

Exploring the Mediterranean Climate through Regional Climate Modelling

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MEDUSSE COST Action
Outreach Event
Limassol - Cyprus



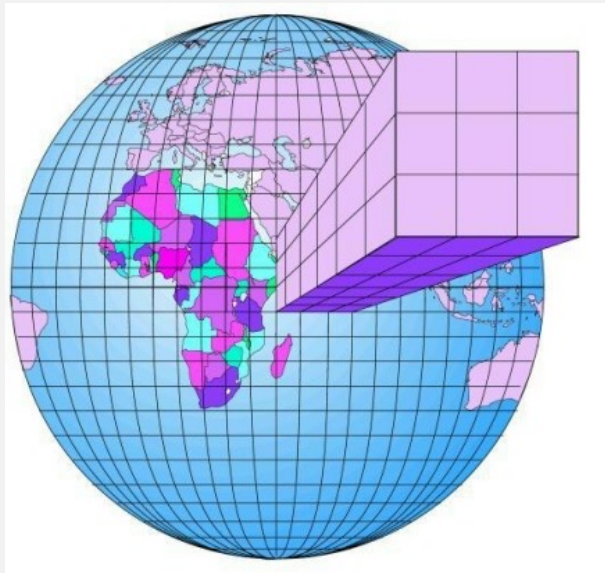
The Abdus Salam
International Centre
for Theoretical Physics



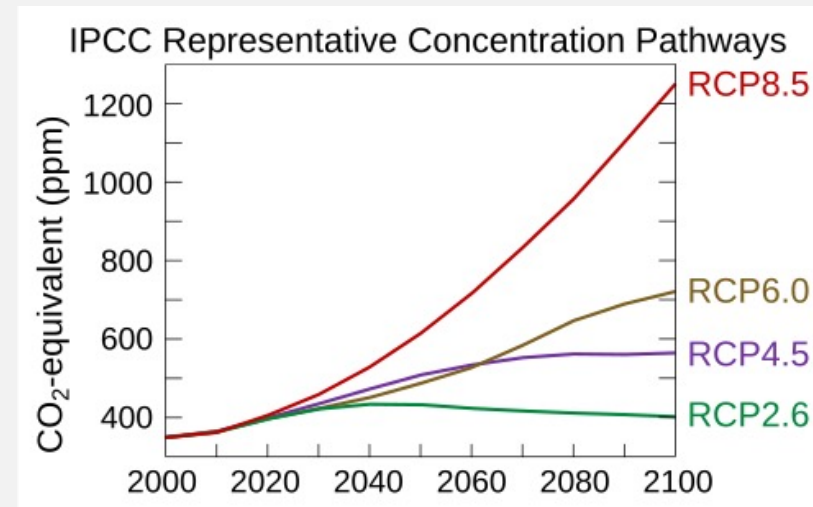
Climate projections

Numerical simulations of the Earth's climate system over future decades to centuries

Climate models



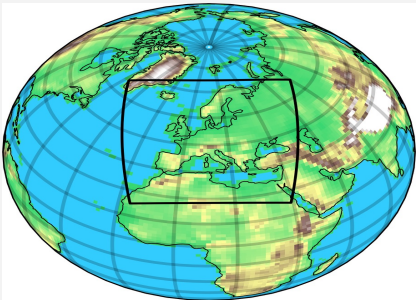
Emission scenarios



Why regional climate modelling?

Why do we need regional climate models if we already have global climate models?

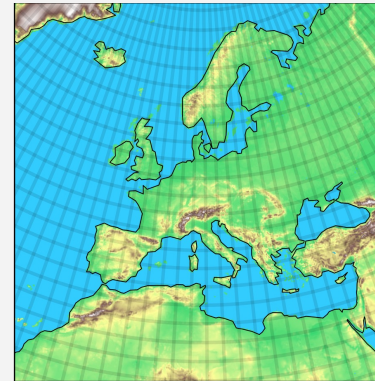
GCMs: Large-scale climate,
Global consistency



Global climate forcing:

- circulation,
- greenhouse gases,
- large-scale warming

RCMs: Regional climate



→ Need for physically
consistent regional
climate information

- Complex topography
- Coastlines & land–sea contrasts
- Mesoscale processes
- Climate extremes

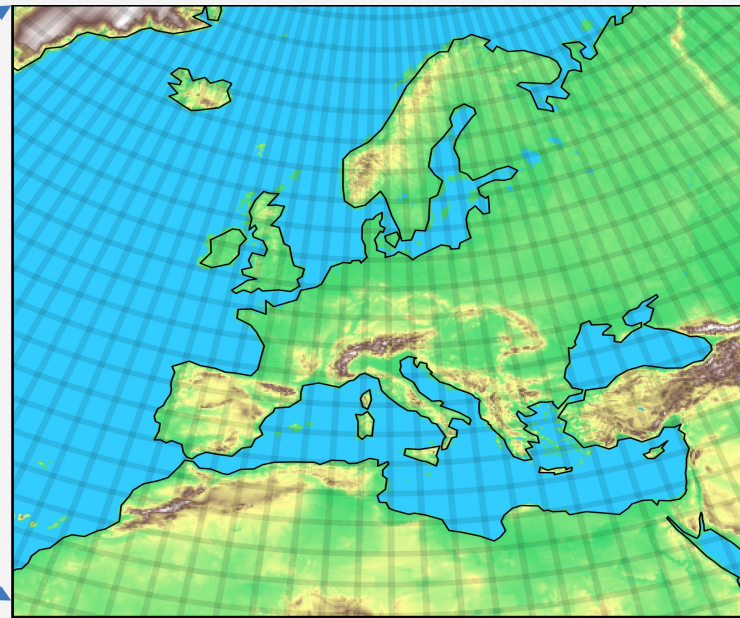
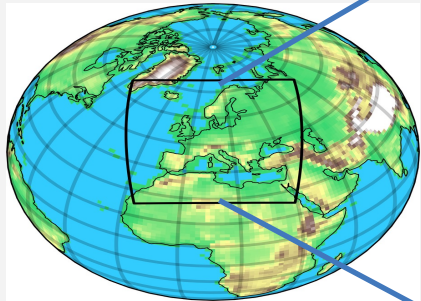
Dynamical downscaling: how does it work?

From large-scale forcing to regional processes

LARGE-SCALE FORCING

REGIONAL MODEL

GCM / Reanalysis



Atmospheric dynamics
Radiation
Clouds & convection
Land-surface processes

Physical parameterizations

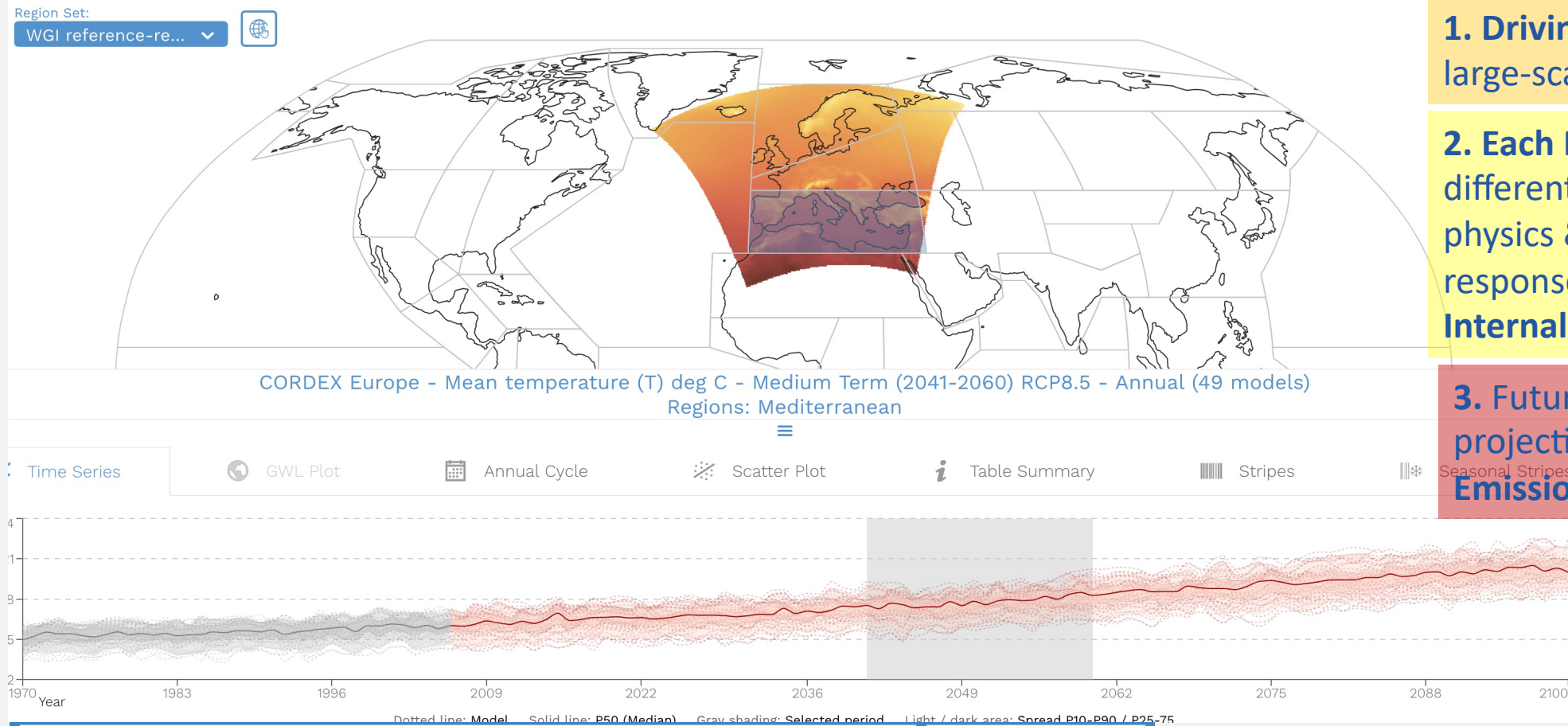
REGIONAL RESPONSE

Dynamical downscaling $\neq$ spatial interpolation

Lateral Boundary Conditions
(wind, temperature, humidity,
pressure / geopotential)

Ensemble approach against uncertainty

One simulation is not enough!



1. Driving GCM
large-scale response

2. Each RCM has
different
physics & regional
response:
Internal variability

3. Future
projections:
Emission scenario

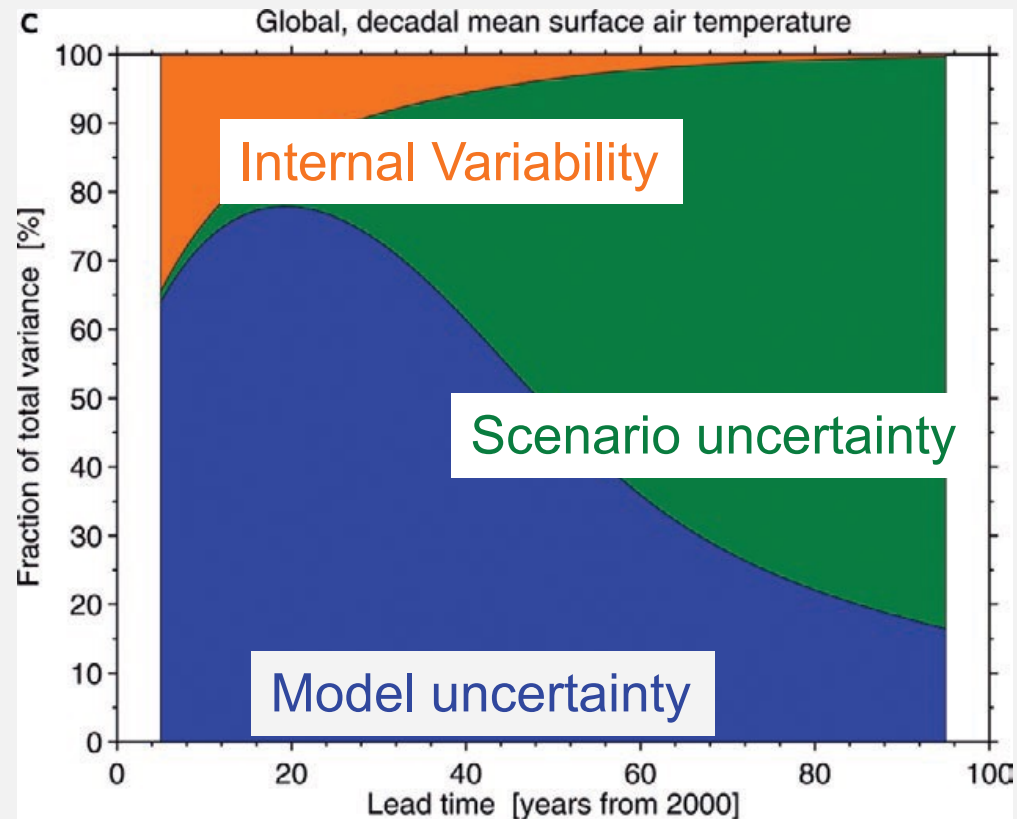
Mean temperature (T) - (deg C)
Medium Term (2041-2060) (RCP8.5)
CORDEX Europe - Annual (49 models)-Mediterranean

One simulation is not enough

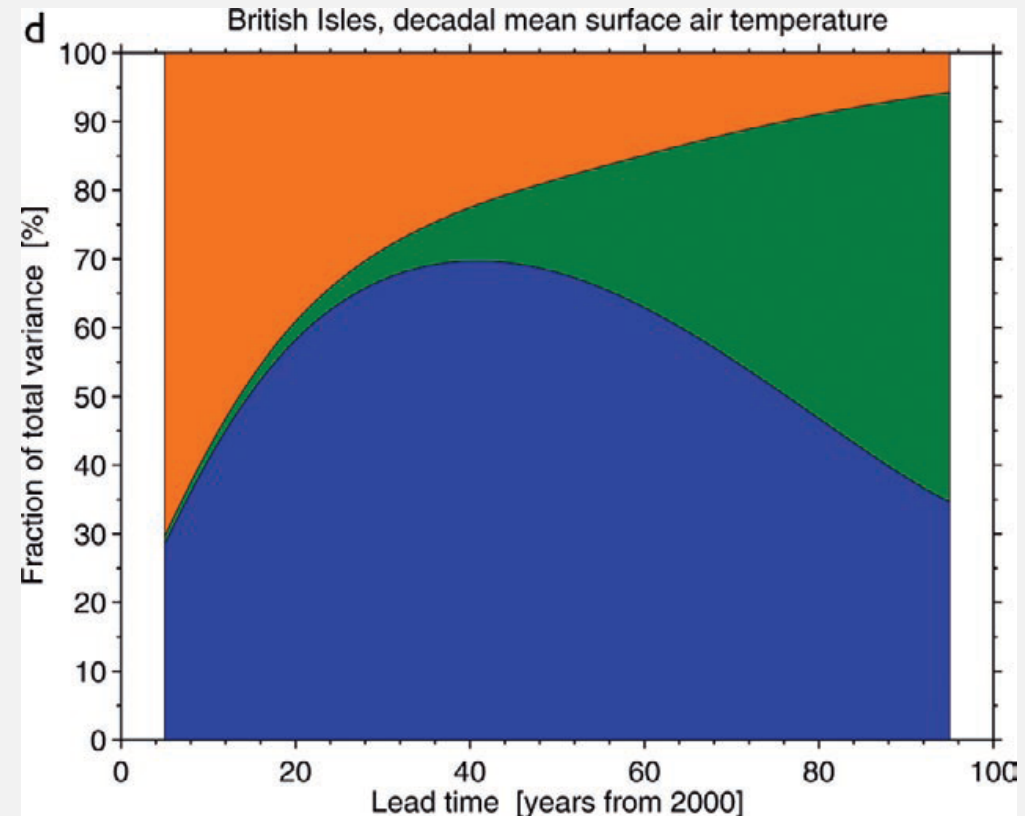
Ensemble approach for uncertainty estimate

Global

Decadal temperature



Regional



Does resolution matter?

From RCMs to convection-permitting models

GCM	RCM	CP RCM
~100 km	~10–50 km	~1–5 km
large-scale circulation	topography/coasts	convection
broad climate signal	regional gradients	local extremes



CONVECTION PARAMETERIZED

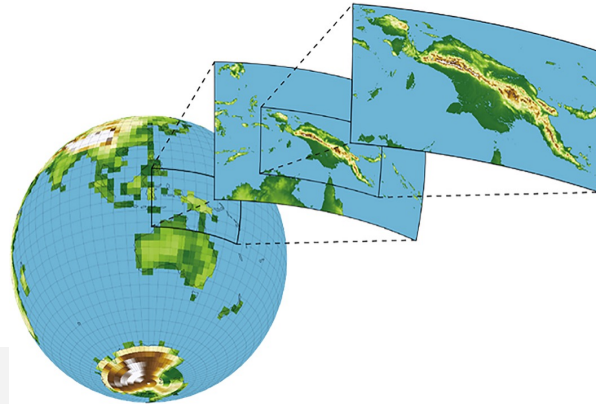


EXPLICIT CONVECTION!

WHY CONVECTION? **Extreme precipitation** is unusually intense or prolonged rainfall events, often linked to **convective** systems. These events can cause floods, landslides, and other socio-economic impacts.

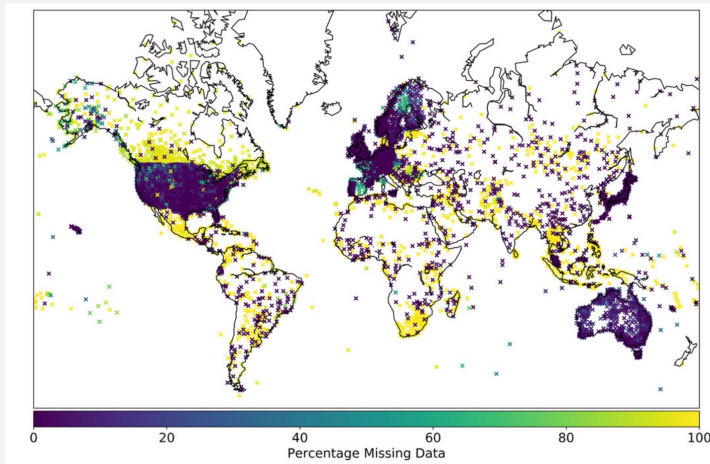
What do we need for CP climate modelling?

❖ Boundary conditions



❖ Telescopic nesting
Most common:
(two-step nesting strategy)

❖ Observations to evaluate the results



From Lewis et al., [2019](#)

- ❖ Different spatial distribution
- ❖ % of missing data

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

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

Does resolution matter?

From RCMs to convection-permitting models

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CONVECTION PARAMETERIZED



EXPLICIT CONVECTION!

WHY CONVECTION? **Extreme precipitation** is unusually intense or prolonged rainfall events, often linked to **convective** systems. These events can cause floods, landslides, and other socio-economic impacts.

- convective organization

- precipitation intensity

- diurnal cycle

- sub-daily extremes

Why is the Mediterranean an ideal RCM laboratory?



- ❖ Complex orography
- Land–sea contrasts
- ❖ Small and semi-enclosed
- Mediterranean Sea
- ❖ Mesoscale circulation
- ❖ Convective precipitation
- ❖ Air–sea interactions
- ❖ Climate extremes



<https://equal-earth.com/physical/>

Why is the Mediterranean an ideal RCM laboratory?

Cyclones

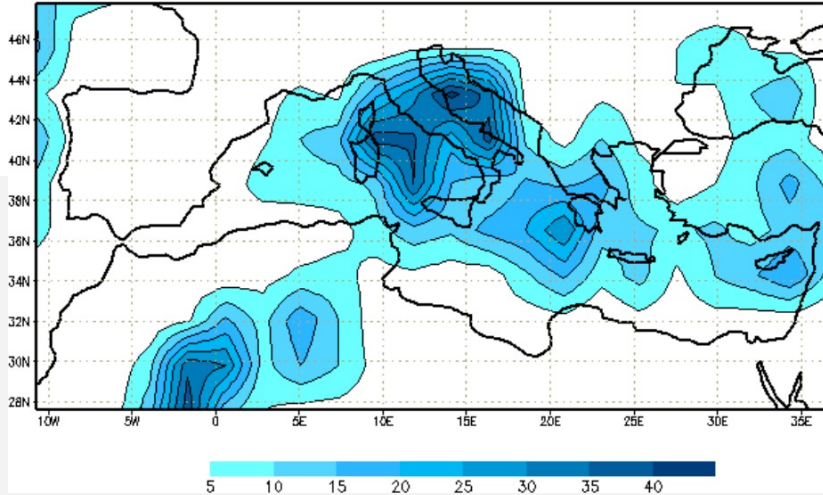


Figure 1. Number of intense cyclones over the 45 years of the ERA-40 period at mature stage per squares of $2.25^\circ \times 2.25^\circ$ (Flaounas et al. 2022)

Cyclone occurrences are more frequent in winter, with tracks located along the northern and central part of the Mediterranean basin, while in summer, cyclone occurrences become frequent over North Africa.

Regional winds

Mean Sea level Pressure (hPa) and mean Wind Direction (EIN75)

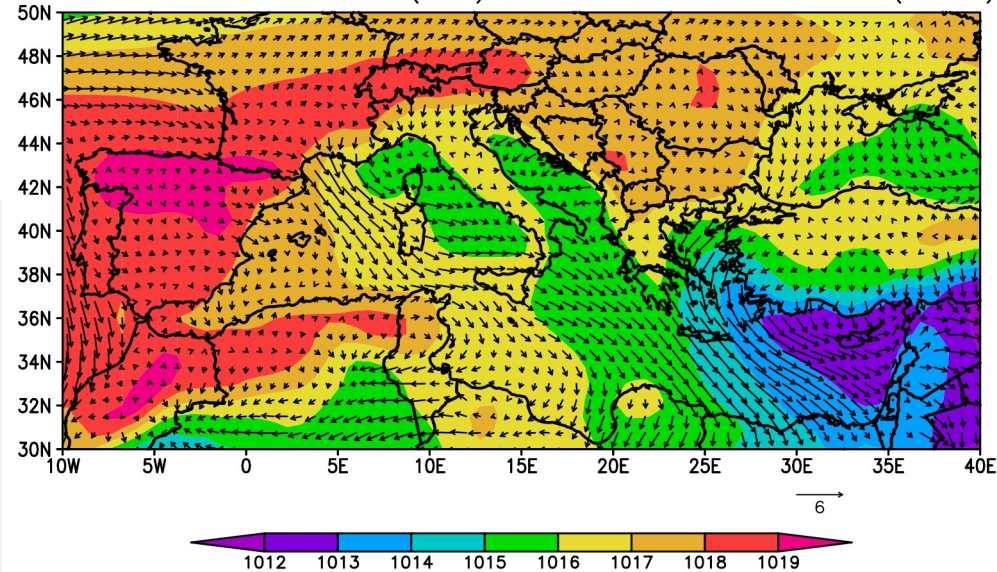


Figure 2. Annual mean sea-level pressure (color unit hPa) and near-surface (10 m) wind speed/direction (unit m s^{-1}) for the period 1979-2017 (Dulac et al. 2023)

Large islands, sharp land-sea contrasts and surrounding mountain chains such as the Alps, Dinarides, Apennines and Atlas strongly affect the atmospheric dynamics across spatial and temporal scales and in particular, the low-level air mass circulation and the regional winds

Why is the Mediterranean an ideal RCM laboratory?

Bathymetry

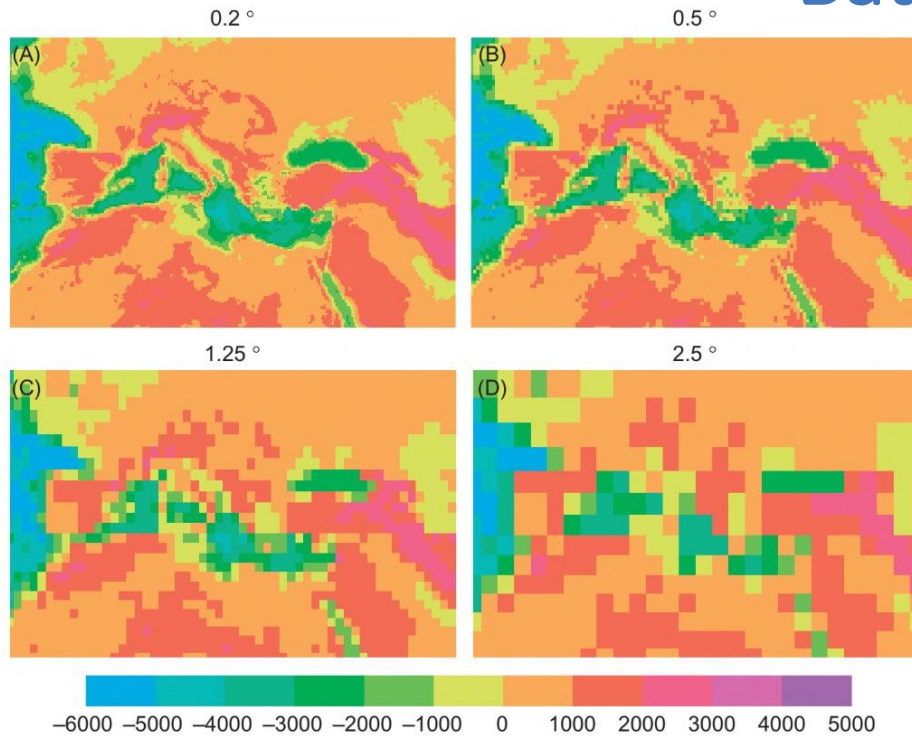


Figure I.3 Representation of bathymetry and topography of the Mediterranean region aggregating data in cells of increasing size: (A) 0.2°, (B) 0.5°, (C) 1.25°, and (D) 2.5°.

Figure from: Lionello et al. 2012

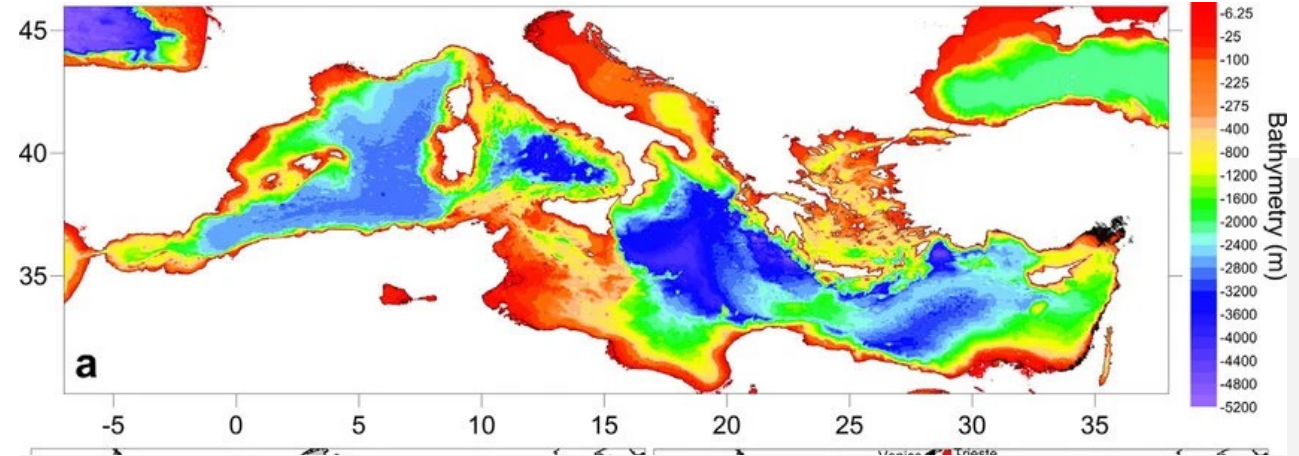
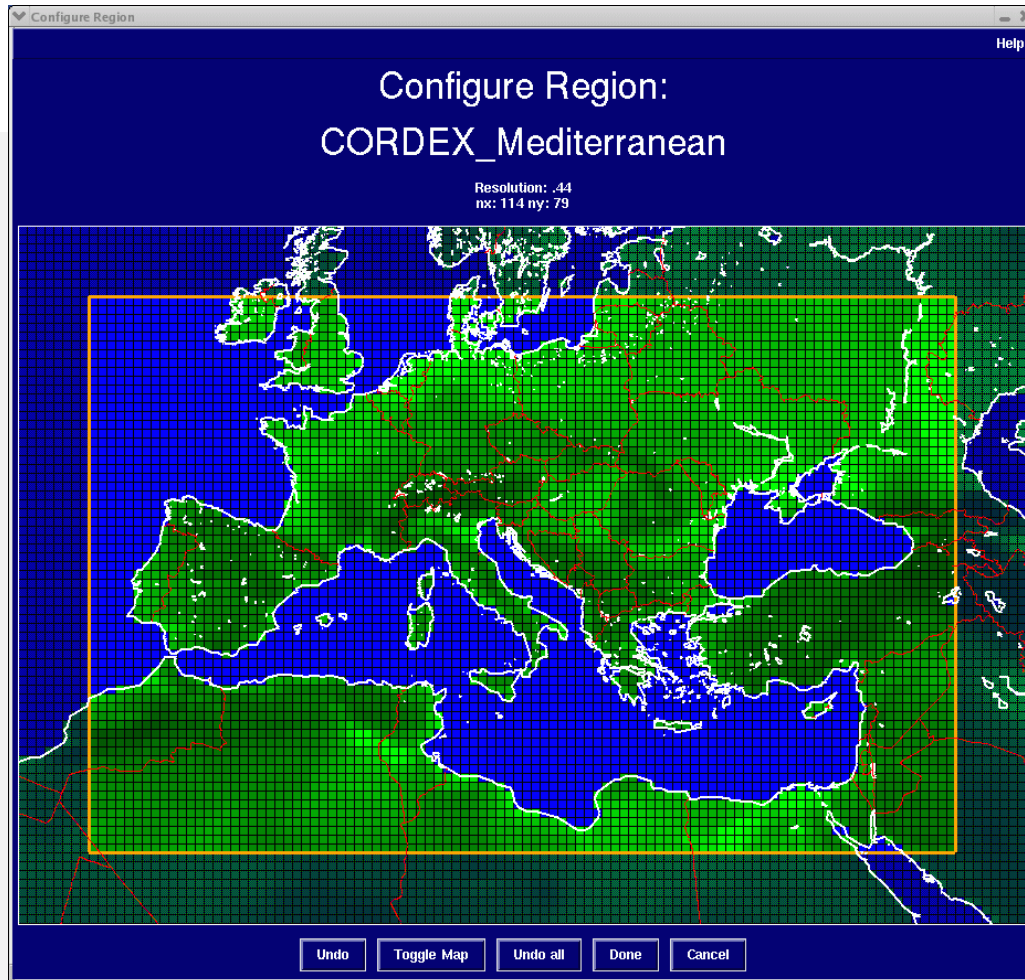


Figure from: Androulidakis et al. 2015

The bathymetry of the basin is also extremely complex, featuring narrow and shallow straits, gulfs, islands, and peninsulas that significantly affect the spatial patterns and intensity of the ocean circulation across different temporal and spatial scales.

How do we model the Mediterranean climate system?

The Med-CORDEX Initiative

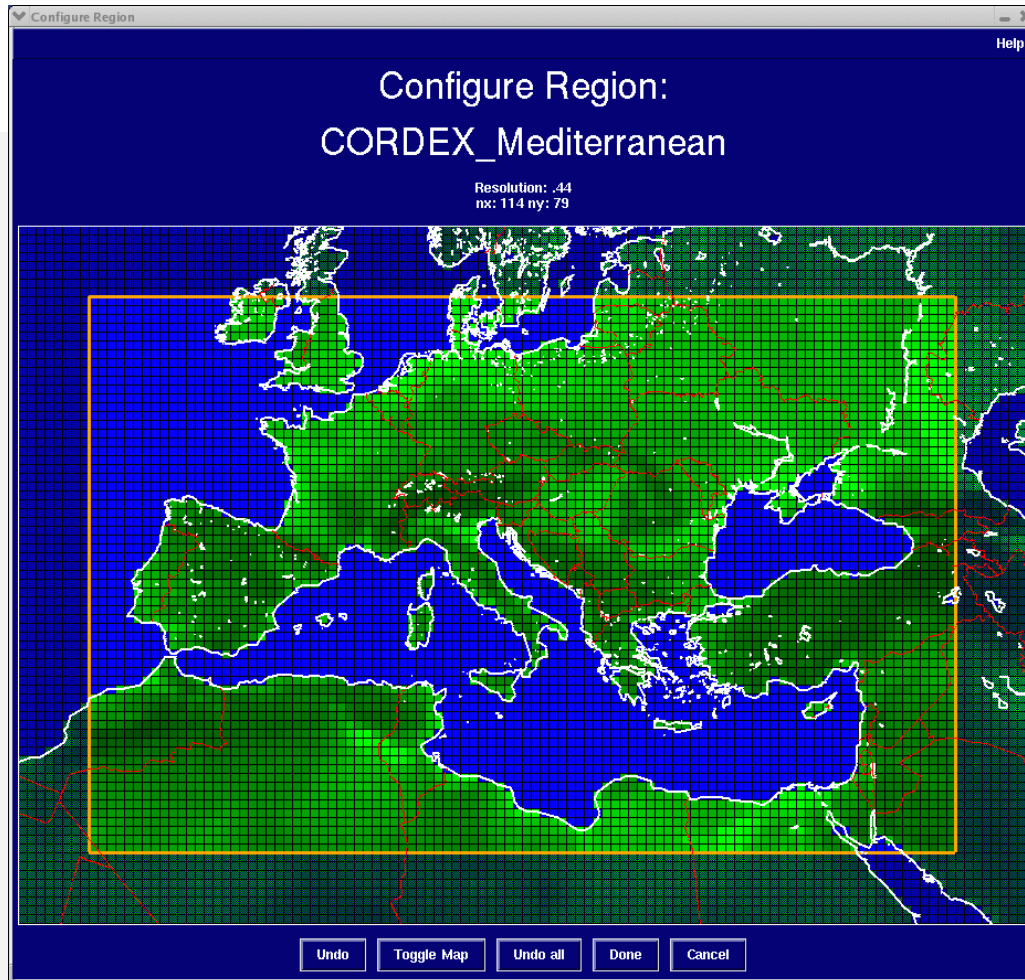


Why is Med-CORDEX special?

- ❖ A regional climate system approach : Med-CORDEX goes beyond atmosphere-only regional modelling by explicitly considering interactions among **atmosphere, ocean and land**.
- ❖ High-resolution, coordinated multi-model **experiments**: a common framework allows the comparison of different RCMs, driving GCMs and coupled configurations, helping assess model uncertainty and robustness.
- ❖ From processes to regional climate change: Med-CORDEX provides a framework to investigate how **fine-scale processes and regional feedbacks** influence Mediterranean climate variability, extremes and future change.

How do we model the Mediterranean climate system?

The Med-CORDEX Initiative



Participating Institutions by Country:

- **France:** CNRM (Centre National de Recherches Météorologiques), IPSL (Institut Pierre-Simon Laplace), and LMD (Laboratoire de Météorologie Dynamique).
- **Italy:** CMCC (Centro Euro-Mediterraneo sui Cambiamenti Climatici), ENEA, ICTP (International Centre for Theoretical Physics), and OGS.
- **Germany:** GUF (Goethe University Frankfurt) and AWI-GERICS (Alfred Wegener Institute / Climate Service Center Germany).
- **Spain:** UCLM (University of Castilla-La Mancha).
- **Serbia:** University of Belgrade.
- **Turkey:** ITU (Istanbul Technical University)

How do we model the Mediterranean climate system?

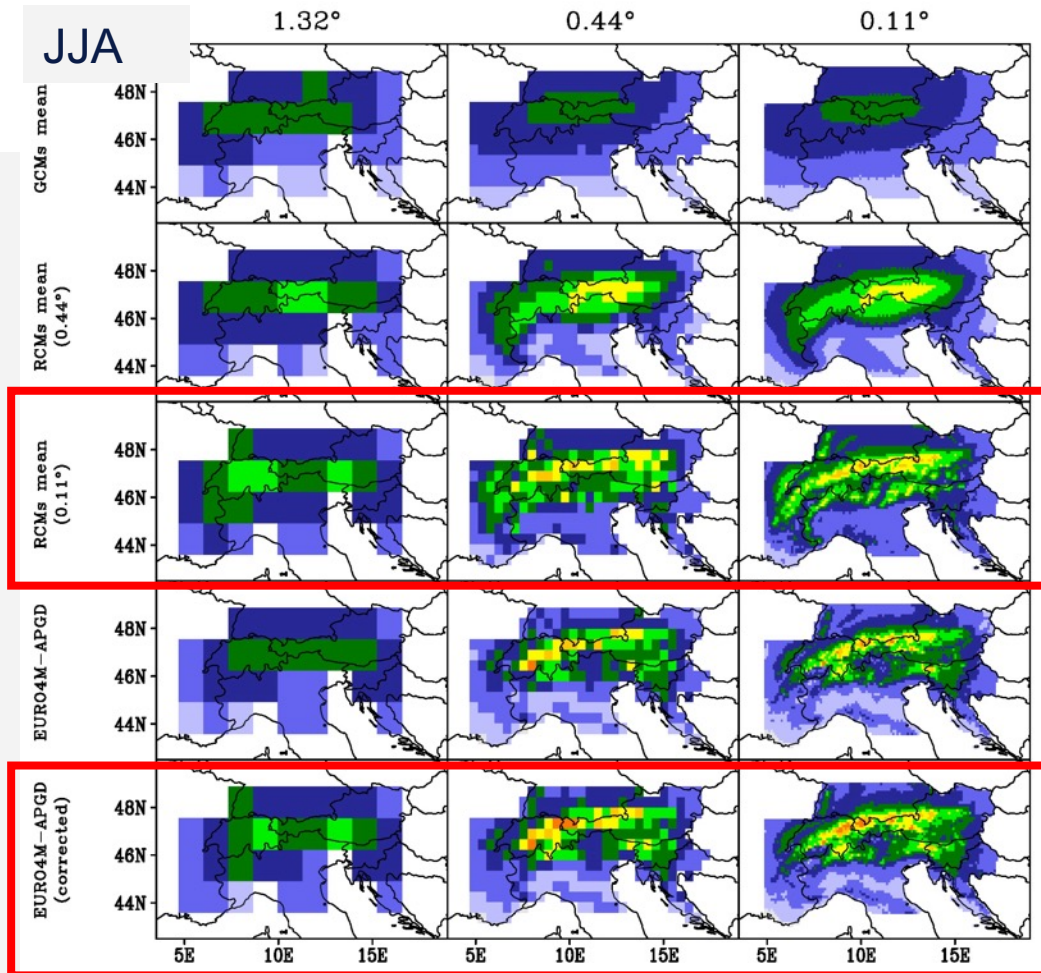
The Med-CORDEX Initiative

Institution	Atmospheric Component	Ocean Component	Common Characteristics
CNRM (France)	ALADIN	NEMO-MED	Advanced river routing (TRIP) to close the water cycle
CMCC/ENEA (Italy)	COSMO-CLM / RegCM	NEMO-MED / MITgcm	High-resolution sea-surface interactions
ICTP (Italy)	RegCM4	MITgcm	Standard and convection-permitting scales
GERICS (Germany)	REMO	MPlom	Adapted for high-latitude and regional sea coupling
Univ. of Belgrade (Serbia)	EBU-POM	POM (Princeton Ocean Model)	Strong in regional coupled coastal and basin physics

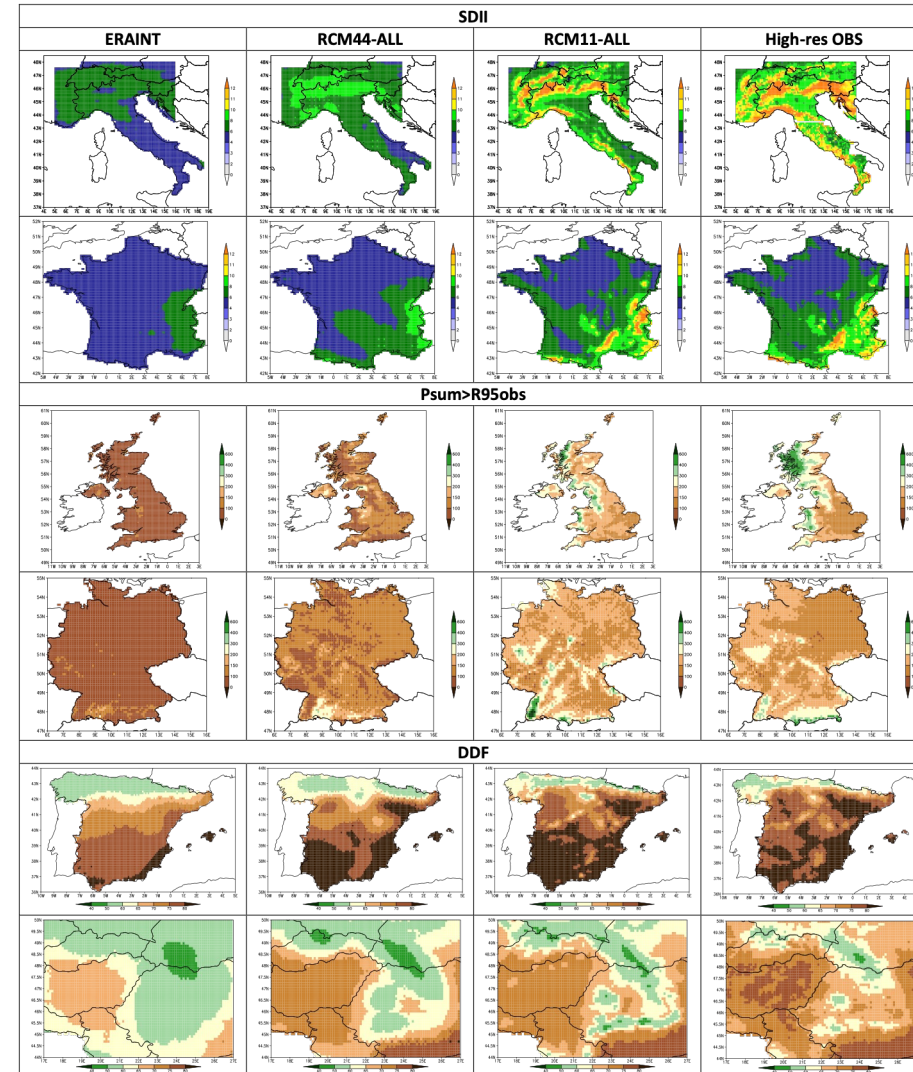
Med-CORDEX: main findings

High spatial resolution added value over land

Spatial pattern of precip



Torma et al. 2015



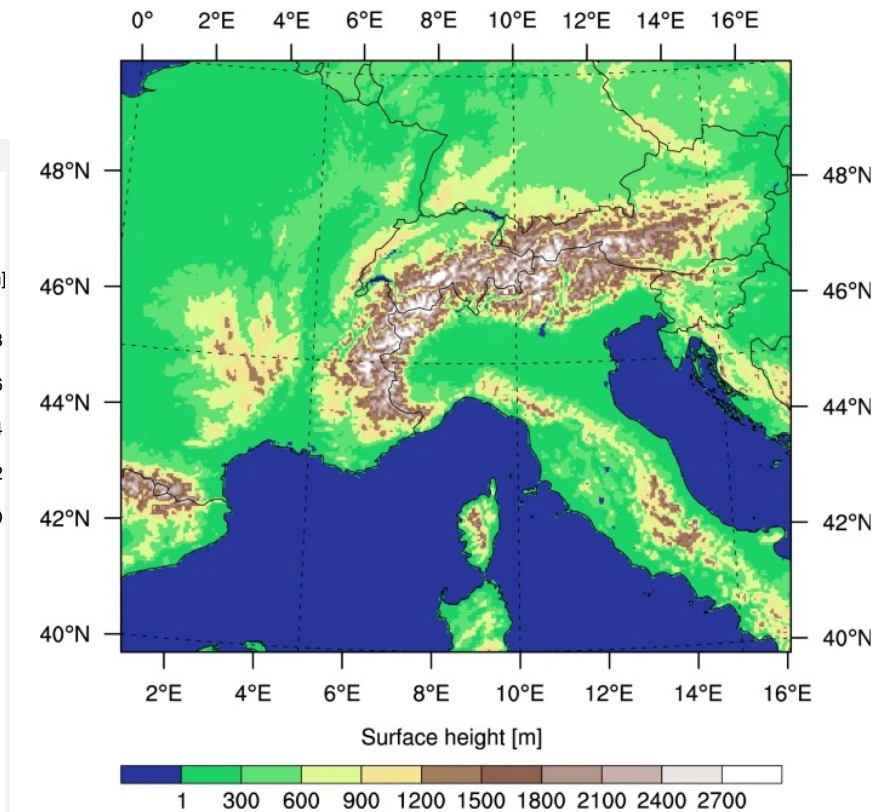
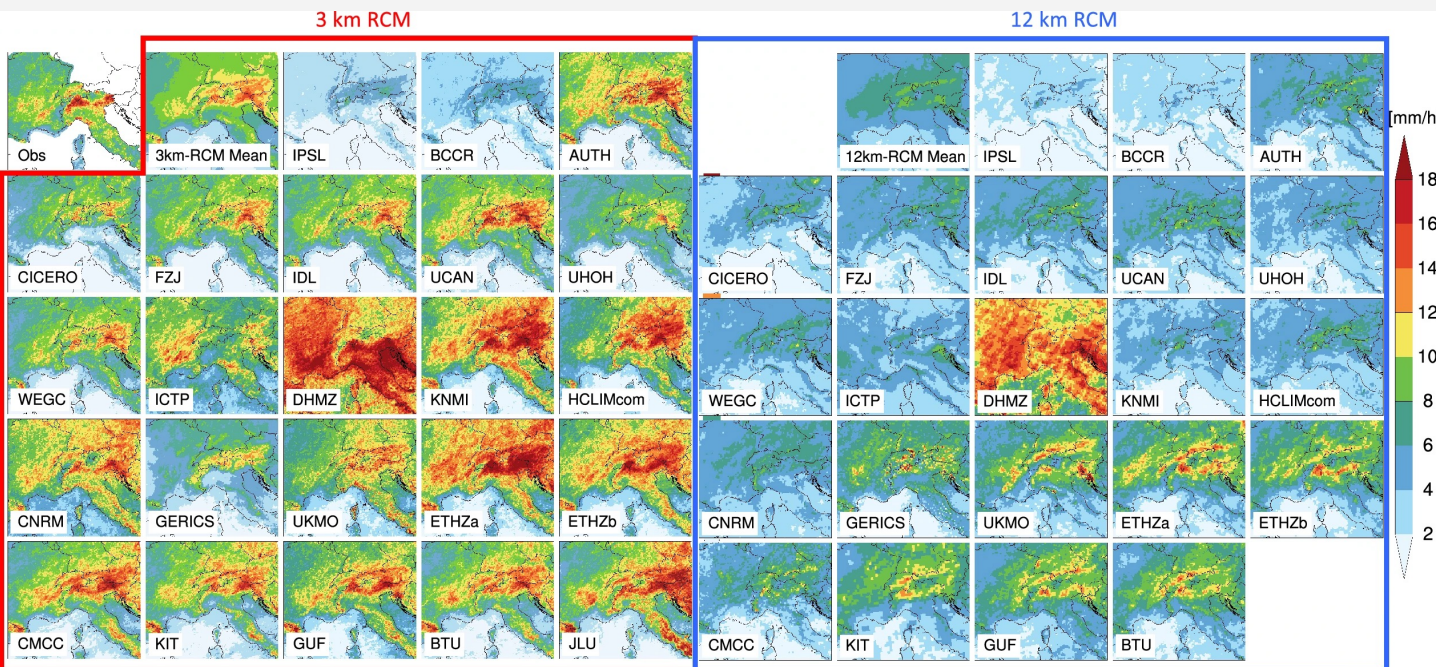
Fantini et al. 2018

Precip extremes

Med-CORDEX: main findings

High spatial resolution added value over land

Heavy hourly precipitation (p99.9)
in the summer season



(Ban et al., 2021)

☯ Med-CORDEX: main findings

High spatial resolution added value over ocean

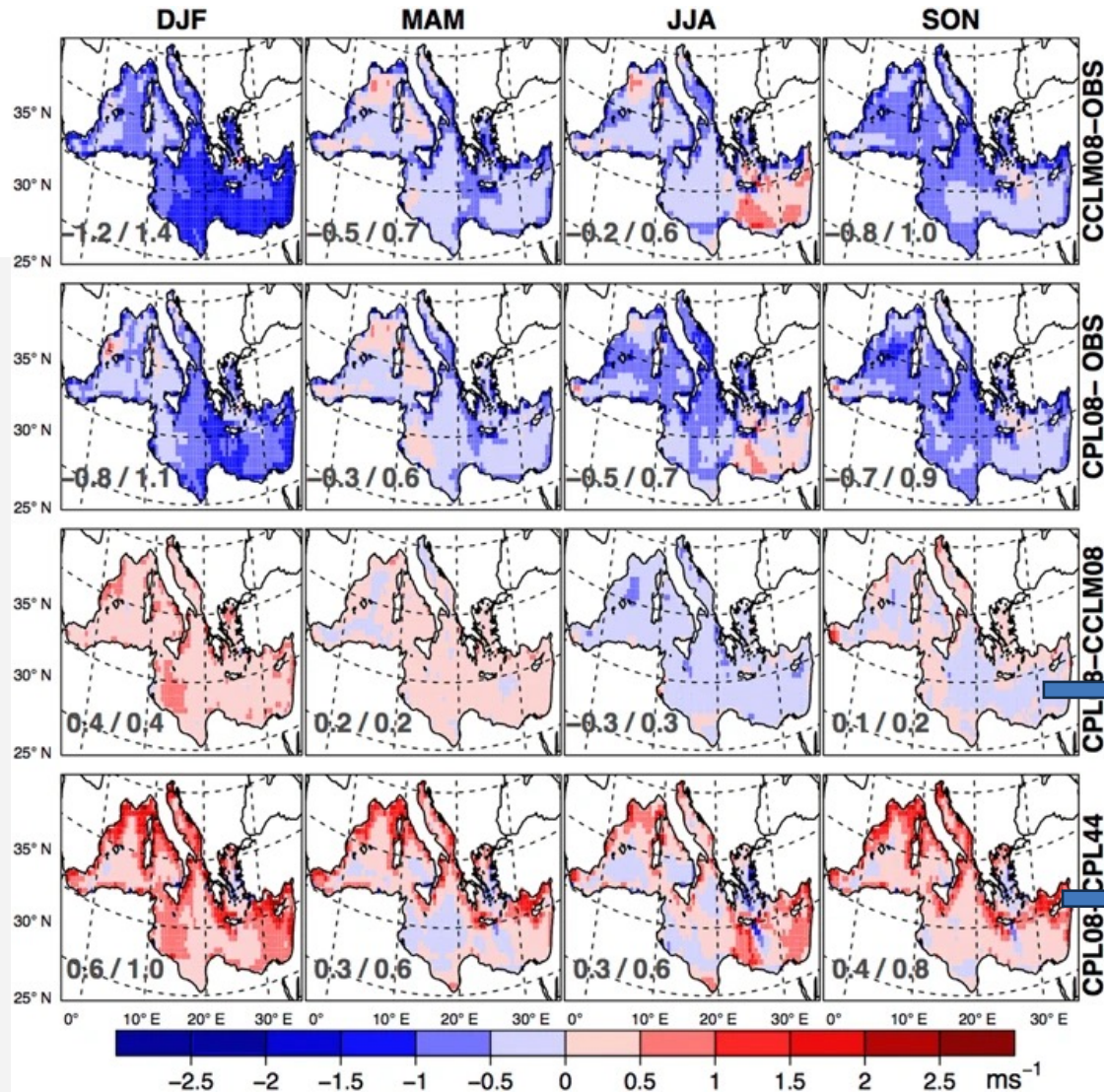
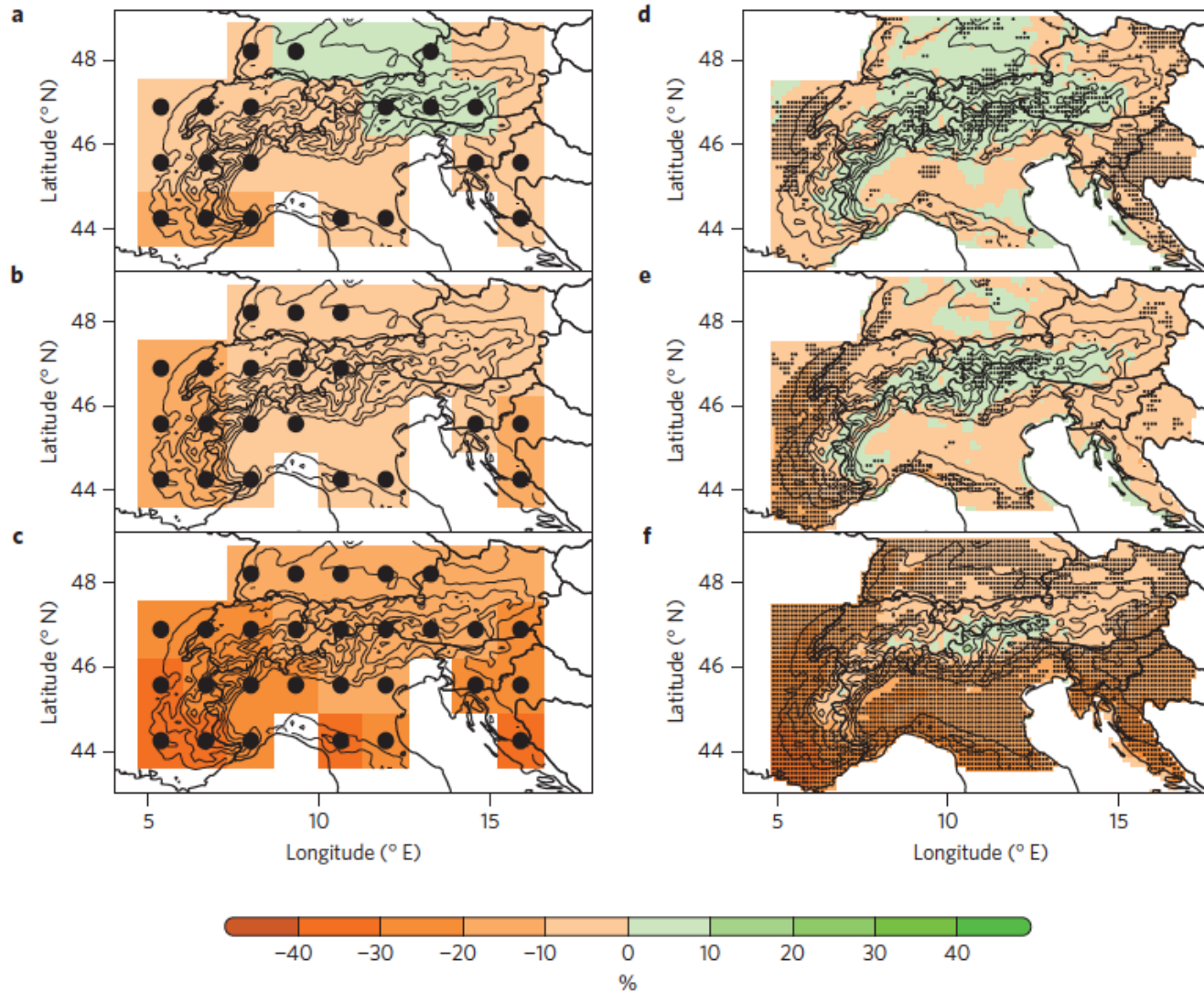


Figure taken from Akhtar et al. (2018)

- ❖ Higher horizontal spatial resolution (typically 12 km) has been shown to clearly **improve the representation of the spatial and temporal variability** of daily wind field over the Mediterranean Sea
- ❖ The comparison of simulated and observed 10-m wind speed reveals that the **differences are particularly large in near-coastal areas**, especially in areas that are associated with intense wind systems
- ❖ CPL08 vs CCLM08: The **ocean coupling** improves the 10-m wind speed simulation by about 1% over the simulated period
- ❖ The **impact of atmospheric grid resolution** is more pronounced than the impact of coupling in the simulation experiment set-up tested.

Med-CORDEX: main findings

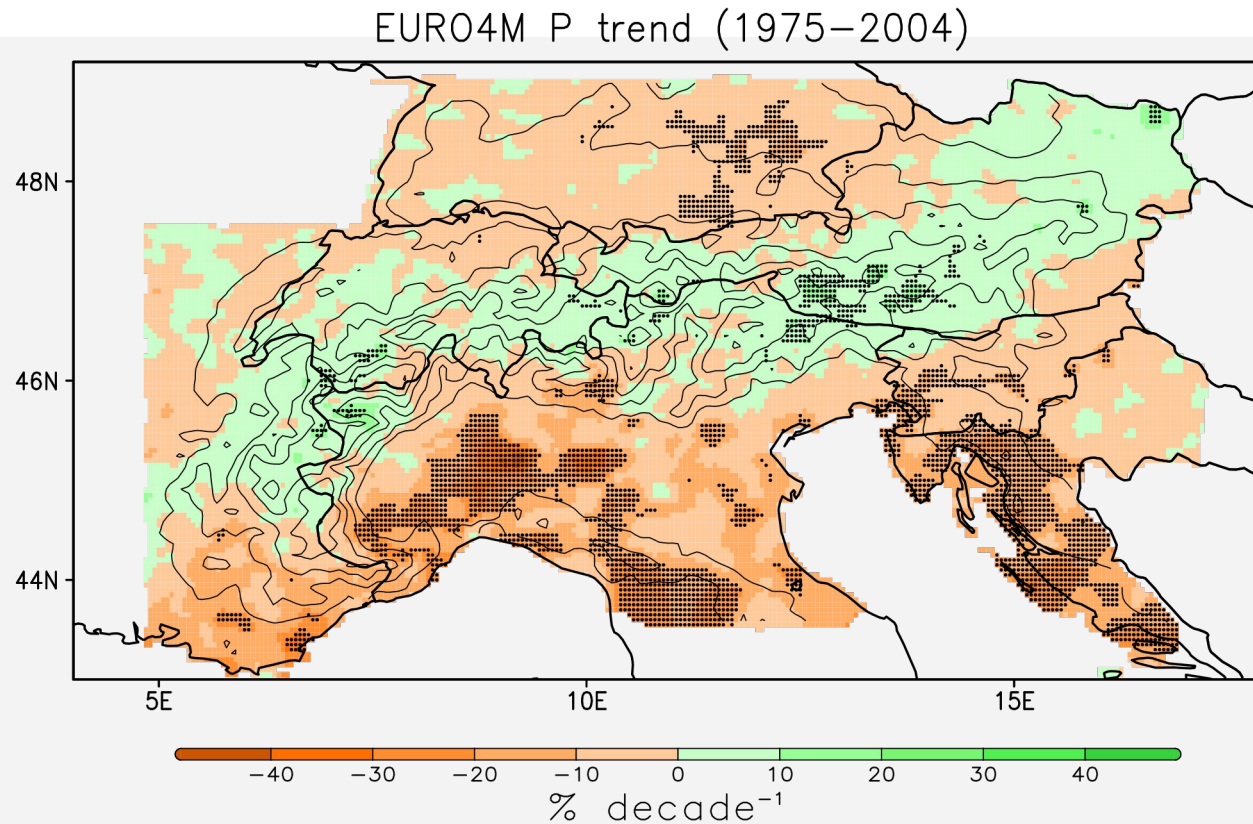
Future Climate: Mean climate over land



Med-CORDEX high-resolution regional simulations provide added value by resolving regional and orographic features, including enhanced surface warming at higher elevations and increases in summer convective precipitation over the highest Alpine areas.

Med-CORDEX: main findings

Future Climate: Mean climate over land



Process investigation: this effect is associated with increased convective rainfall due to enhanced potential instability by high-elevation surface heating and moistening.

Med-CORDEX: main findings

Future Climate: Extreme precipitations and droughts

Dual hydroclimatic signal

- ❖ LESS precipitation events on average >> mean drying & MORE intense precipitation extremes
- ❖ > DRY SPELLS: longer and more frequent
- ❖ Strong north–south contrasts in future precipitation extremes
- ❖ very rare events (50–100-year maxima) may intensify almost everywhere (Zittis et al. 2021)

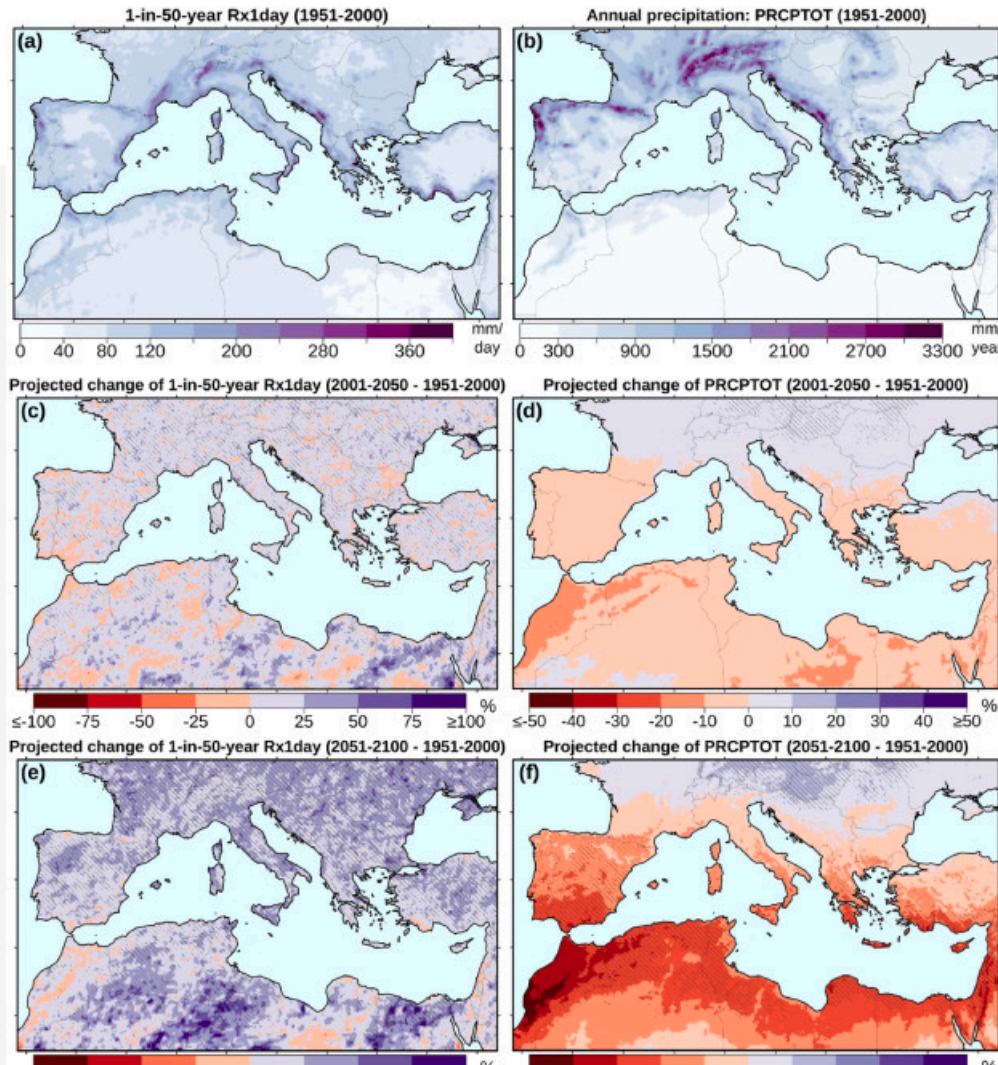


Fig. 4. Simulated climatology of maximum daily precipitation (Rx1day, left panels) and total annual precipitation (PRCPTOT, right panels) for the 1951–2000 reference period (mean of 33 EURO-CORDEX simulations) (a, b), and projected changes for two future periods (e–f); taken from **Zittis et al. 2019**.

Med-CORDEX: main findings

Future Climate: Extreme precipitations and droughts

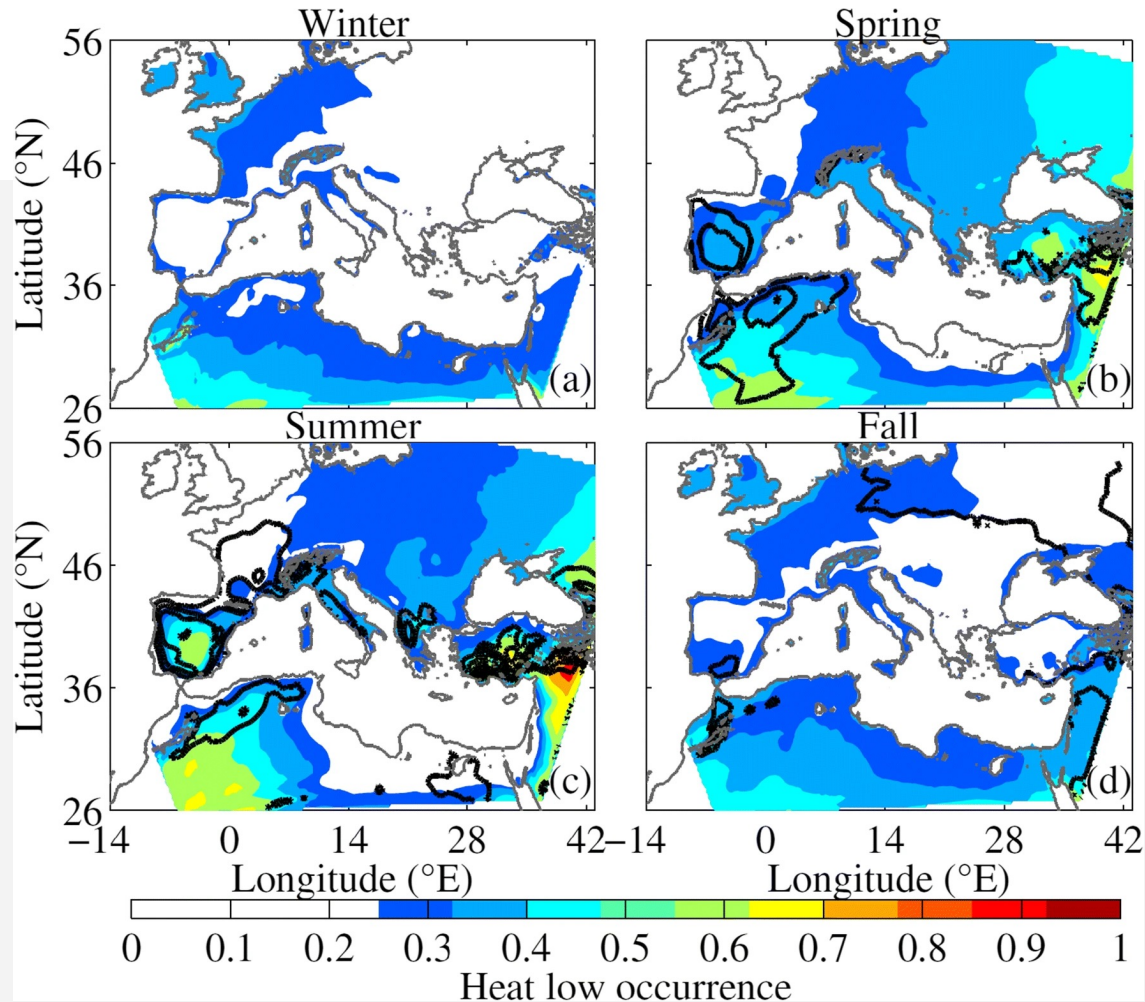


Figure taken from Drobinski et al. (2020)

- ❖ Heat lows are cyclonic circulation anomalies associated with surface heating over land
- ❖ The cyclonic circulation scales with the temperature gradient between land and ocean **which increases with climate change**, reinforcing the cyclonic circulation over Sahara and the Iberian Peninsula

The dynamics are therefore key in the warming and drying of the Mediterranean region, with extreme aridification over the Sahara and Iberian Peninsula.

Med-CORDEX: main findings

Future Climate: Extreme precipitations and droughts

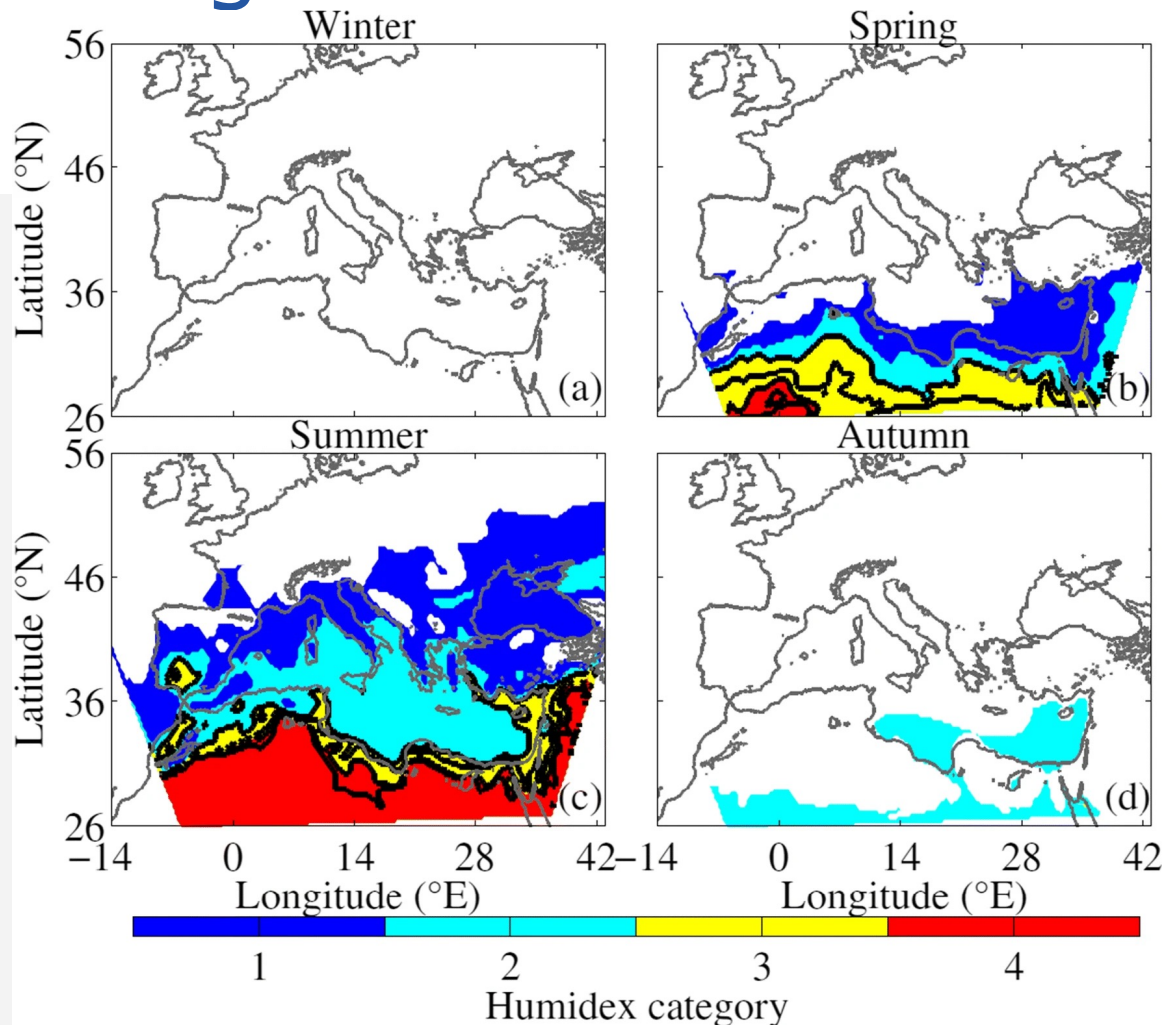
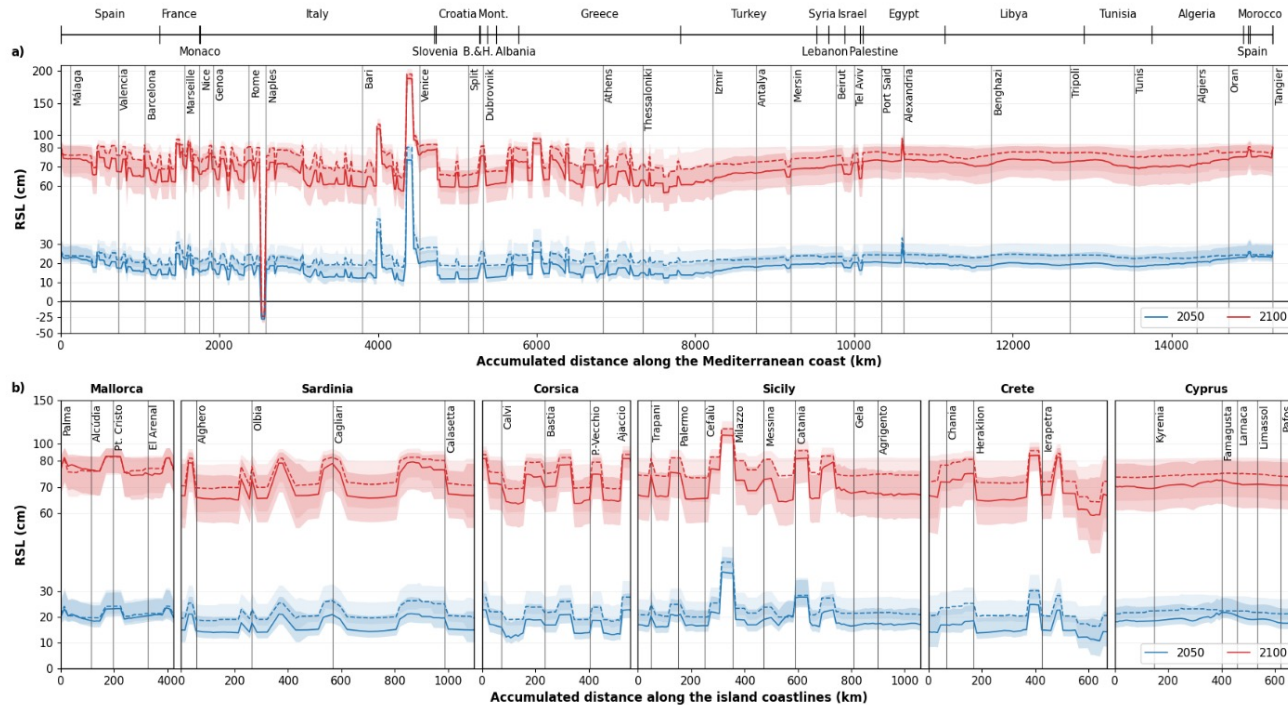


Figure taken from Drobinski et al. (2020)

- ❖ The pattern is very similar in the present climate but in some locations contoured in black solid line, the humidex category increases by +2 with respect to its present category.
- ❖ In spring and summer, the area of the regions of risk categories 1 to 4 increases by +54% and 50%, respectively.
- ❖ In winter and autumn, regions not exposed in the present climate should be exposed in a warmer climate.
- ❖ The case of the Iberian Peninsula stresses the role of the heat low in the change of humidex category which goes from category 1 or 2 to 3 or 4 so a situation which is dangerous for human health.

Med-CORDEX: main findings

Future Climate: Sea level



Solid lines ($RCSM_{MMEM}$) and dashed lines (GCM_{MMEM})

Relative sea-level rise (cm) along the accumulated distance (km). Projected median changes by 2050 (blue) and 2100 (red) under the SSP5-8.5 scenario, relative to 1995–2014. Shaded areas indicate the 17th–83rd percentile uncertainty range. Figure taken from: **Parras-Berrocal et al. 2025**

First multi-model ensemble assessment of future Mediterranean sea level based on **RCSMs**

- ❖ substantial **inter-model spread** in regional sea level patterns and underscoring the importance of a **multi-model framework** for robust regional projections.
- ❖ By combining this regional ensemble of multi-decadal simulations with surface mass balance and vertical land motion, the authors produce **the first basin-wide map of relative sea level for the Mediterranean**, with projected 2100 changes ranging from **–39 cm to +170 cm under SSP5-8.5**.
- ❖ **Strong spatial variability** and the importance of local information for coastal adaptation
- ❖ Regional and global ensemble means are broadly consistent, although the **GCM_{MMEM} projects higher values than the $RCSM_{MMEM}$** .



Improving the marine biogeochemistry representation

❖ NEMOMED8 / OGSTM-BFM

Ocean: $1/8^\circ$ horizontal resolution (~ 12 km)

Atmosphere: 50 km forcing (CNRM-CM)

River: Freshwater flux at surface, climatology (biogeochemical properties) Solidoro et al. (2022)

❖ MFS16 / OGSTM-BFM

Ocean: $1/16^\circ$ horizontal resolution (~ 6 km)

Atmosphere: approximately 80 km forcing (CMCC-CM)

River: Freshwater flux at surface, climatology (biogeochemical properties)

Reale et al. (2022)

❖ RegCM4.7 / MITgcm-BFM

Ocean: $1/128^\circ$ (~ 800 m)

Atmosphere: 3 km convection-permitting

River: CHyM open-boundary discharge; climatological biogeochemistry

Cossarini et al. (2017); Pichelli et al. (2021)

Finer grids reveal localized climate change signals

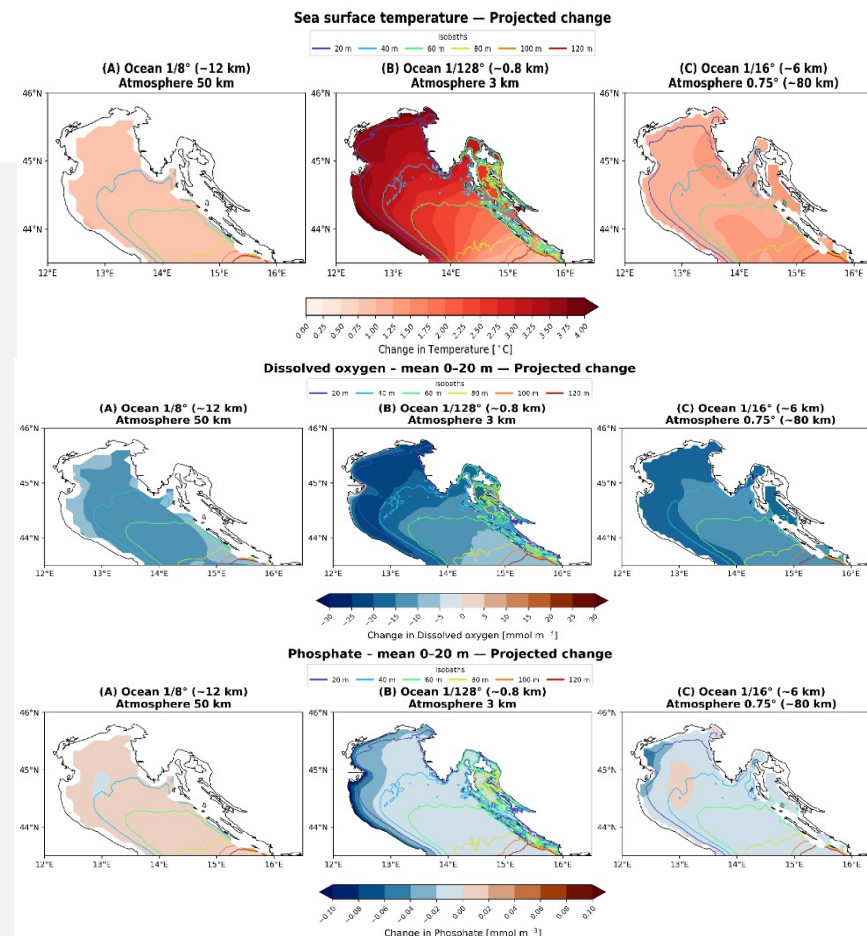


Figure taken from: **High resolution coupled simulations for climate projections of the Northern Adriatic Sea**. Presenter: Marco Reale



Improving the marine biogeochemistry representation

❖ RegCM4.7 / MITgcm-BFM

Ocean: $1/128^\circ$ (~800 m)

Atmosphere: 3 km convection-permitting

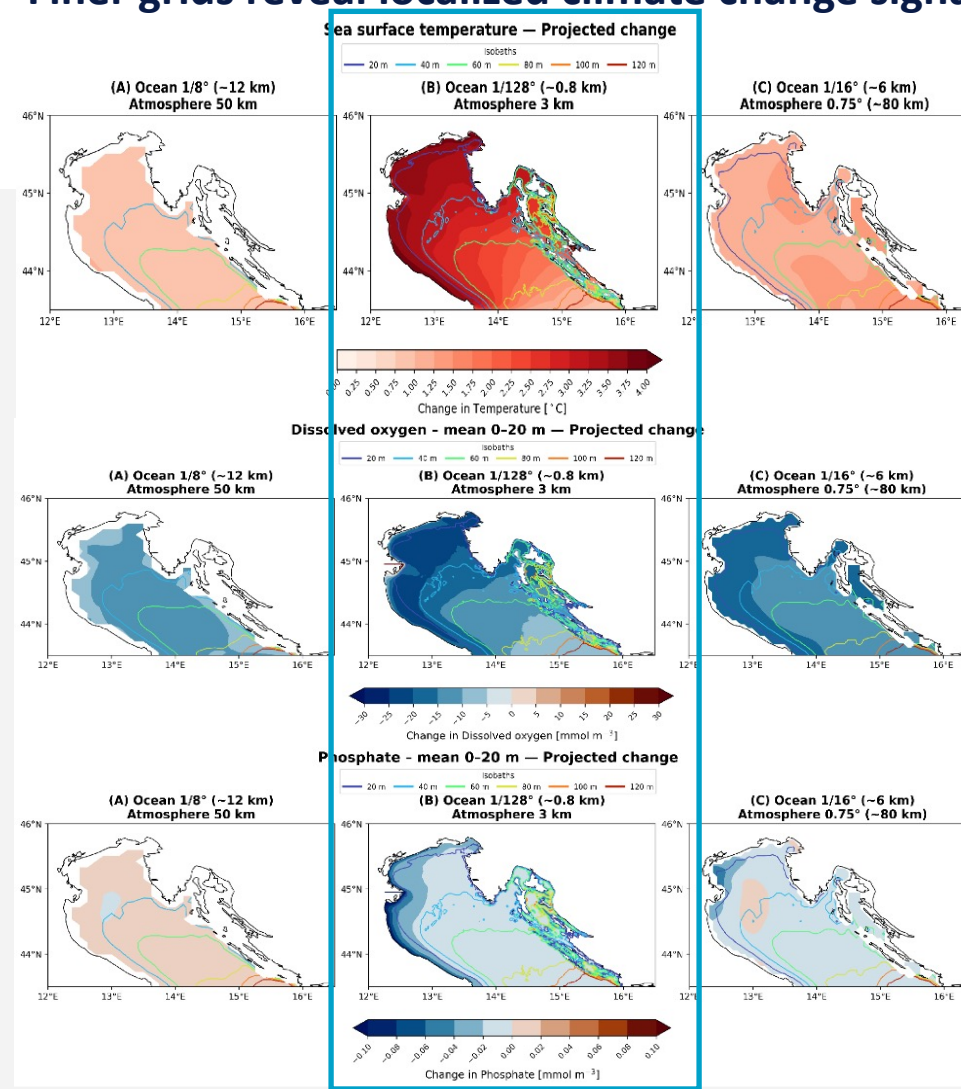
River: CHyM open-boundary discharge; climatological biogeochemistry

Cossarini et al. (2017); Pichelli et al. (2021)

The combined refinement of the ocean and atmosphere reveals coastal gradients and river-influenced structures that remain smoothed in the coarser configurations.

For more details: High resolution coupled simulations for climate projections of the Northern Adriatic Sea. Presenter: Marco Reale

Finer grids reveal localized climate change signals



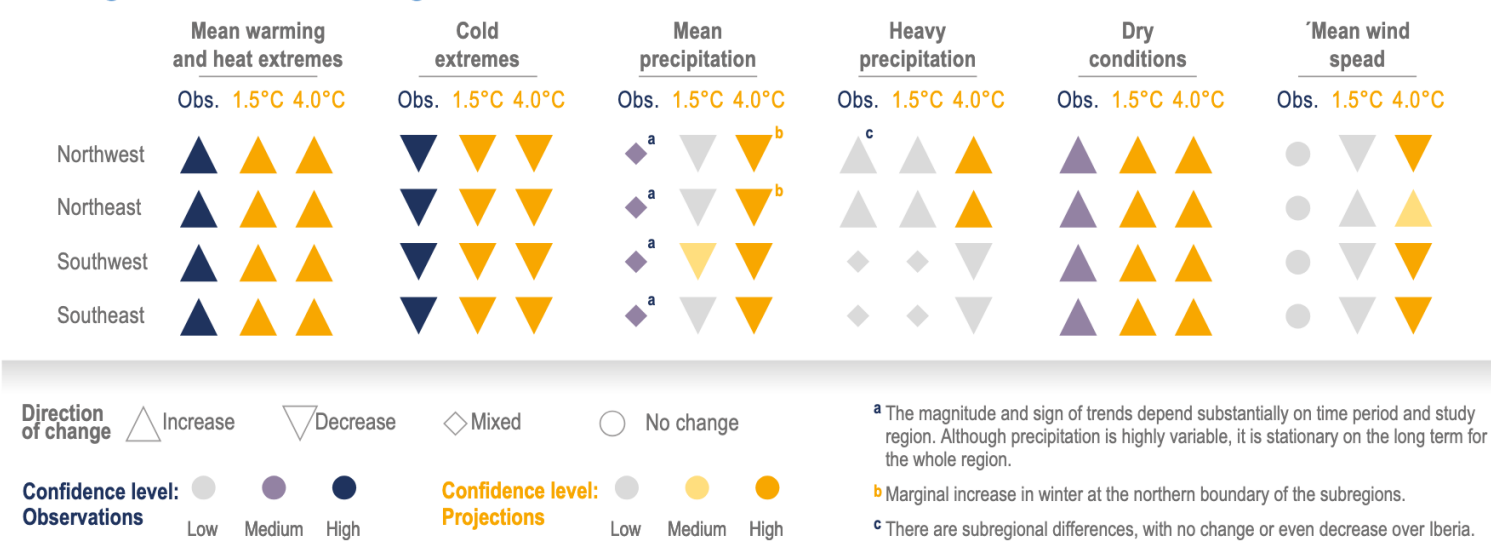
From Regional Climate Modelling to Climate Assessment

The contribution of the RCM community to climate assessment reports

Cross-Chapter Paper 4

Mediterranean Region

Synthesis of observed and projected (1.5°C and 4.0°C global warming levels) changes in climate drivers affecting the Mediterranean region

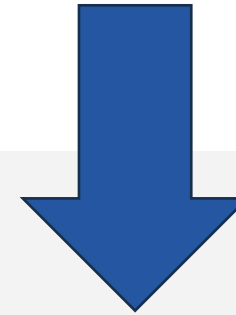


- ❖ Warming & heat extremes ↑
- ❖ Drought / aridity ↑
- ❖ Mean precipitation ↓ in many areas
- ❖ Heavy precipitation ↑ in parts of the region

Figure CCP4.3 | Observed and projected (at global warming levels of 1.5°C and 3°C) direction of change of climate drivers and confidence levels for Mediterranean land sub-regions.

From Regional Climate Modelling to Climate Assessment

The contribution of the RCM community to climate assessment reports



In preparation:

❖ Second Mediterranean Assessment Report (MAR2)

❖ IPCC AR7



Looking Ahead: Bridging Knowledge Gaps

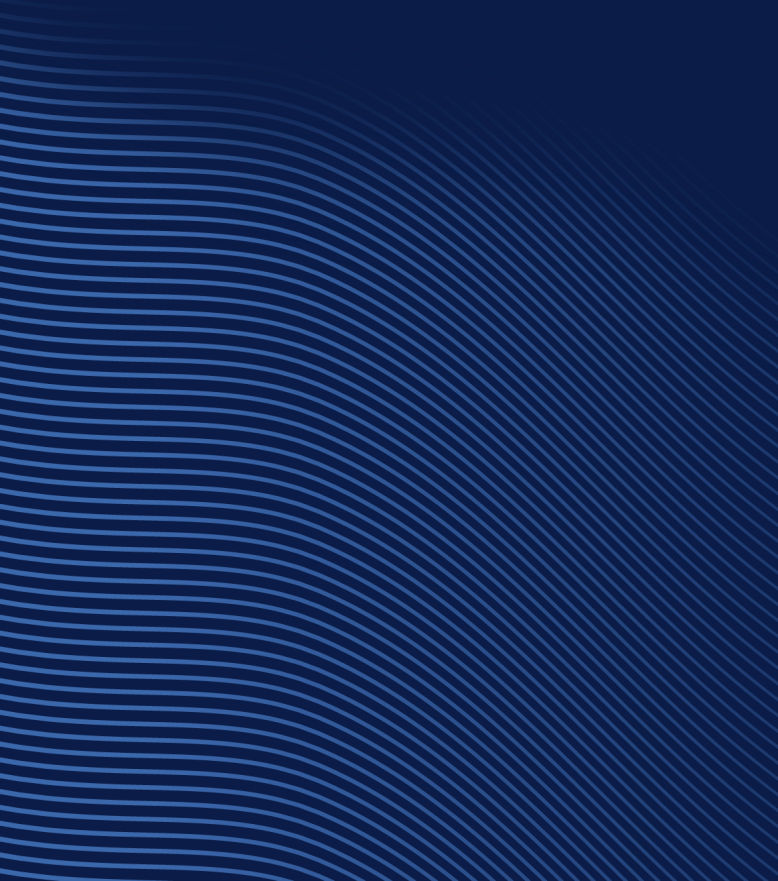
Med-CORDEX Phase 3 and CORDEX-CMIP6



12 km resolution simulations over all the CORDEX domains and the production of HOURLY data!

- ❖ Heat stress
- ❖ Capturing daytime peak conditions
- ❖ Nighttime conditions are critical for recovery
- ❖ Improved representation of humidity effects
- ❖ Avoiding biases from daily aggregation

- ❖ Capturing the diurnal cycle
- ❖ More realistic assessment of human exposure
- ❖ Higher relevance for mortality and health studies
- ❖ Critical for energy and infrastructure applications
- ❖ Essential for urban heat analysis



Thank you!

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