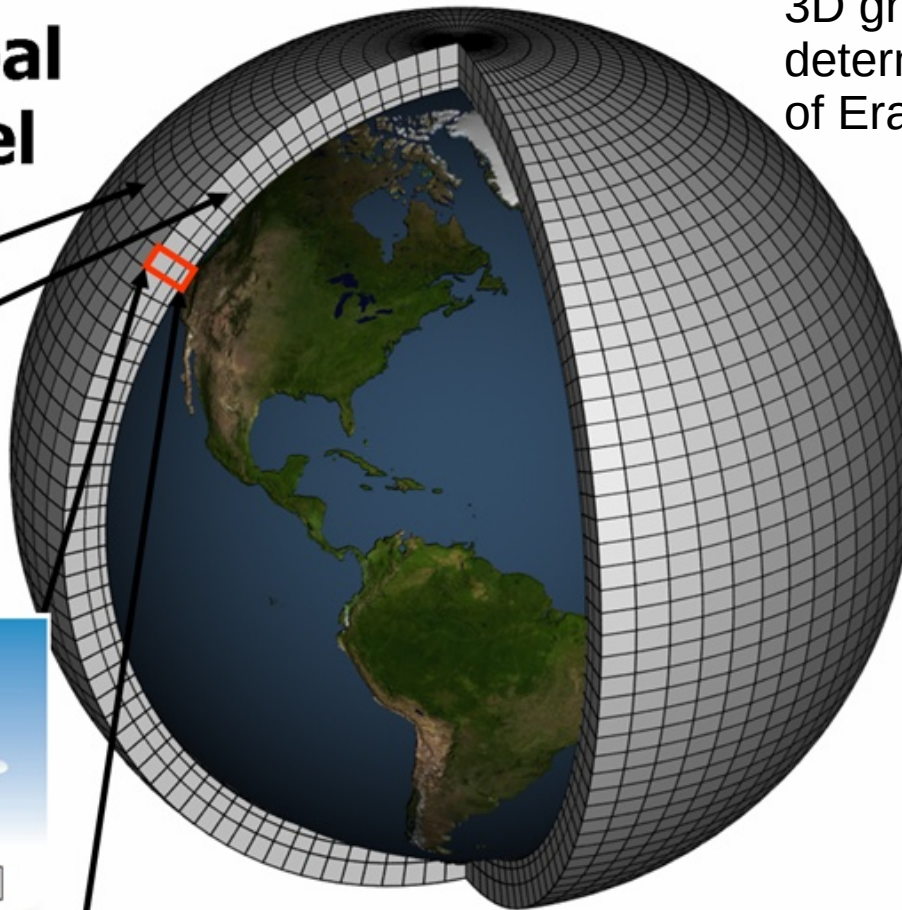
1. Introduction

Main (IPCC) tools: global models

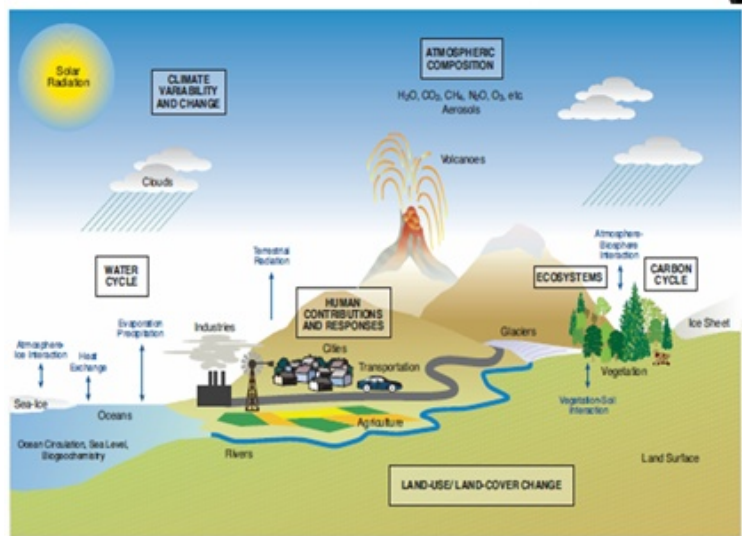
Schematic for Global Atmospheric Model

Horizontal Grid (Latitude-Longitude)

Vertical Grid (Height or Pressure)



GCMs are numerical representation on a 3D grid of the processes determining the evolution of Earth's climate

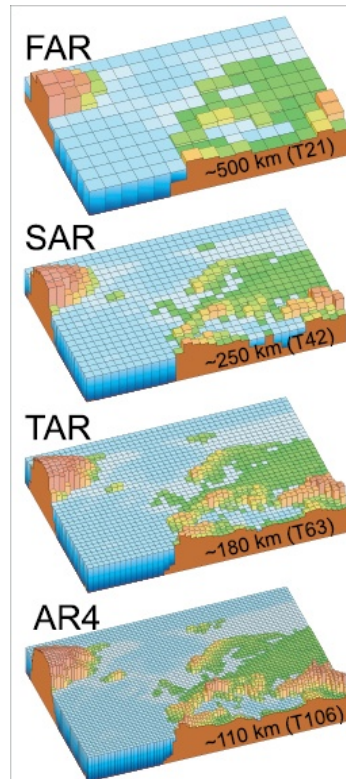
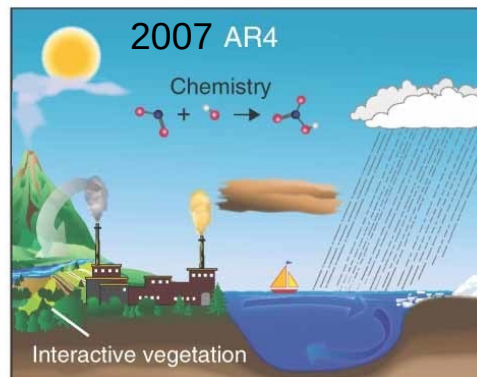
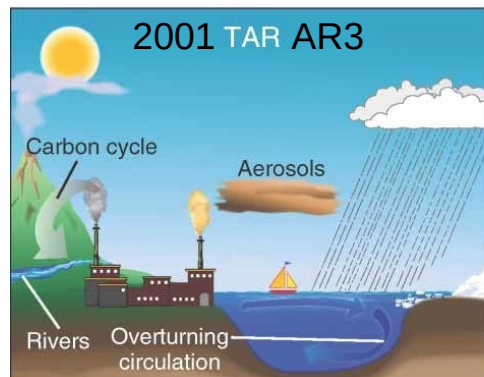
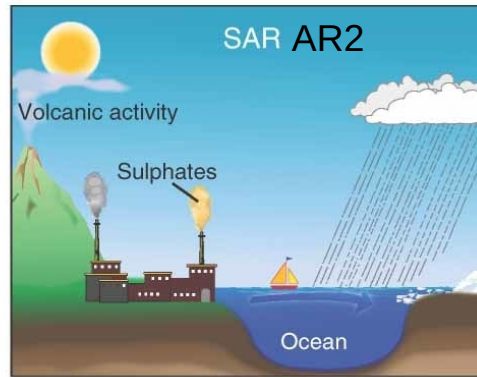
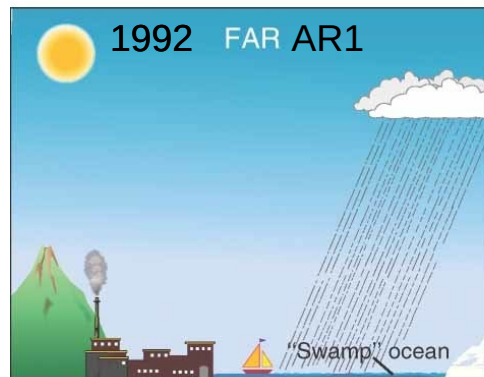
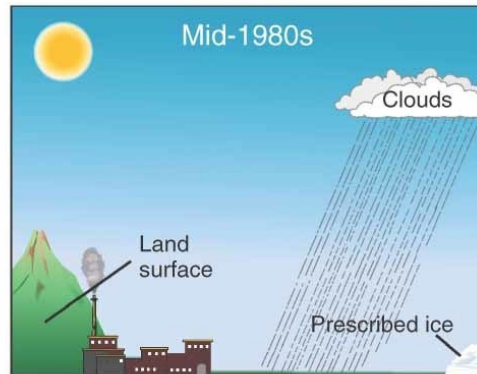
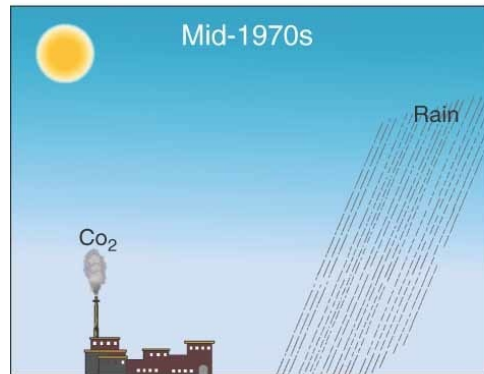


Global Climate Model (GCM)
or General Circulation Model (GCM)
or **Earth System Model (ESM)**

1. Introduction

Evolution of GCMs

The world in global climate models



Improvements in spatial resolution and complexity

AR = Assessment report from IPCC

Following the resolution, the processes are

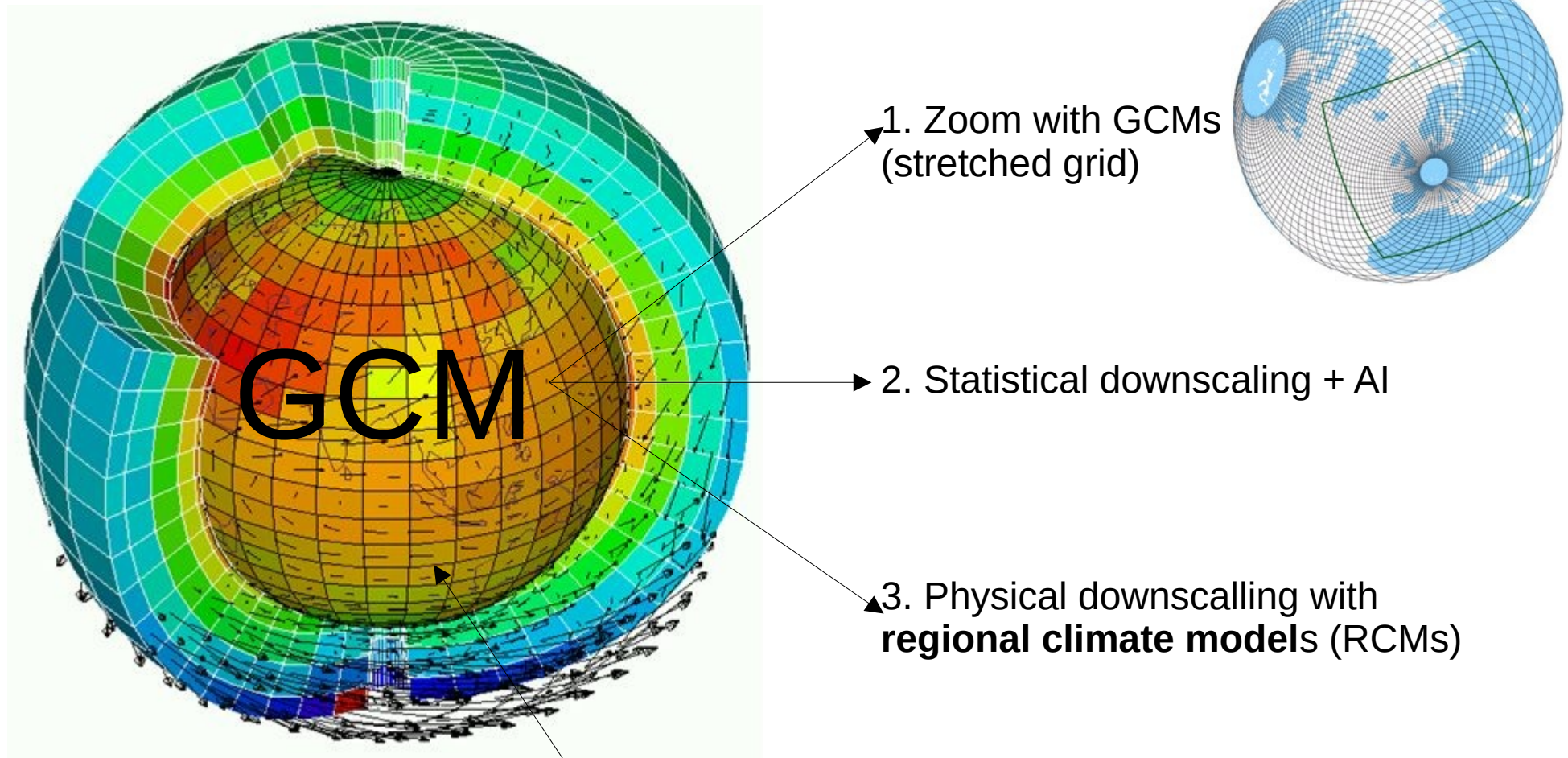
1. fully resolved thanks to physical equations

2. parametrised (like convection or turbulence) by taking into account their effects at larger scales.

Source: IPCC AR4

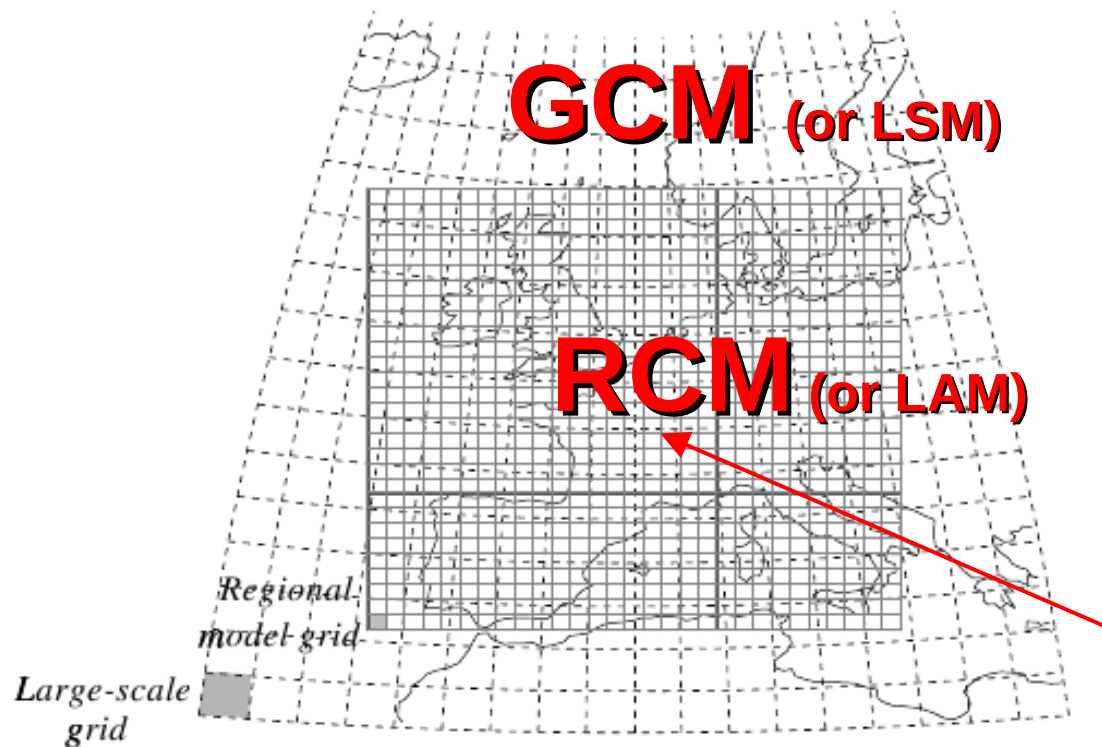
1. Introduction

Several tools are available for producing sub-GCM scale regional climate information:



The resolution remains too coarse to capture regional and local processes

2. RCM: how it works



A RCM is "**nested**" in a GCM in order to locally increase the model resolution.

The **initial conditions** (IC) and **lateral boundary conditions** (LBC) come from GCMs (as a "one-way nesting").

A 6-hourly forcing is enough.
(3-hourly if the integration domain is small)

RCM (regional climate model)
or
LAM (limited area model)

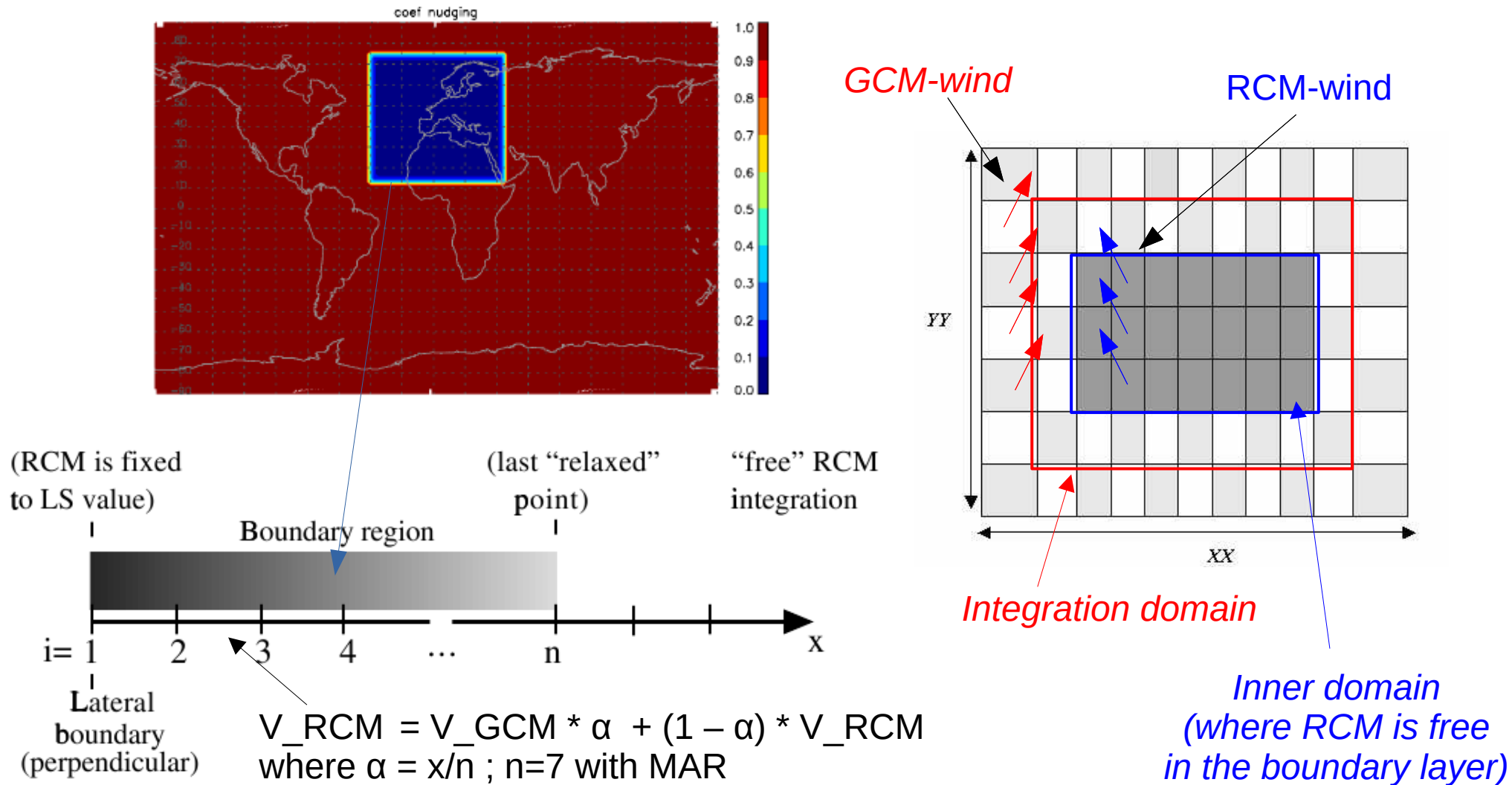
A same RCM can be forced by

- "free" GCMs for performing **future projections** (IPCC),
- weather forecast global models (like GFS, ECMWF) for performing **forecast**,
- reanalysis (perfect GCM where observations are assimilated into) for performing **hindcast**

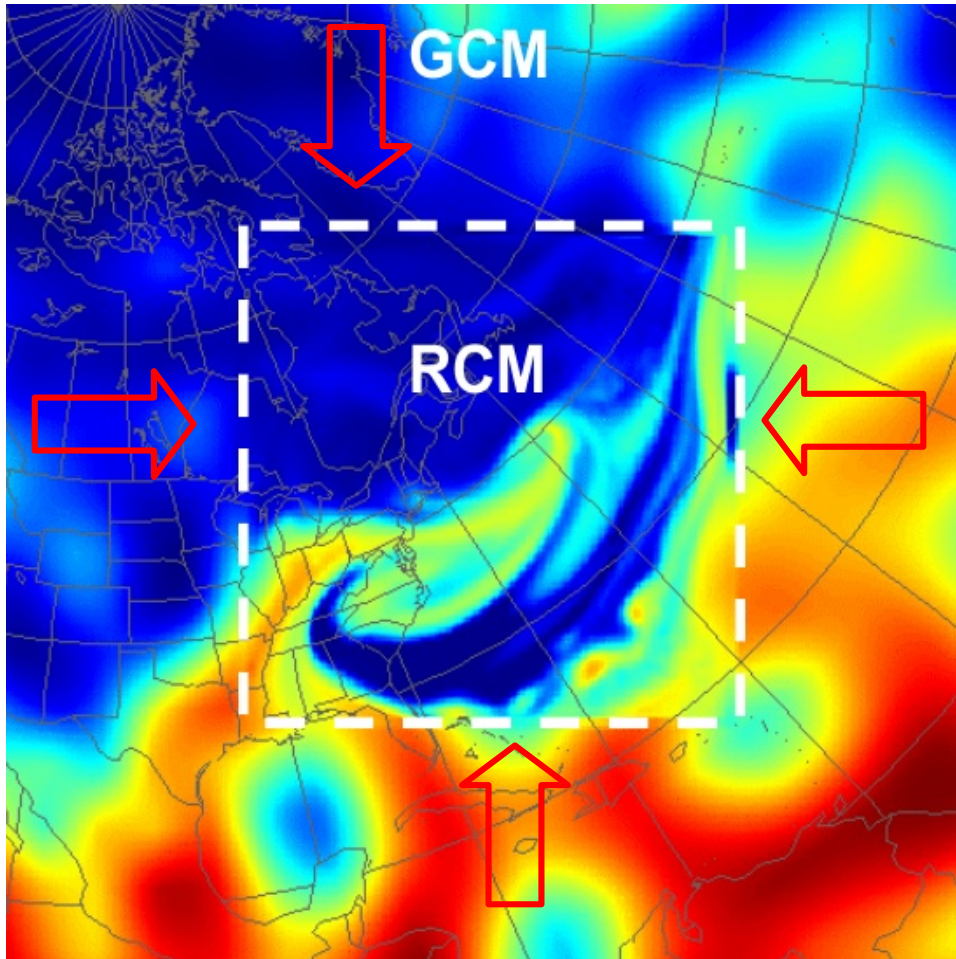
2. RCM: how it works

Relaxation or Buffer zone

The boundary between the GCM and the RCM



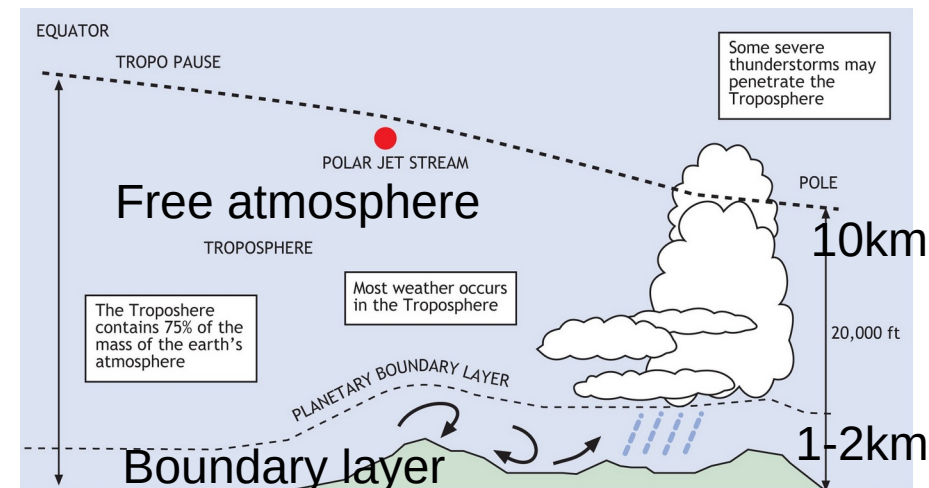
2. RCM: how it works



6-hourly forcing: **U,V,T,Q,SP**
(+ clouds)
(+ oceanic conditions)

A dynamical equilibrium is reached into the interior domain:

- mainly in the **planetary boundary layer** (except clouds)
- the general circulation is driven by GCM in the **free atmosphere**
- as clouds impacts T + Q in the free atmosphere => this impacts also U + V



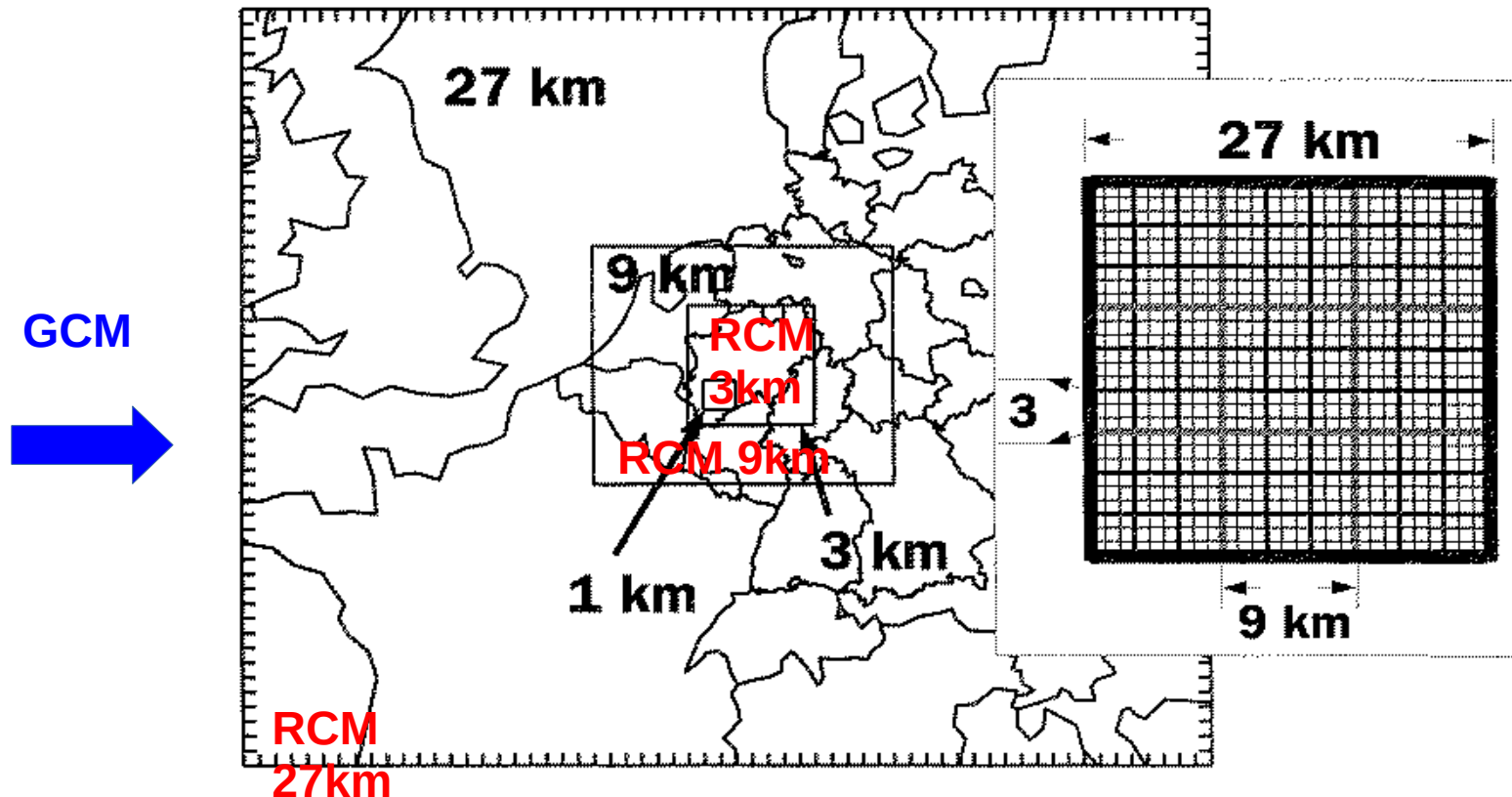
2. RCM: how it works

One way nesting:

The low resolution fields are only used to force the higher resolution model.
(If reanalysis is used at boundaries, this methodology could amplify biases of RCMs)

Two way nesting:

The model is run at different resolutions at the same time (e.g. WRF model)

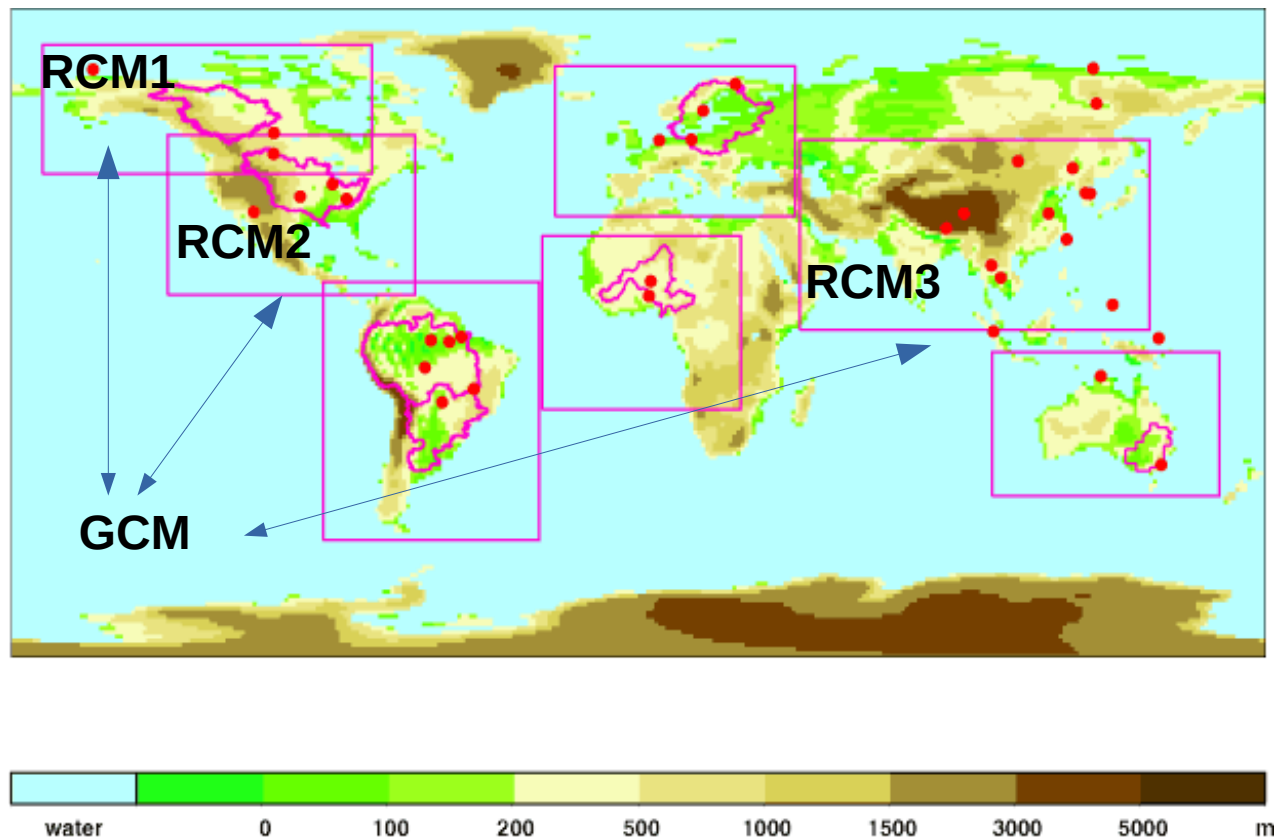


2. RCM: how it works

Two way nesting

The results of the nested RCMs are used in the forcing GCM to improve some area (e.g. the polar areas)

The dream for regional climate modeller ... ;-)

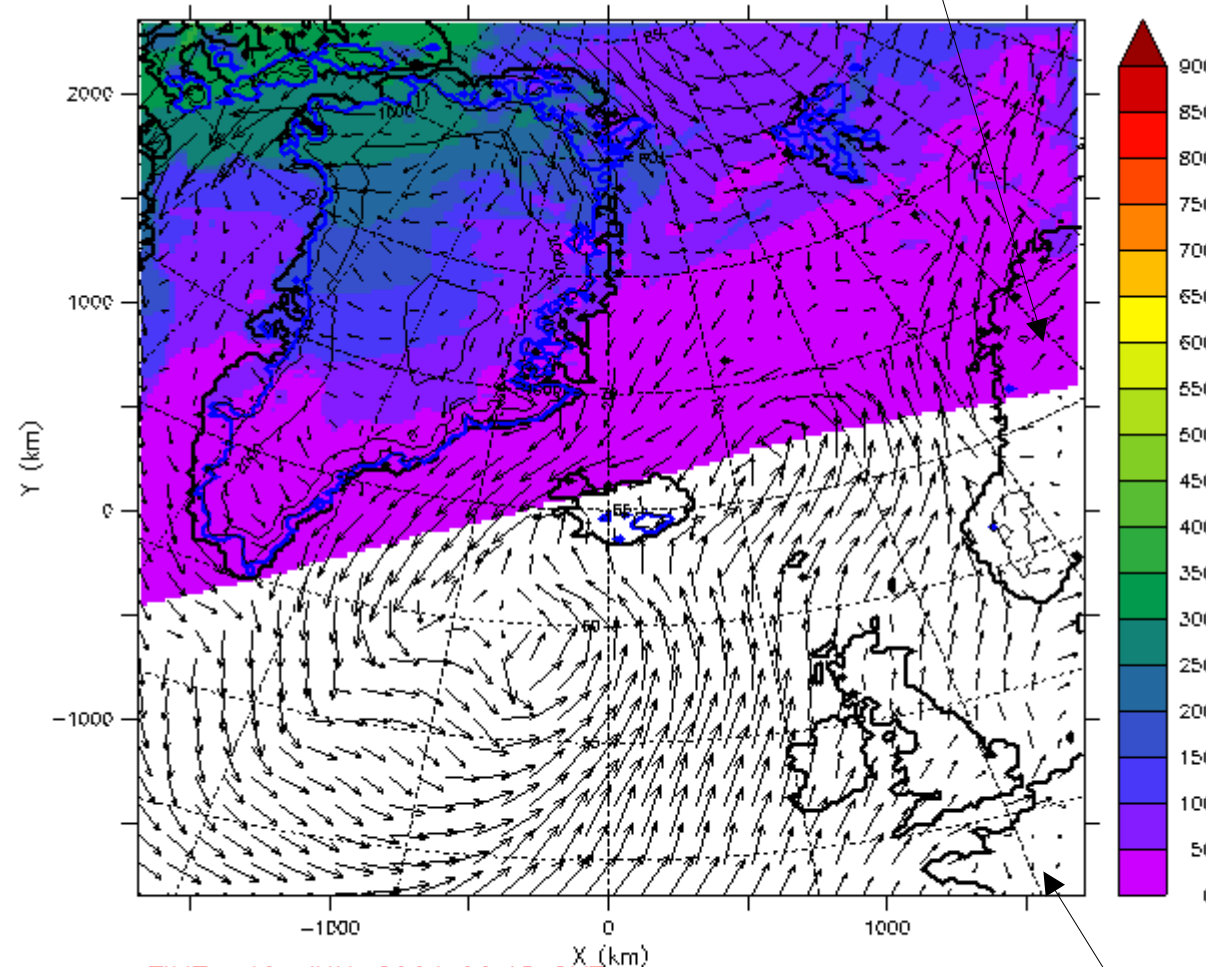


2. RCM: how it works

Topography from large scale at MAR boundaries

Difficulties of the **choice of the integration domain and spatial resolution**:

- resolution / 2 => computer time x 8
- integration domain **too small** => RCM not enough free
- integration domain **too large** => RCM simulates its own circulation
- **topography** at the boundary => possible instabilities in RCM
- RCM needs **enough pixels** to simulate its clouds + precipitation
- max a **factor 8-10** between the GCM and RCM resolution
- the RCM results could **depend** to the selected domain & resolution



TIME : 10-JUN-2021 00:15 GMT

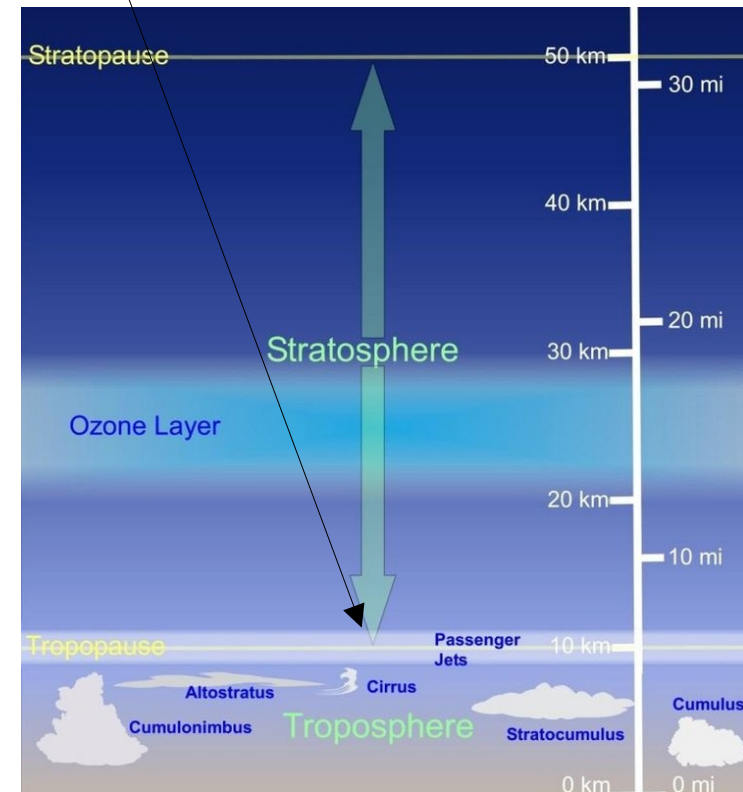
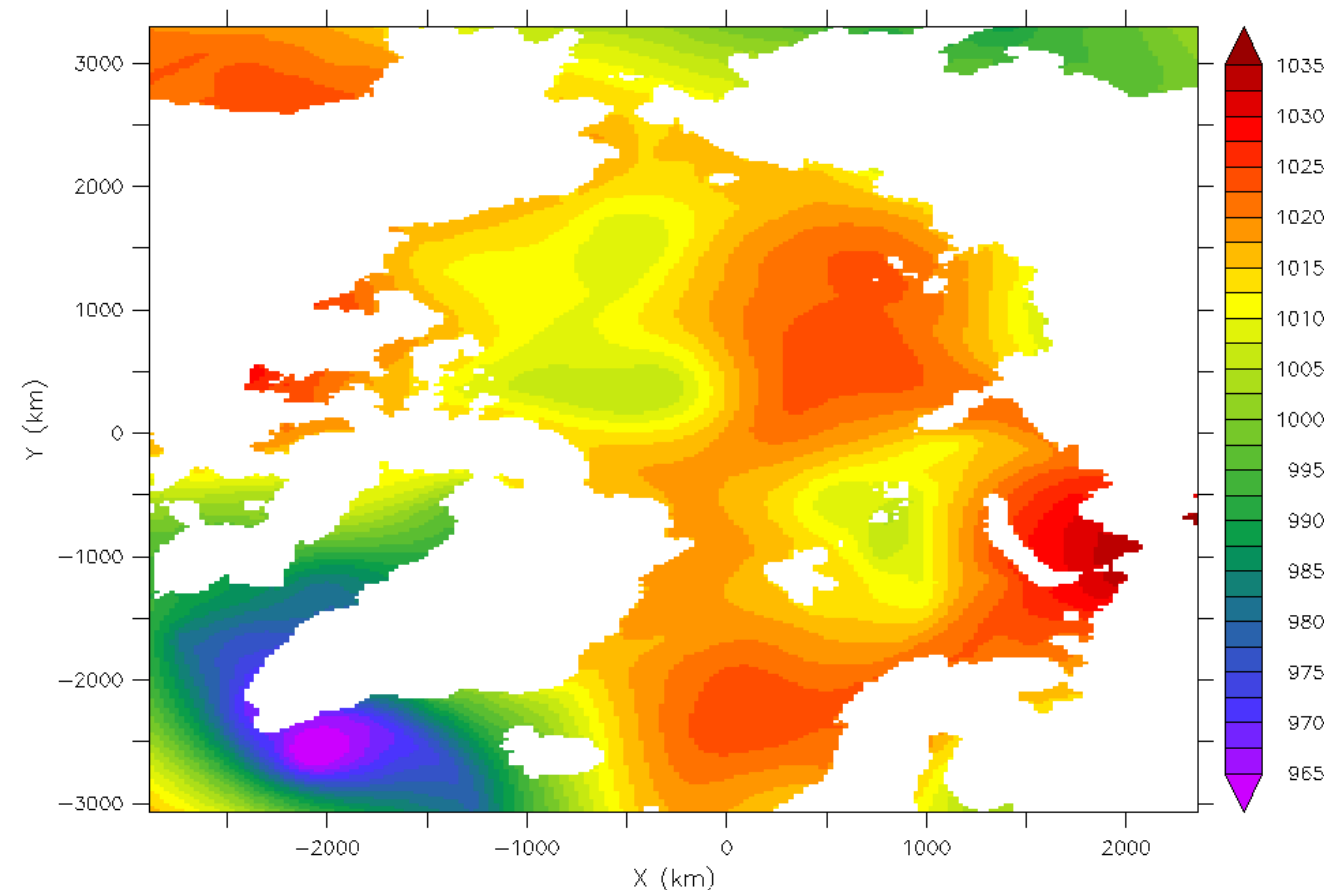
Solar radiation (w/m^2) + 10m wind

MAR run at 15 km forced by ERA5

No cloud in MAR at the boundary

2. RCM: how it works

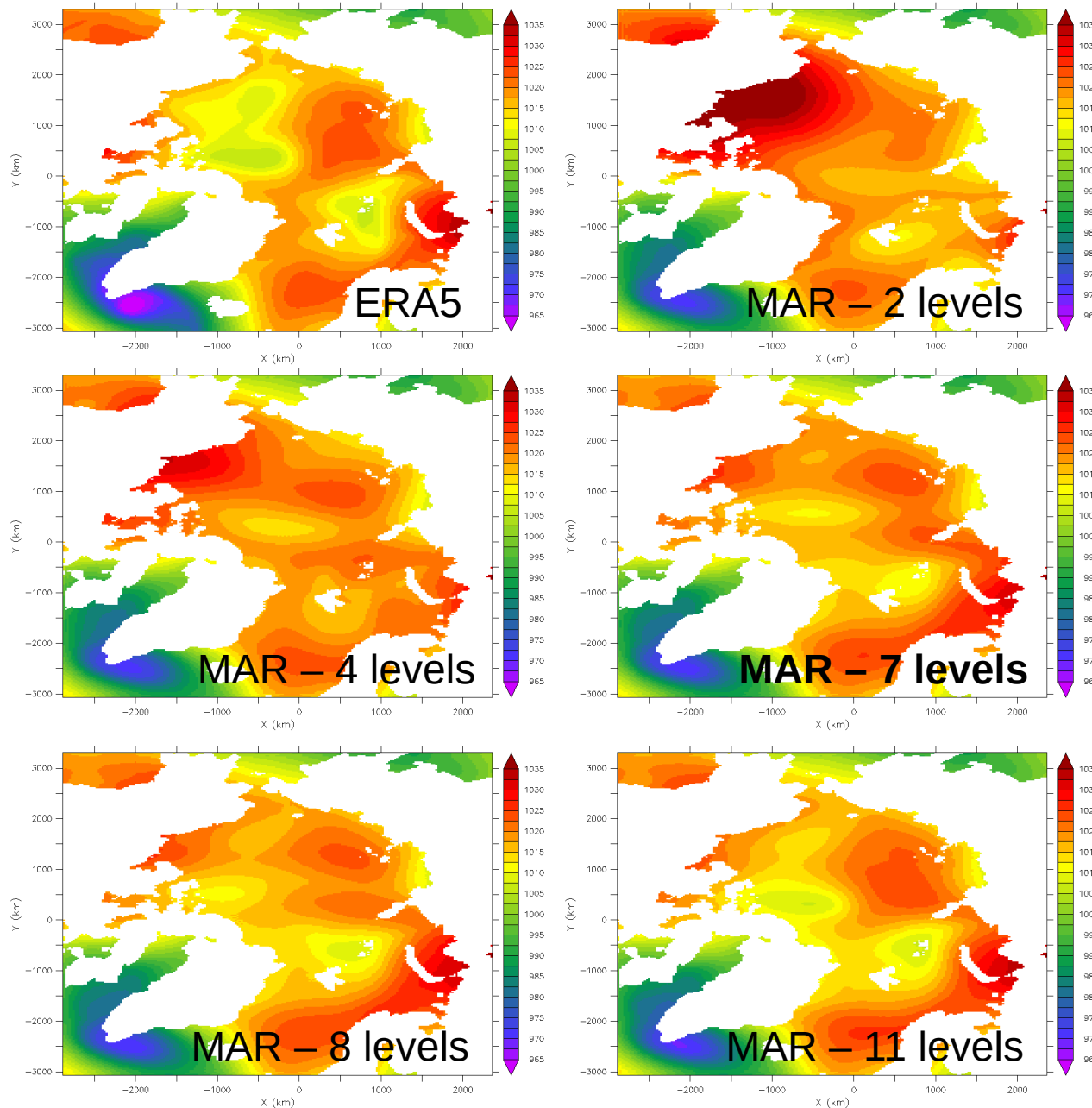
If the integration domain is too large (like for the CORDEX-Arctic domain), an **upper boundary forcing** is needed in the upper troposphere and stratosphere



Surface pressure from ERA5 on 10 Nov 2019 (hPa) over the **CORDEX MAR domain (25km)**

2. RCM: how it works

impact on clouds and precipitation



MAR – 7 forced levels

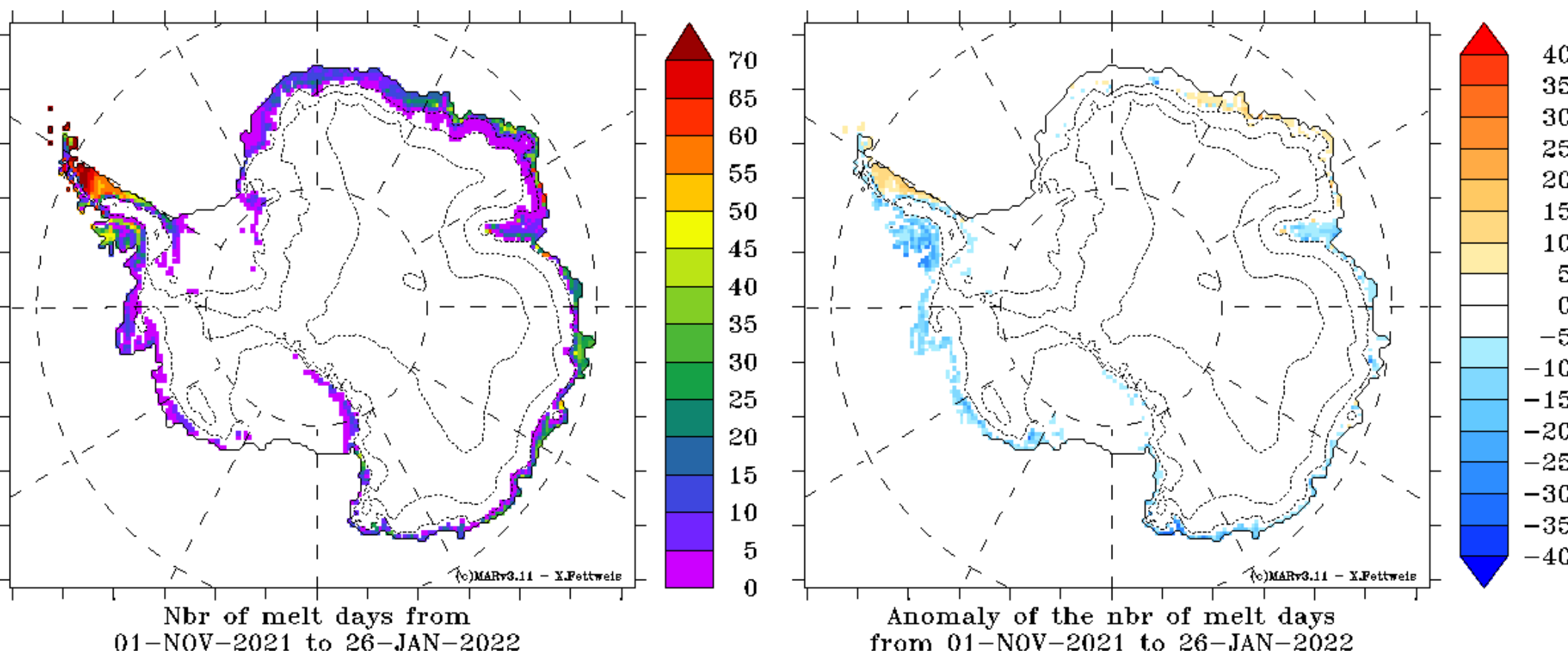
Level #	sigma	altitude	α (wind)	α (temperature)
1	0.099	14867	0.6667	0.6667
2	0.137	13136	0.6516	0.6516
3	0.181	11566	0.5985	0.2992
4	0.232	10128	0.5	0.1667
5	0.288	8793	0.3601	0.09
6	0.351	7536	0.1995	0.0399
7	0.421	6334	0.0598	0.01
8	0.498	5180	0	0
9	0.582	4082	0	0
10	0.669	3071	0	0
11	0.753	2192	0	0
12	0.827	1481	0	0
13	0.886	951	0	0
14	0.928	585	0	0
15	0.957	349	0	0
16	0.975	203	0	0
17	0.985	116	0	0
18	0.992	66	0	0
19	0.995	37	0	0
20	0.997	21	0	0
21	0.998	12	0	0
22	0.999	8	0	0
23	0.999	4	0	0
24	1	2	0	0

Sigma =
 $\frac{\text{pres} - \text{pres}_{\text{surf}}}{\text{pres}_{\text{surf}} - \text{pres}_{\text{top}}}$
 Upper boundary layer:
 $X_{\text{RCM}} = X_{\text{GCM}} * \alpha$
 $+ (1 - \alpha) * X_{\text{RCM}}$

where X= U,V,T

3. RCM added values (1)

1. The RCM physics and parameters can be tuned for a specific area/climate while the GCM physics needs to work well over each climate.



MAR forced by GFS over Antarctica where the convection scheme and vegetation scheme are switched off and turbulence scheme can be tuned for very stable polar conditions.

3. RCM added values (2)

2. Higher spatial resolution for a reduced computer time allows to better take into account local circulations and processes.

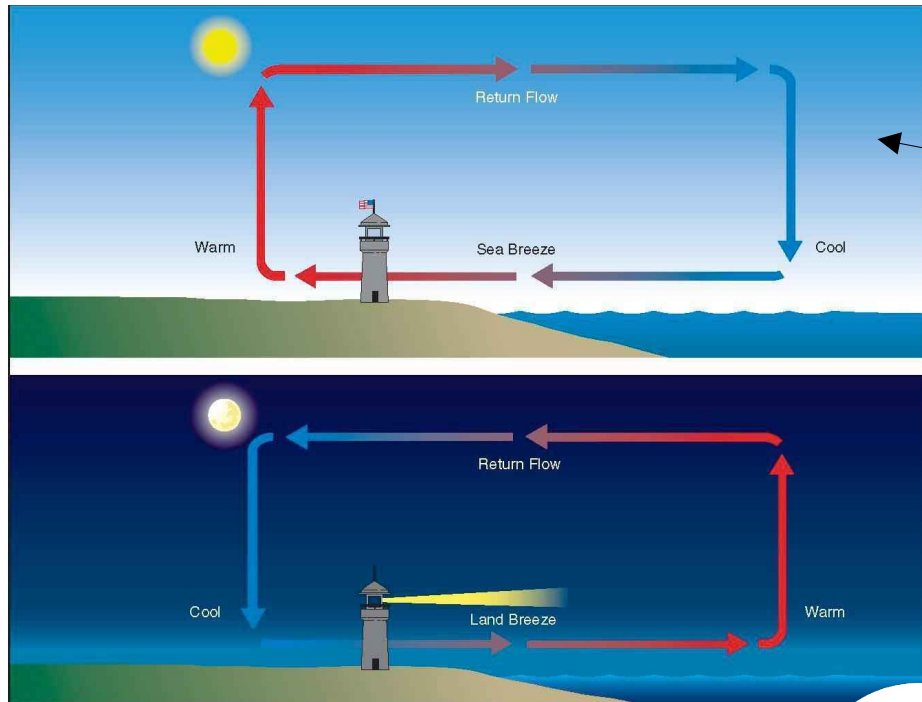
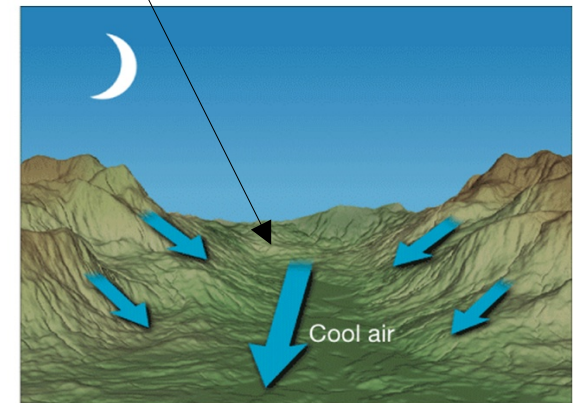
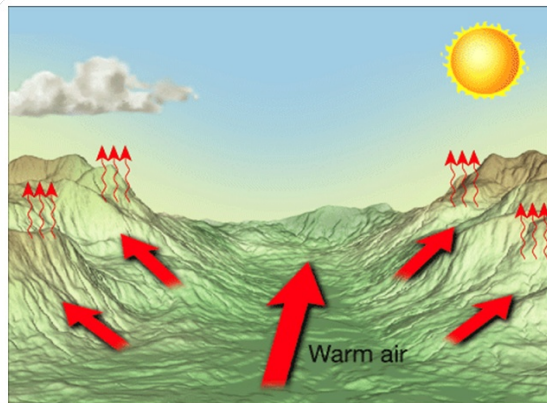


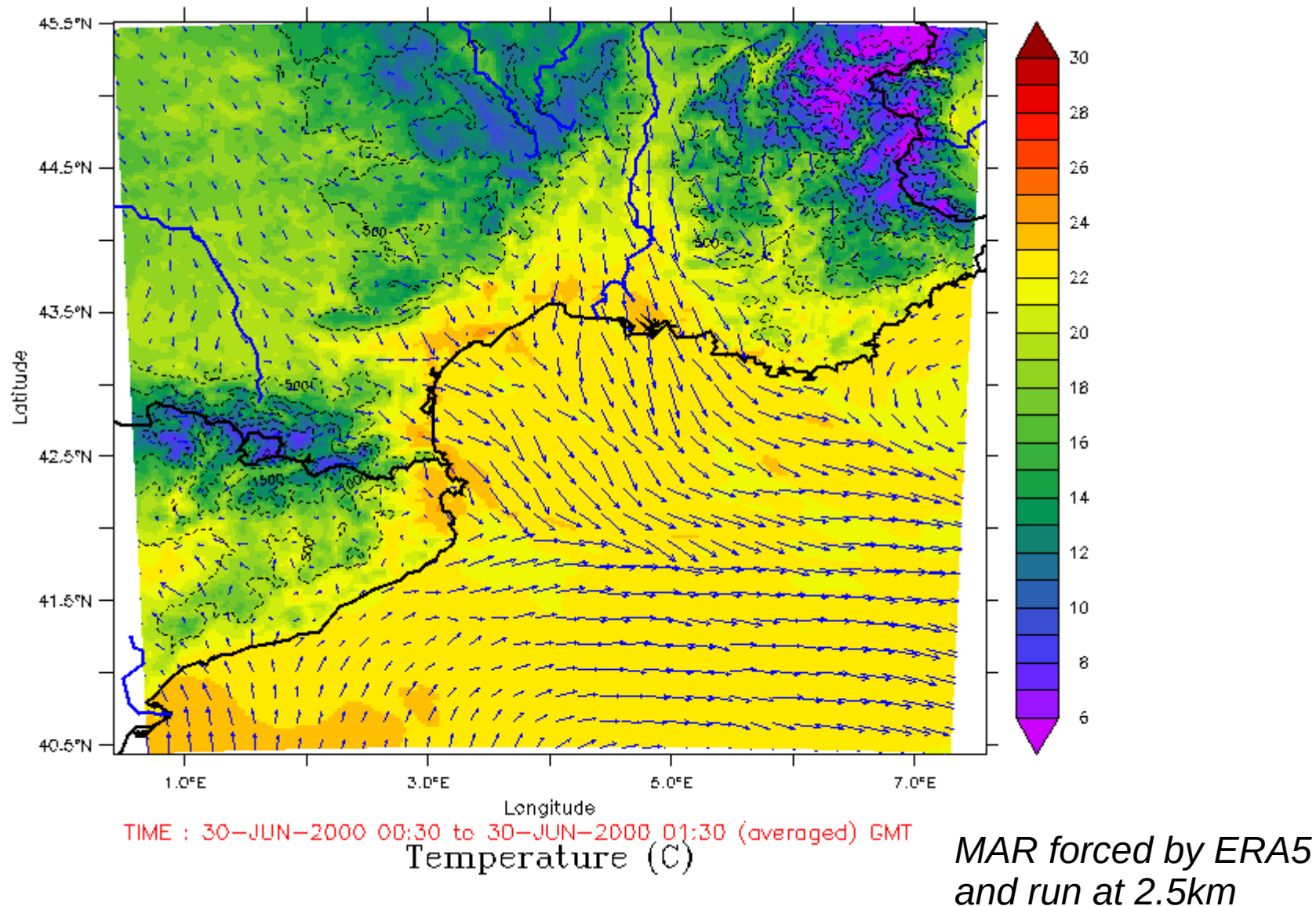
Figure 10-13. Sea breeze and land breeze wind circulation patterns.

E.g. **Sea Breezes** during day or **katabatic flows** going down the mountains during night



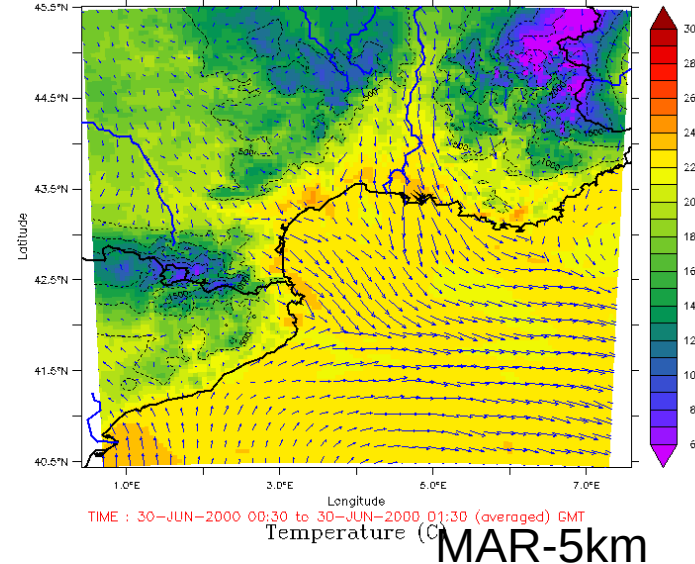
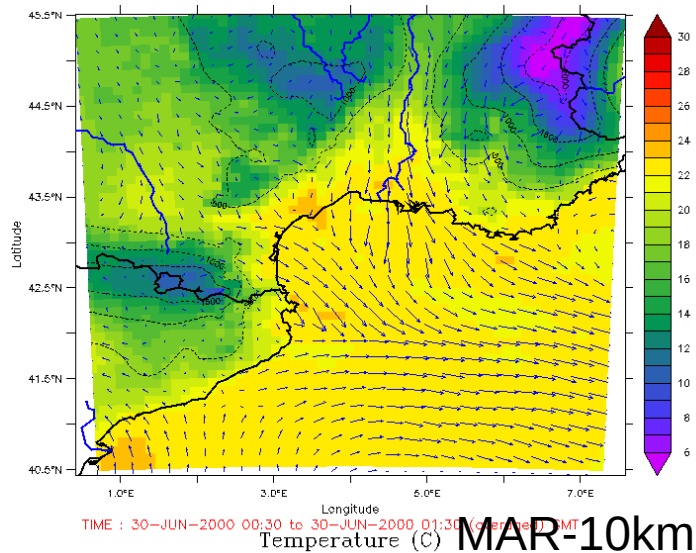
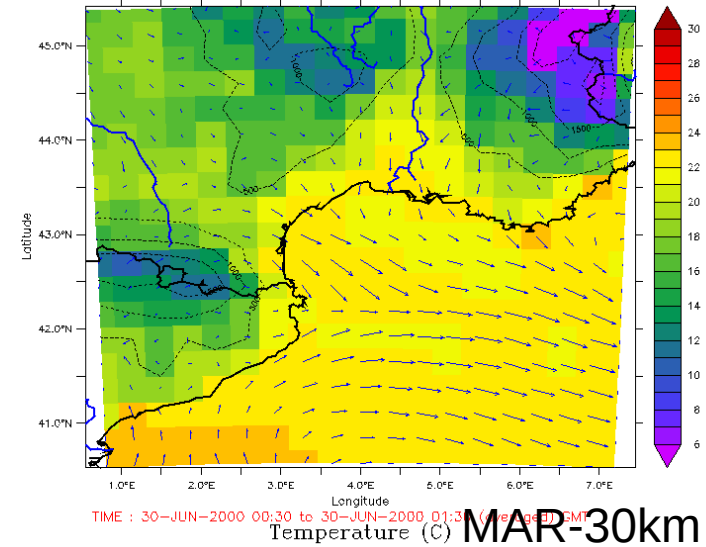
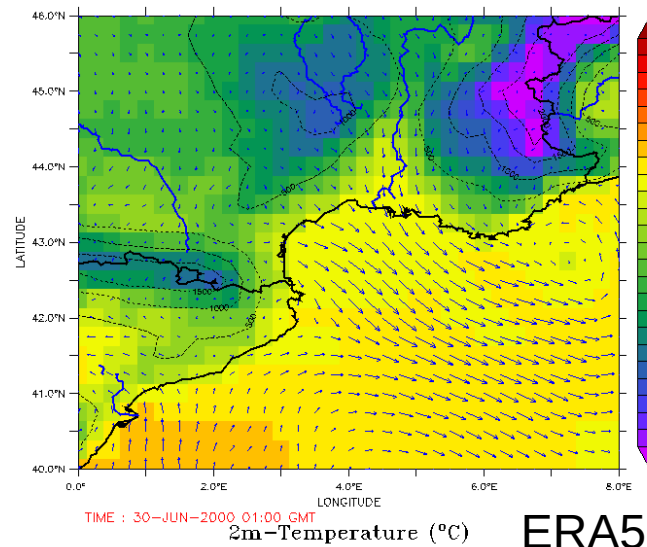
3. RCM added values (2)

2. Higher spatial resolution for a reduced computer time allows to better take into account local circulations and processes.



3. RCM added values (2)

2. Higher spatial resolution for a reduced computer time allows to better take into account local circulations and processes.



3. RCM added values (3)

3. Simulation of (extreme) precipitation linked to local topography (barrier) or convective events.



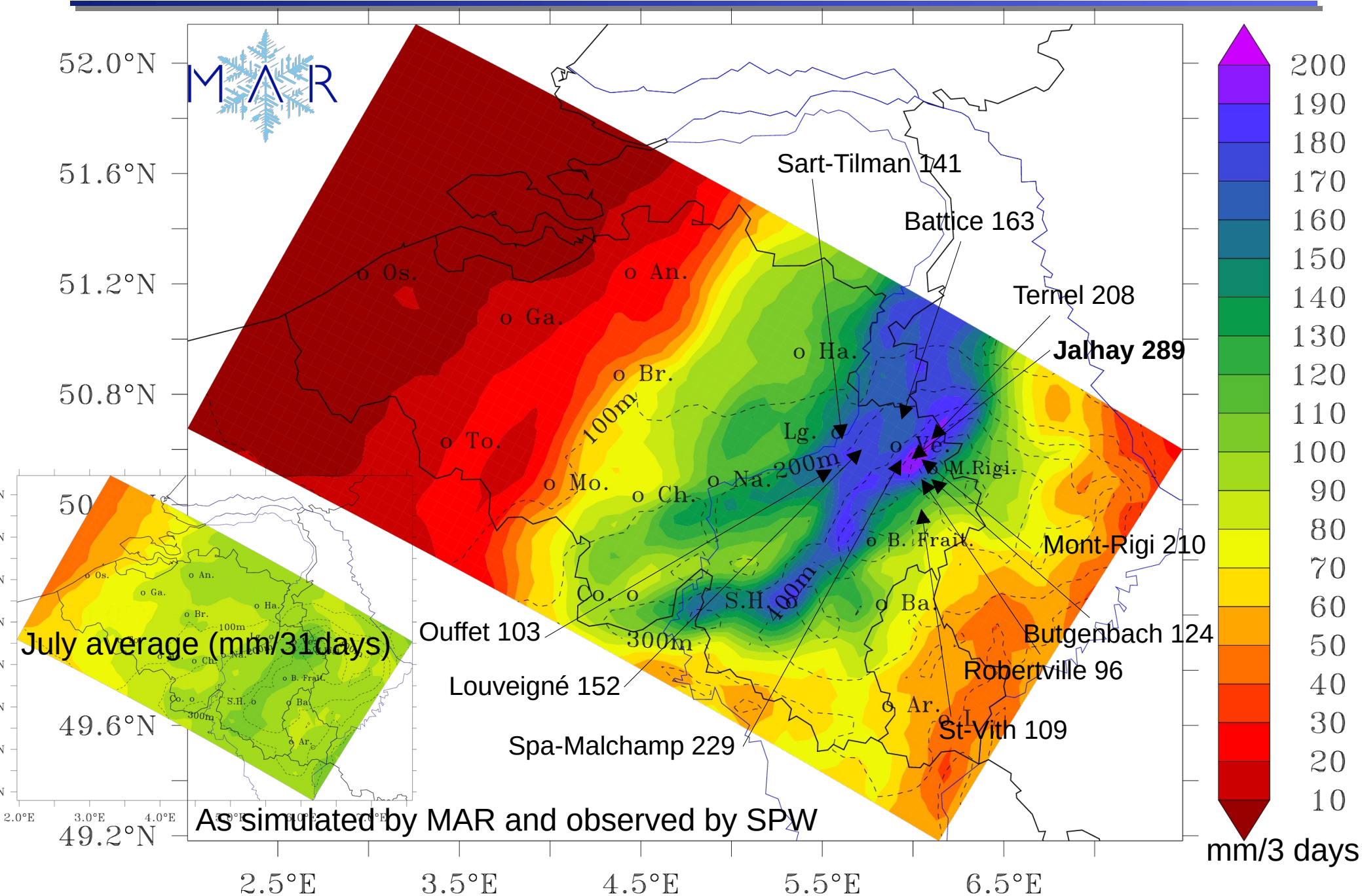
13-15 July 2021 in Belgium!



A lot of damage and 30 people died...

3. RCM added values (3)

Precipitation: 13-15 July 2021

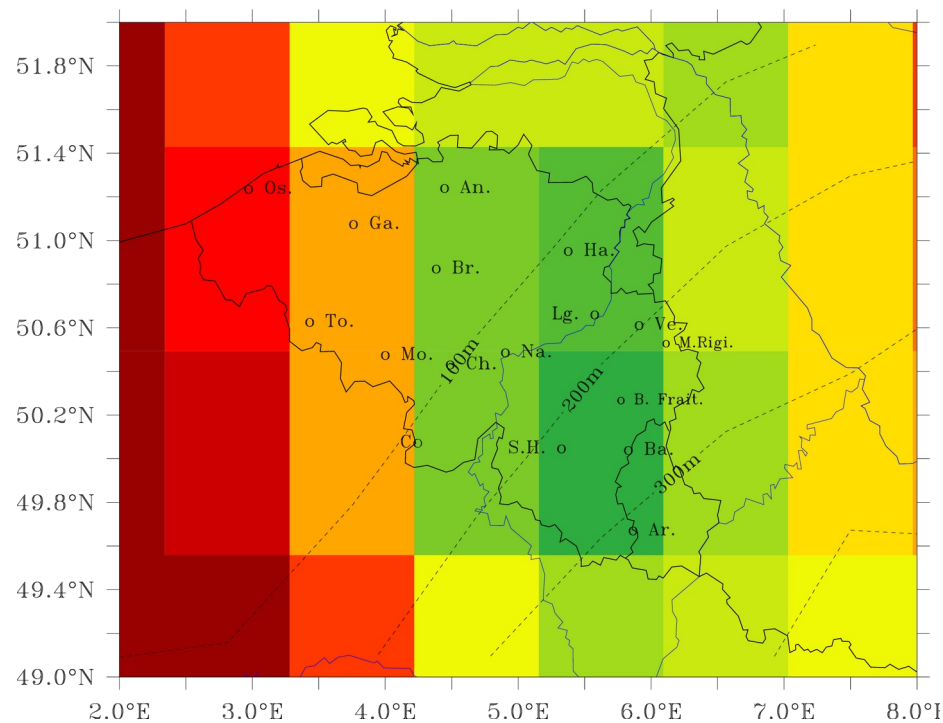


3. RCM added values (3)

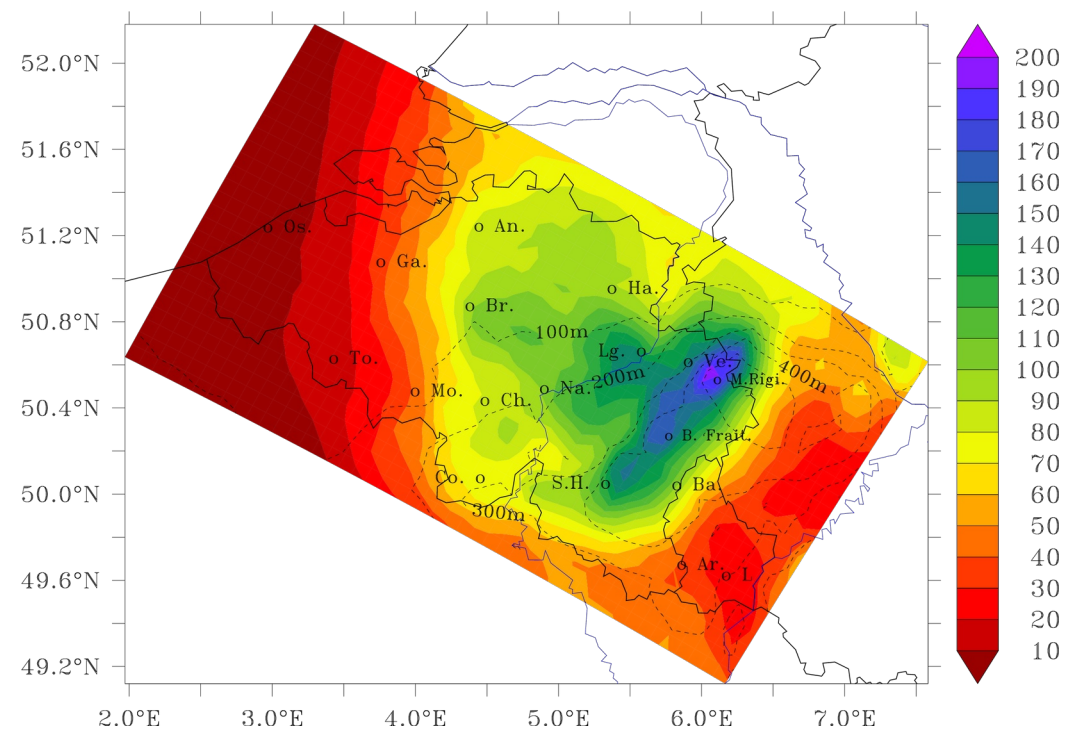
3. Simulation of (extreme) precipitation linked to local topography (barrier) or convective events.

Can we have again this kind of event ?

The same event simulated by MPI vs MAR-MPI



*Precipitation over 31 JUL – 02 AUG 2034
from MPI-ESM1-2-HR (ssp585)*

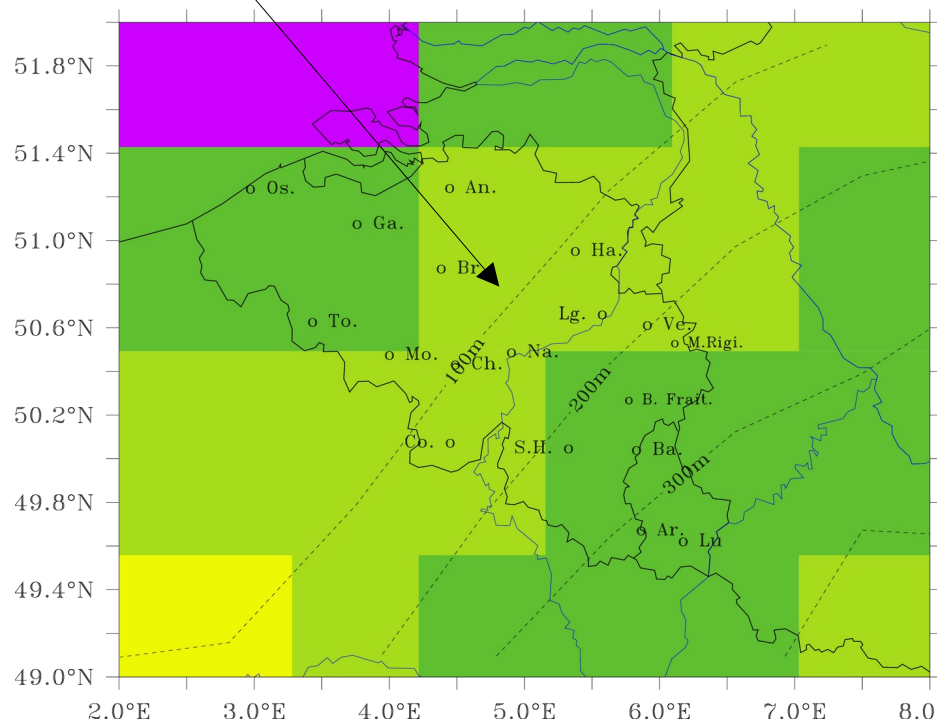


*Precipitation over 31 JUL – 02 AUG 2034
from MAR forced by MPI-ESM1-2-HR (ssp585)*

3. RCM added values (4)

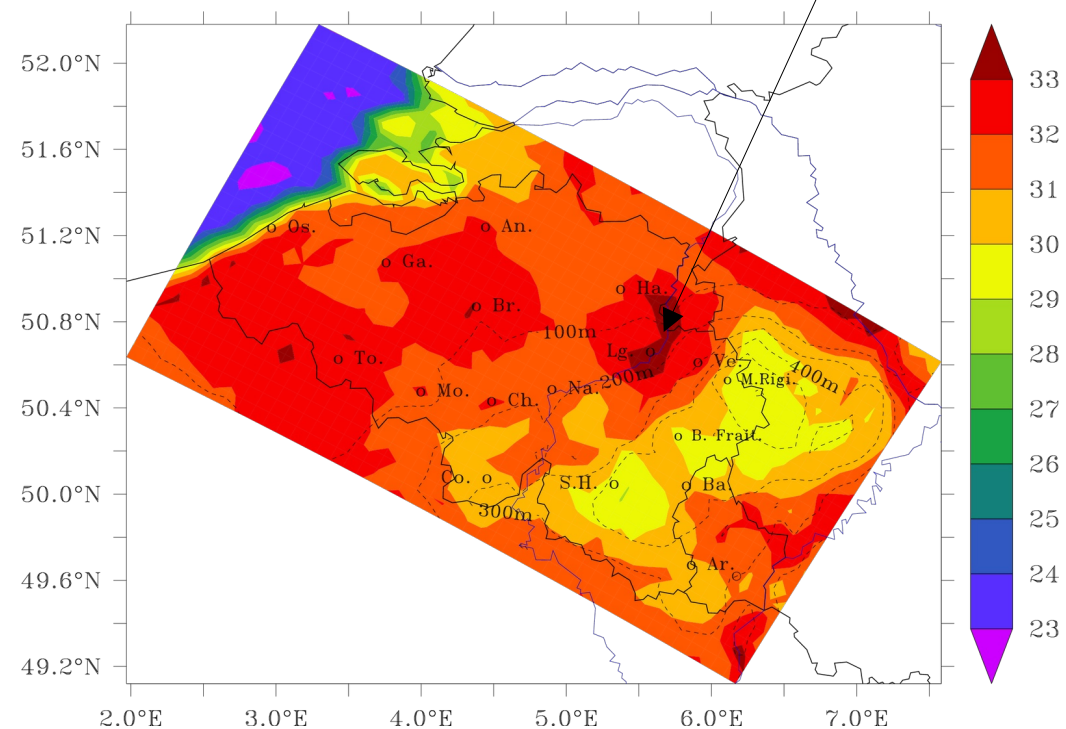
4. Heat waves, droughts, ... and links to complex land use + ability to correct GCM biases in the planetary boundary layer.

MPI-ESM1-2-HR is too cold



*Tmax in Summer 2034
from MPI-ESM1-2-HR (ssp585)*

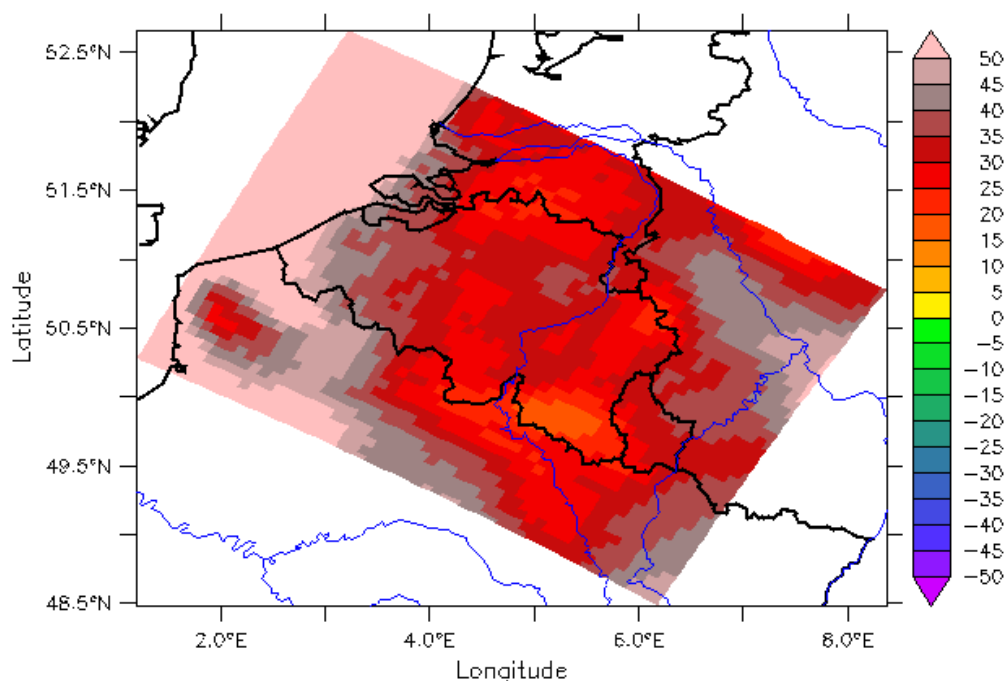
urban heat island effect



*Tmax in Summer 2034
from MAR forced by MPI-ESM1-2-HR (ssp585)*

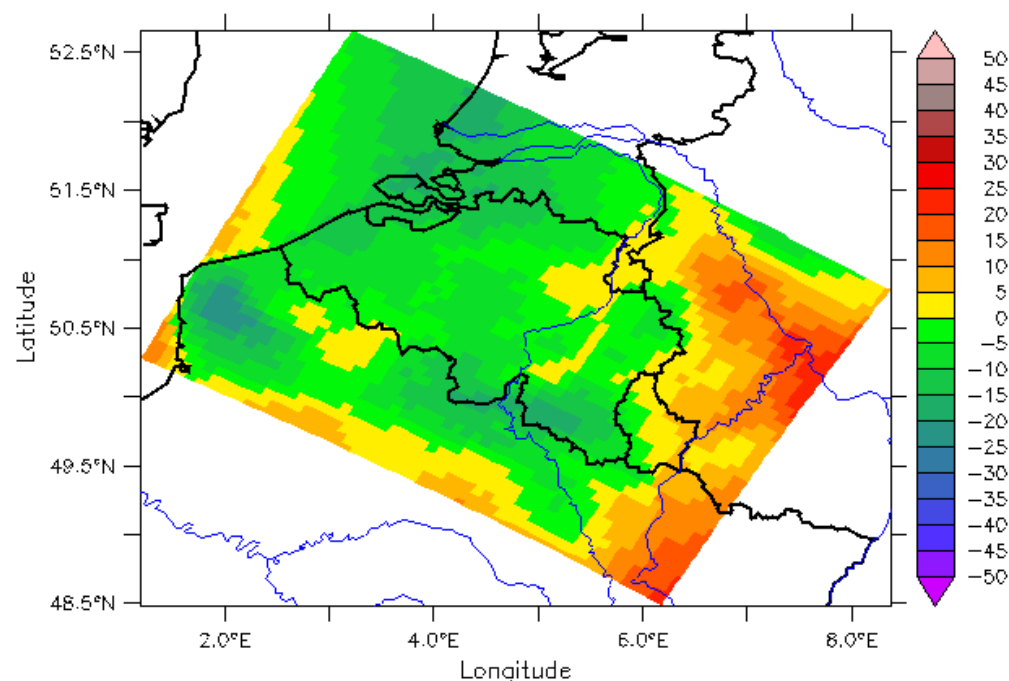
4. RCM drawbacks (1)

1. RCM is not able to correct large scale biases meaning that driving large scale LBC should be of good quality (or corrections is needed)



Precip (%)

Amount of precipitation simulated
by MAR forced by MIROC6 (1981-2010)
vs
MAR forced by ERA5 (1981-2010)



Precip (%)

Amount of precipitation simulated
by MAR forced by MIROC6 (1981-2010)
vs
MAR forced by ERA5 (1981-2010)

*Humidity – 2% at LBC
Temperature – 1°C*

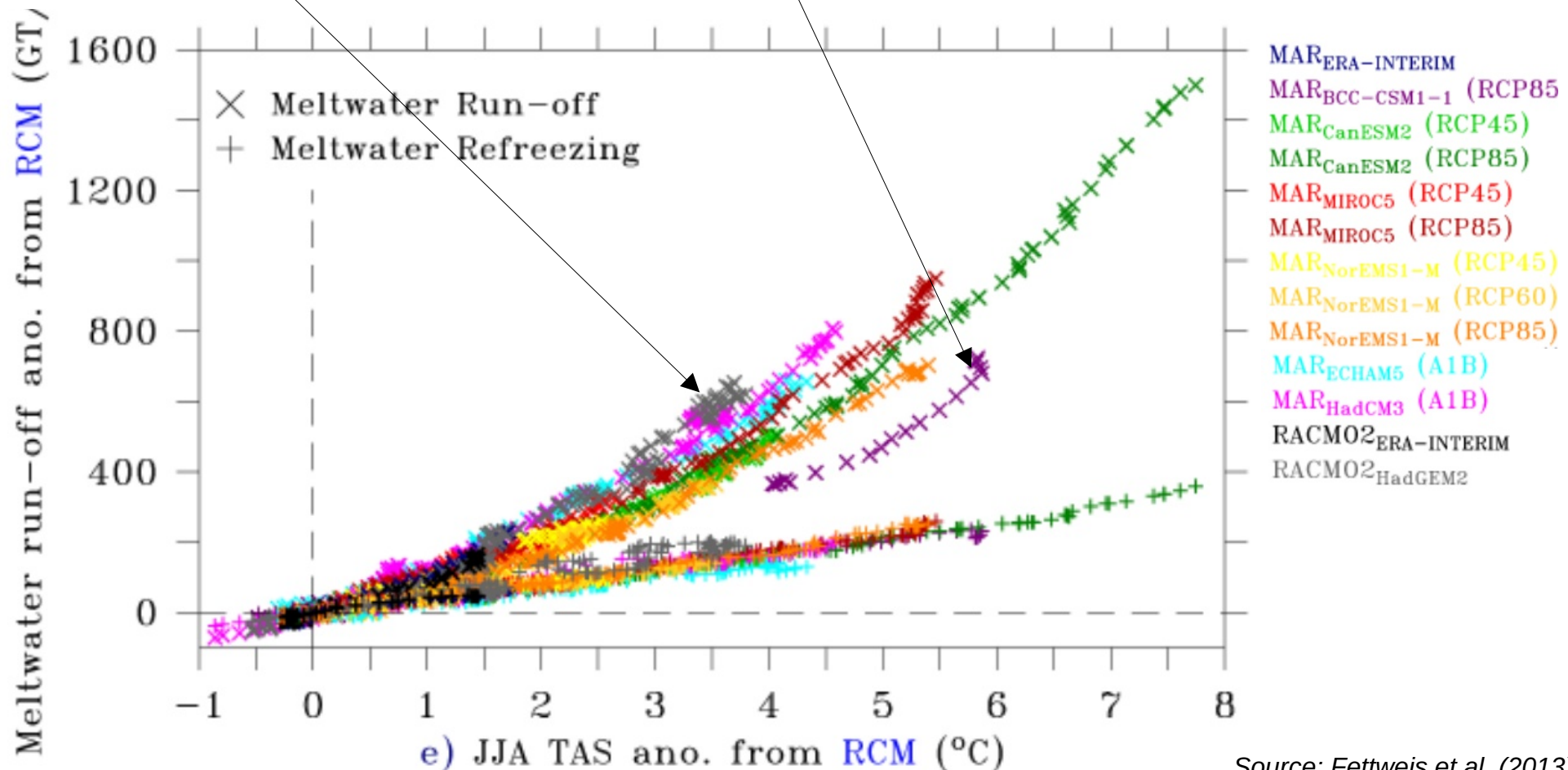
4. RCM drawbacks (1)

1. RCM is not able to correct large scale biases meaning that driving large scale LBC should be of good quality (or corrections is needed)

Response of the melt over the Greenland ice sheet vs temperature anomaly

Simulation too warm over current climate

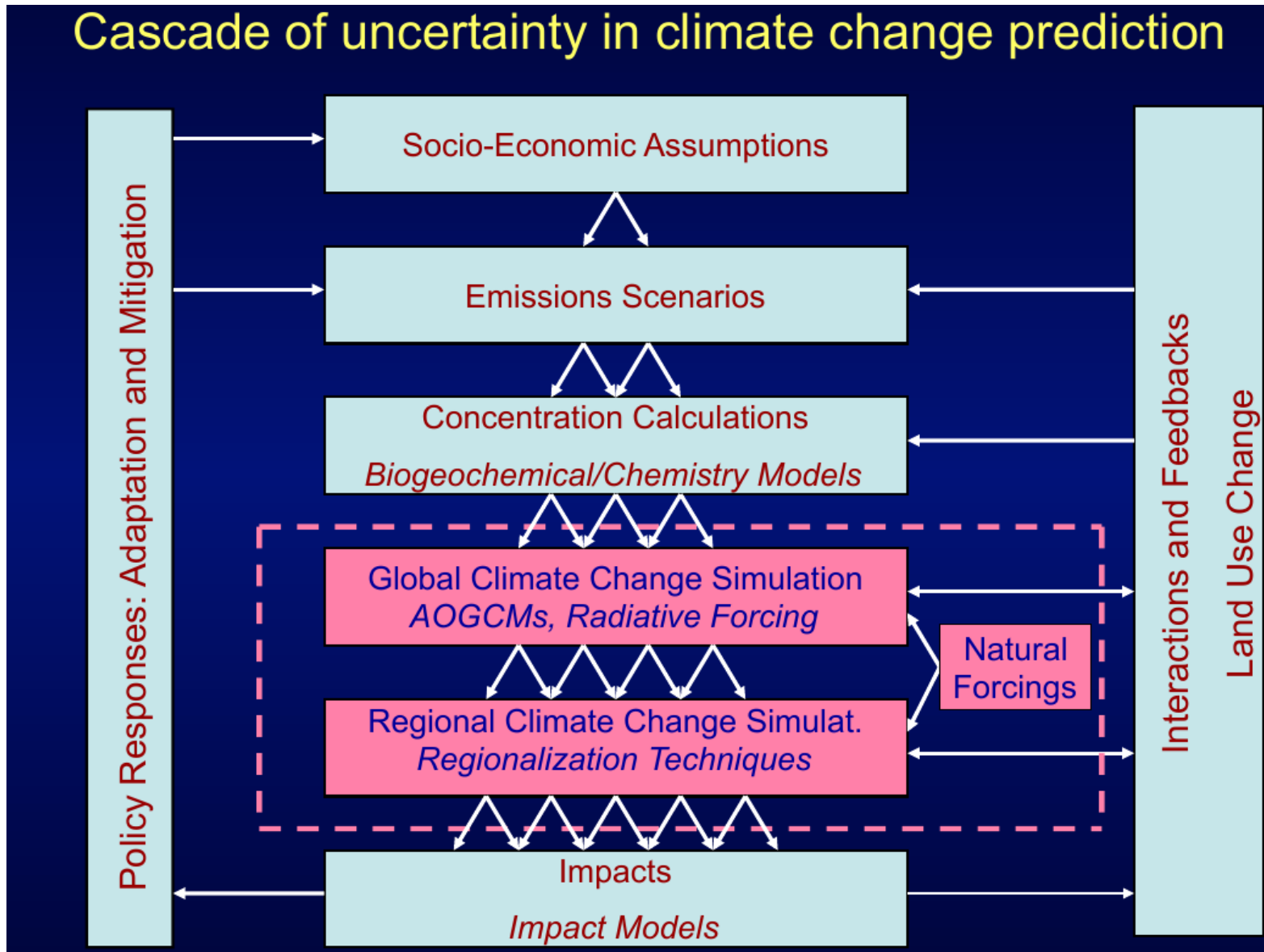
Simulation too cold over current climate



Source: Fettweis et al. (2013)

4. RCM drawbacks (2)

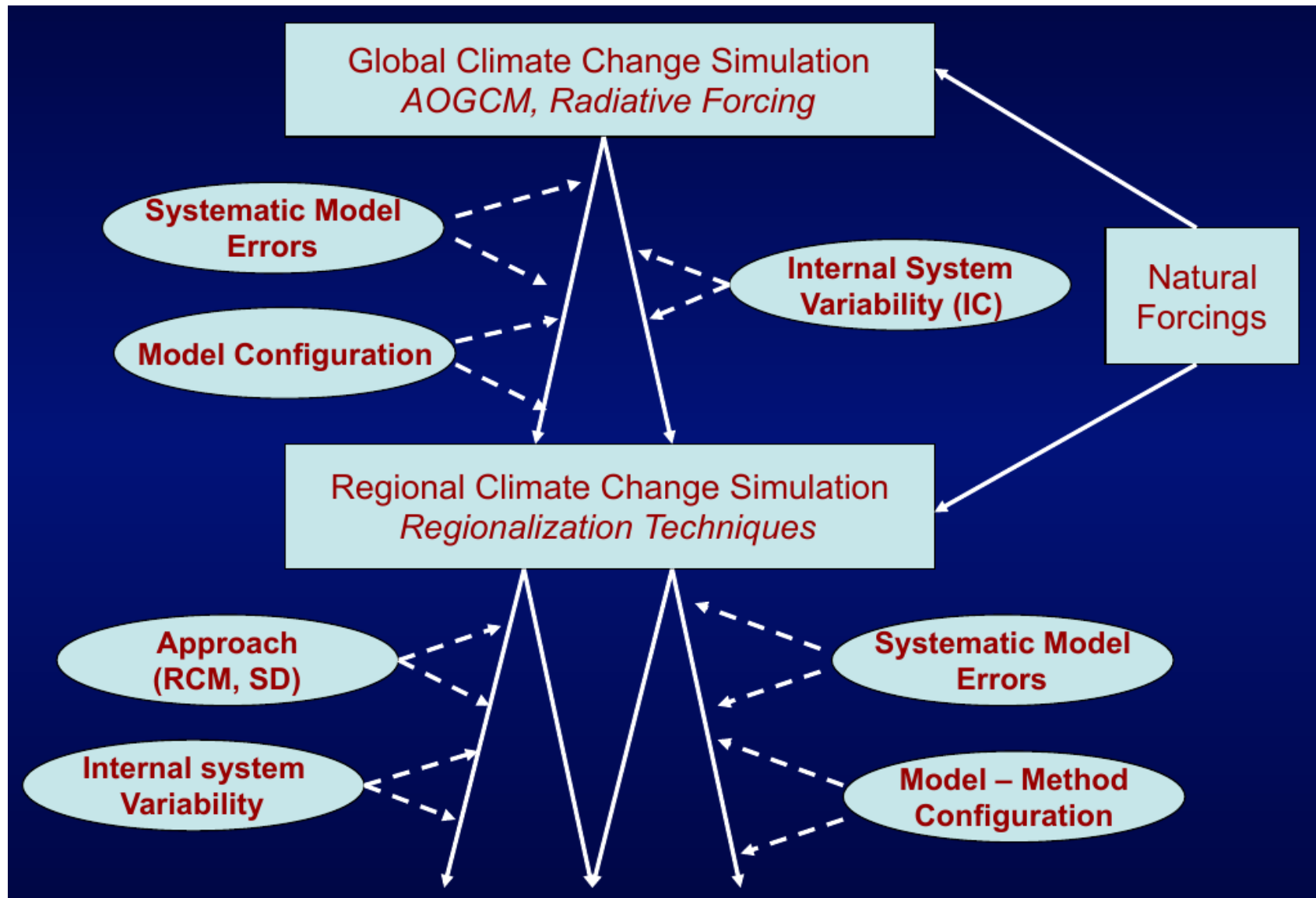
2. Additional computer time and uncertainties for future projections



Source:
Giorgi (2018)

4. RCM drawbacks (2)

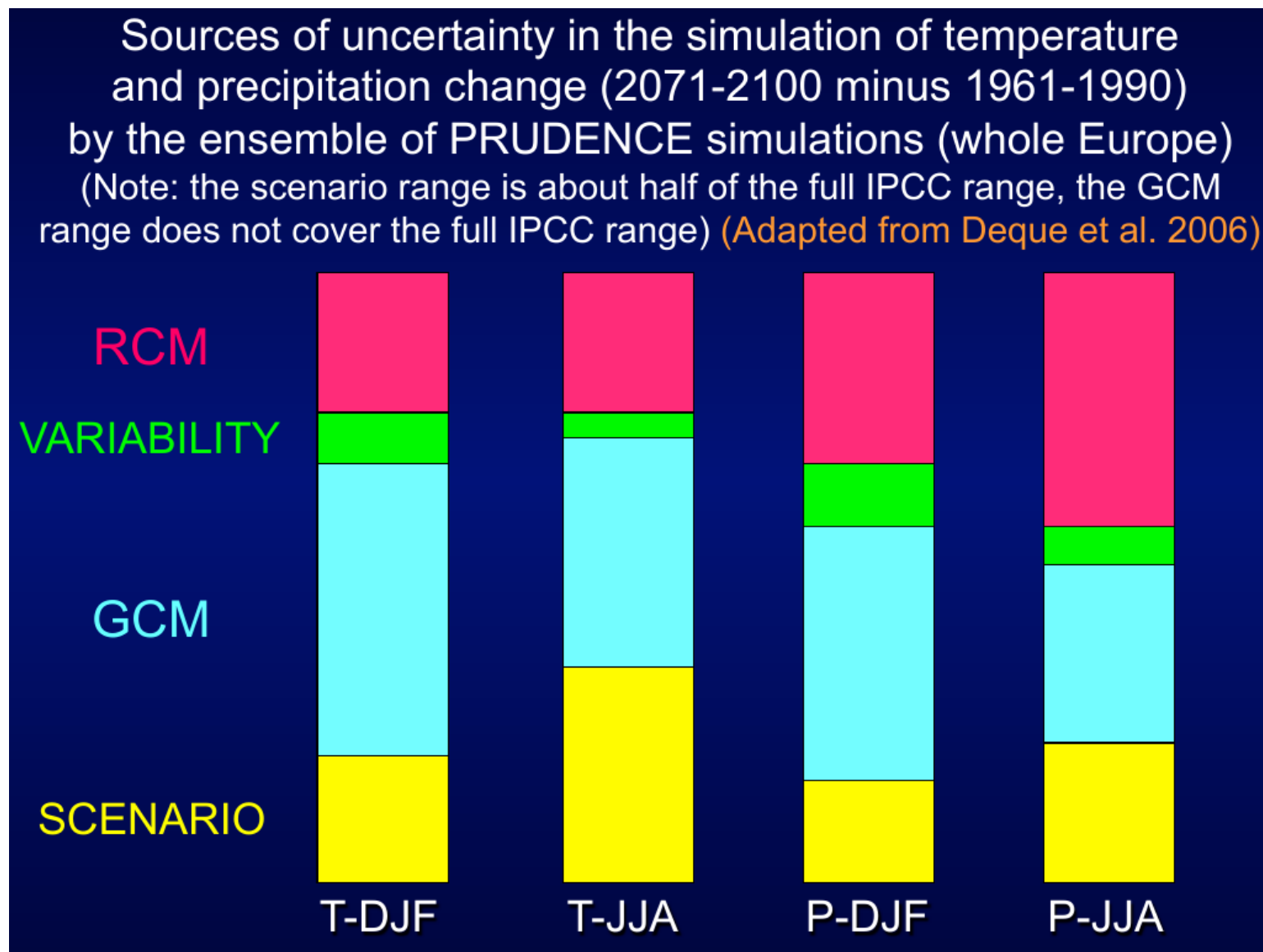
2. Additional computer time and uncertainties for future projections



Source:
Giorgi (2018)

4. RCM drawbacks (2)

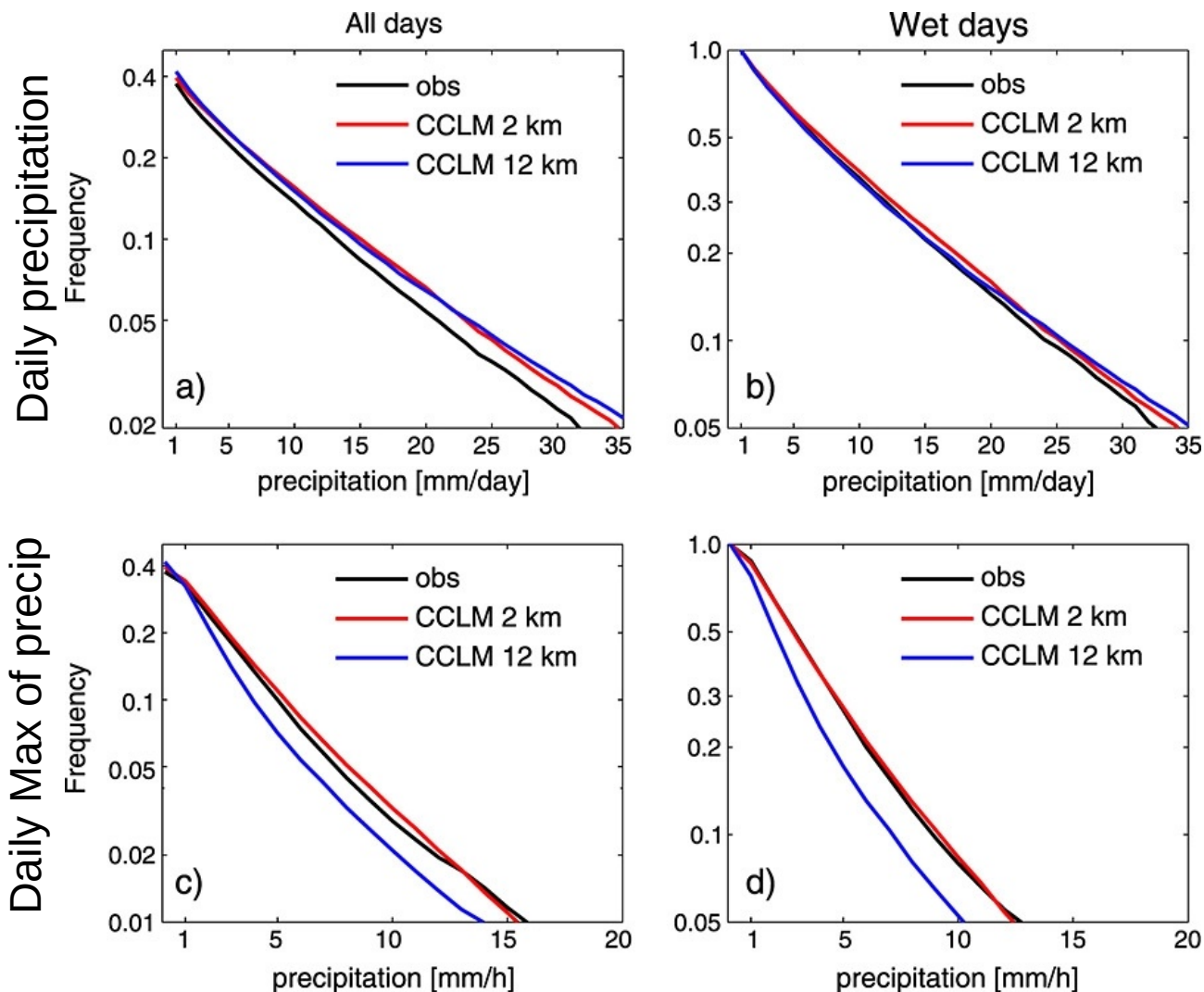
2. Additional computer time and uncertainties for future projections



Source:
Giorgi (2018)

5. RCM next steps (1)

1. Go towards resolution < 5km allowing to explicitly simulate convection (convection-permitting modelling)



Convection permitting models can improve the simulation of precipitation at sub-daily scales

(Prein et al. GRL; 2015)
(Van de Vyver, Journal of Applied Meteorology and limatology, 2021)

Source: Prein et al. (2015)

5. RCM next steps (2)

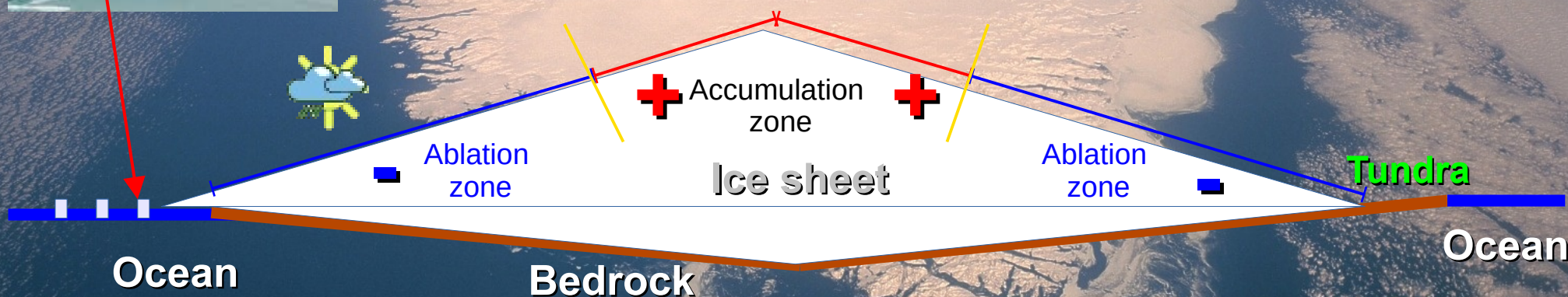
2. Coupling with other (regional) models

For simulating the Greenland ice sheet, MAR (simulating atmosphere and near surface snowpack) has been coupled with

- an ice sheet model (simulating the ice dynamics)
- the regional ocean model NEMO around Greenland

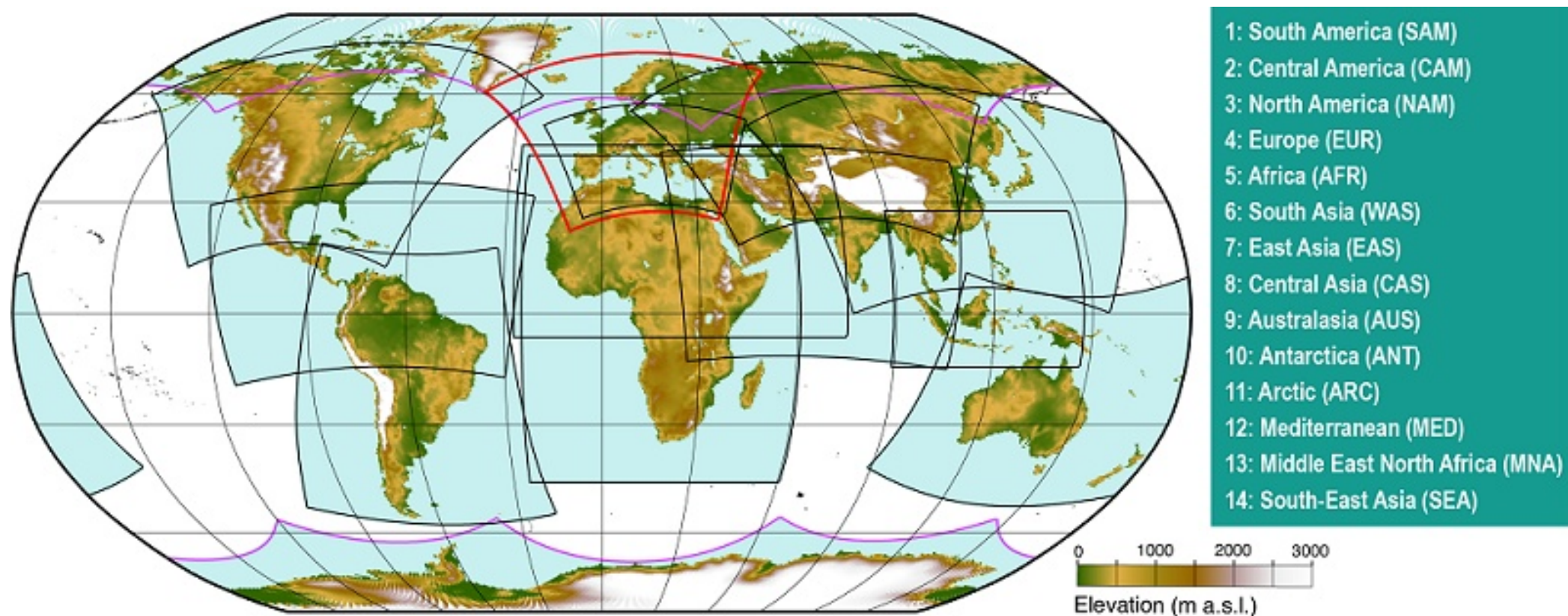
In this area,

- MAR simulates the surface melt
- the ice sheet model produces icebergs (fresh water flux) and glacier advance
- the ocean model produces the basal melting



5. RCM next steps (3)

3. The CORDEX exercises: ensemble of RCMs for specific areas



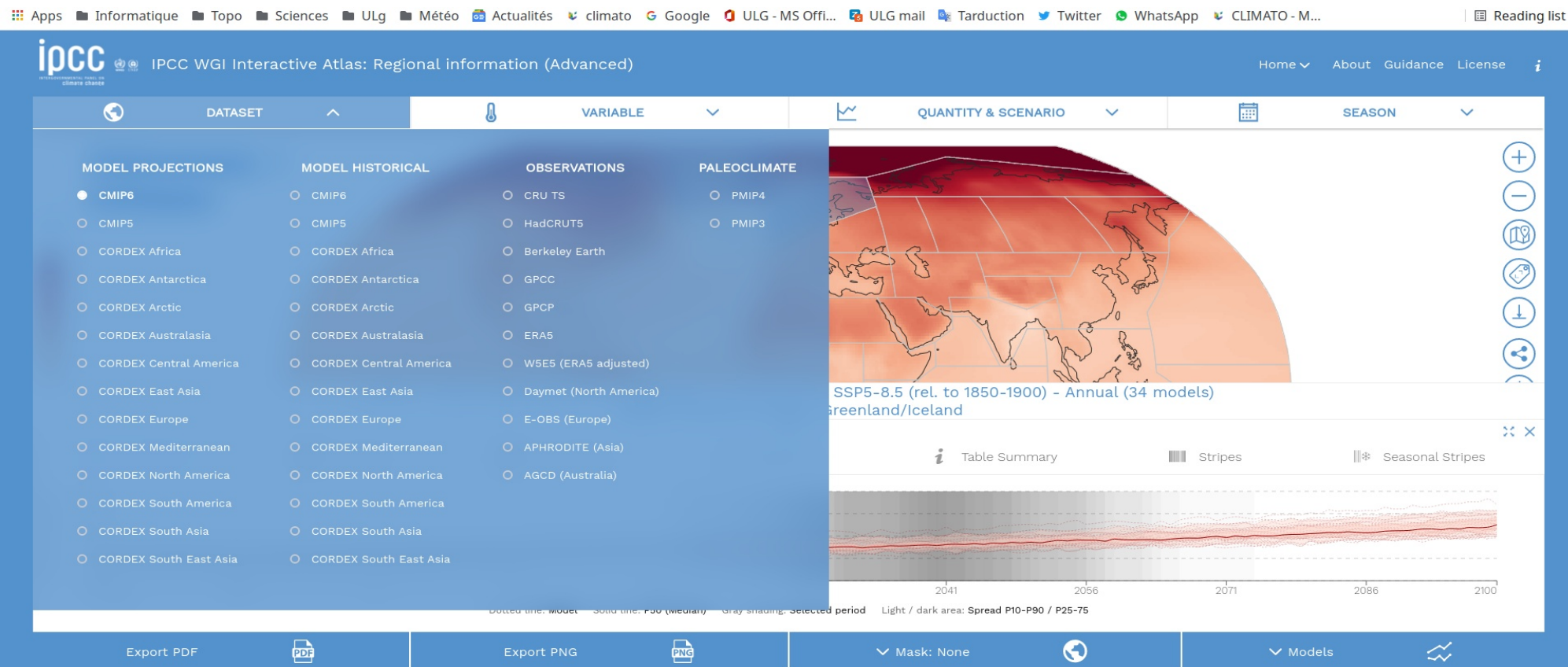
Domains, resolutions (25 or 12.5km), variables, forcings, ... are fixed and used by an ensemble of RCMs

See: <https://cordex.org/>

CORDEX = **CO**ordinated **R**egional climate **D**ownscaling **EX**periment

5. RCM next steps (3)

3. The CORDEX exercises: ensemble of RCMs for specific areas



The CORDEX outputs are used by the **IPCC AR6 atlas**: <http://interactive-atlas.ipcc.ch> but the CORDEX runs use yet the old CMIP5 based scenarios.

6. Conclusions

- Regional modelling has matured in the last decades and has become an **important tool for regional climate studies**.
- Users of RCMs need to be aware of a number of **technical issues**, which need to be well understood (LBC, domain configurations, added values)
- The main new directions in regional climate modelling are the development of **coupled Regional Earth System Models** and very high resolution, cloud resolving models.
- **CORDEX** has become the main international framework for RCM research

The GCMs community want to withdraw the use of RCMs because of

- the additional computer times and uncertainties.
- the GCM ability to reach the resolution of RCM.

BUT

- the problem of using the same physics everywhere will remain.
- the coupling with other models is very expensive and relevant for specific areas (e.g. the polar regions).
- RCM can correct biases over current climate before performing future projections