# Multi-scale assessment of high-resolution reanalysis precipitation fields over Italy

Francesco Cavalleri[1], Cristian Lussana, Francesca Viterbo, Michele Brunetti, Riccardo Bonanno, Veronica Manara, Matteo Lacavalla, Maurizio Maugeri

[1] Ph.D. student at the University of Milan, in collaboration with R.S.E.
former visiting researcher at the Norwegian Meteorological Institute

SCREEN CAPTURE WELCOME

Annual Meeting of the European Meteorological Society

European Conference for Applied Meteorology and Climatology

Barcelona, 5 September 2024

UP3.6 – Global and regional reanalyses, Lecture room A-111

# Outline:

1. Motivations
2. Research questions
3. Reanalysis datasets
4. Observational dataset
5. Methods & Results
6. Key findings

SCREEN CAPTURE
WELCOME

# 1. Motivations

SCREEN CAPTURE
WELCOME

- Precipitation is crucial, and reanalyses can provide complete fields.
- Release of numerous regional and high-resolution reanalyses.
- Widespread use for climate monitoring, AI training, and other applications.
- Need to intercompare and validate them for better utilization.

SCREEN CAPTURE WELCOME

# 2. Research questions

SCREEN CAPTURE
WELCOME

1. What is the **effective spatial resolution** (beyond grid spacing)?

2. At what **frequency** are **intense precipitations** reproduced?

3. What is the **spatial accuracy** of the events in daily fields?

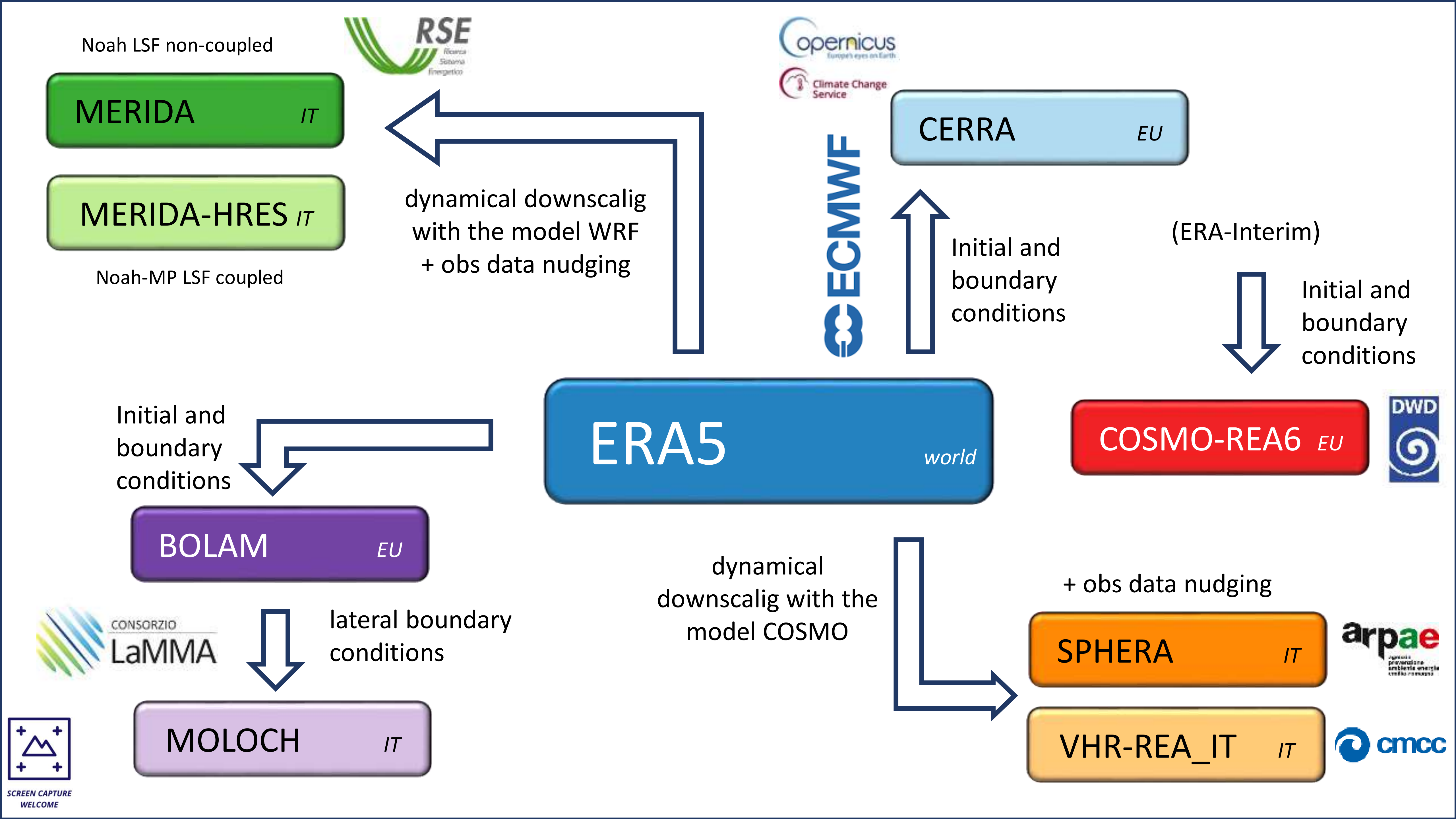
4. How well are **monthly climatological averages** reproduced?

5. To what extent can **long-term trends** from reanalyses be trusted?

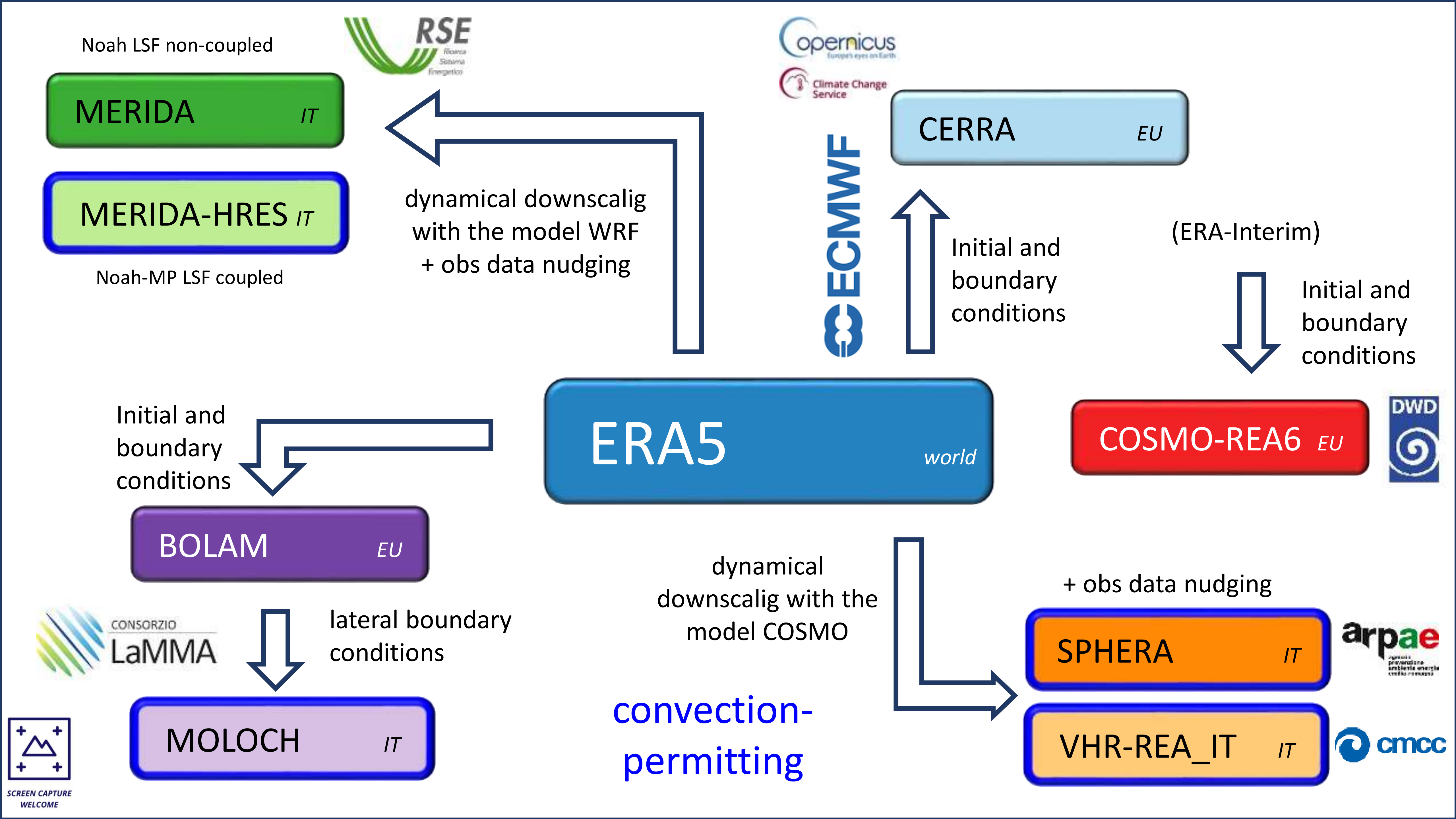
SCREEN CAPTURE WELCOME

# 3. Reanalysis datasets

SCREEN CAPTURE
WELCOME

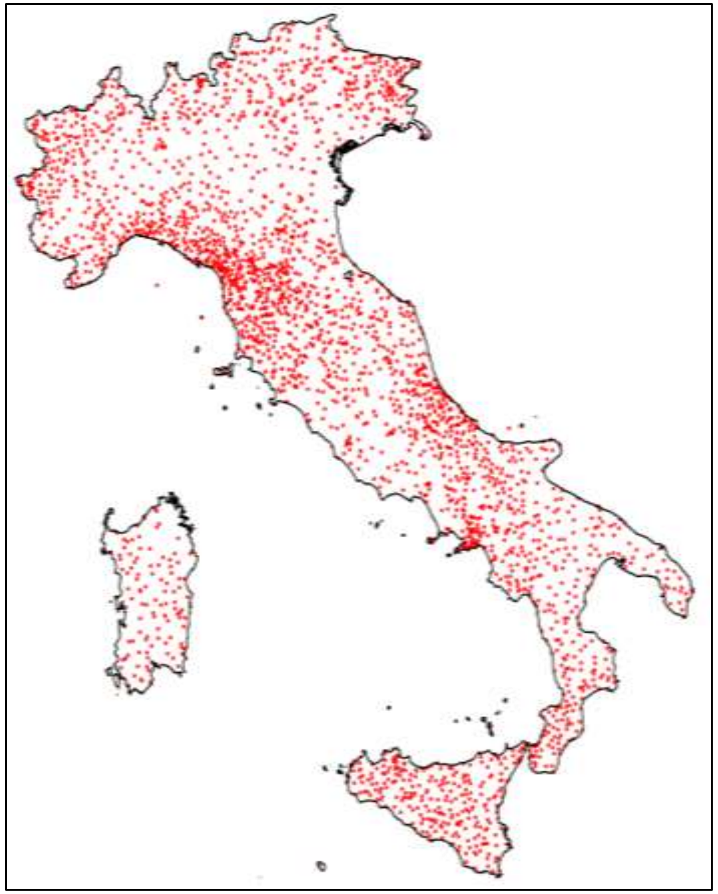


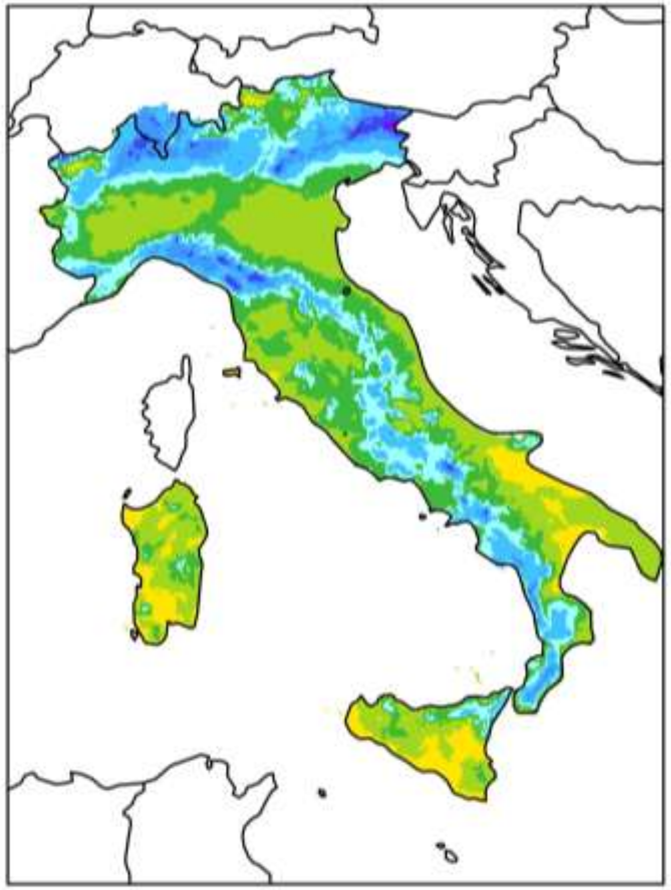
Noah LSF non-coupled
RSE
MERIDA IT
MERIDA-HRES IT
Noah-MP LSF coupled
dynamical downscalig
with the model WRF
+ obs data nudging
opernicus
Climate Change Service
ECMWF
CERRA EU
Initial and
boundary
conditions
(ERA-Interim)
Initial and
boundary
conditions
ERA5 world
COSMO-REA6 EU
DWD
Initial and
boundary
conditions
BOLAM EU
CONSORZIO
LaMMA
lateral boundary
conditions
MOLOCH IT
dynamical
downscalig with the
model COSMO
+ obs data nudging
SPHERA IT
arpae
VHR-REA_IT IT
cmcc
SCREEN CAPTURE
WELCOME


Noah LSF non-coupled
RSE
MERIDA IT
MERIDA-HRES IT
Noah-MP LSF coupled
dynamical downscalig
with the model WRF
+ obs data nudging
opernicus
Climate Change
Service
ECMWF
CERRA EU
Initial and
boundary
conditions
(ERA-Interim)
Initial and
boundary
conditions
Initial and
boundary
conditions
ERA5 world
COSMO-REA6 EU
DWD
BOLAM EU
dynamical
downscalig with the
model COSMO
+ obs data nudging
CONSORZIO
LaMMA
lateral boundary
conditions
SPHERA IT
arpae
VHR-REA_IT IT
cmcc
MOLOCH IT
convection-
permitting
SCREEN CAPTURE
WELCOME

# 4. Observational datasets

SCREEN CAPTURE WELCOME





Weather stations (regional agencies) daily data

Gridded (UniMi/ISAC-CNR) monthly data

SCREEN CAPTURE WELCOME

# 5. Methods & Results

1. Effective spatial resolution

2. Frequency of intense precipitations

⇩

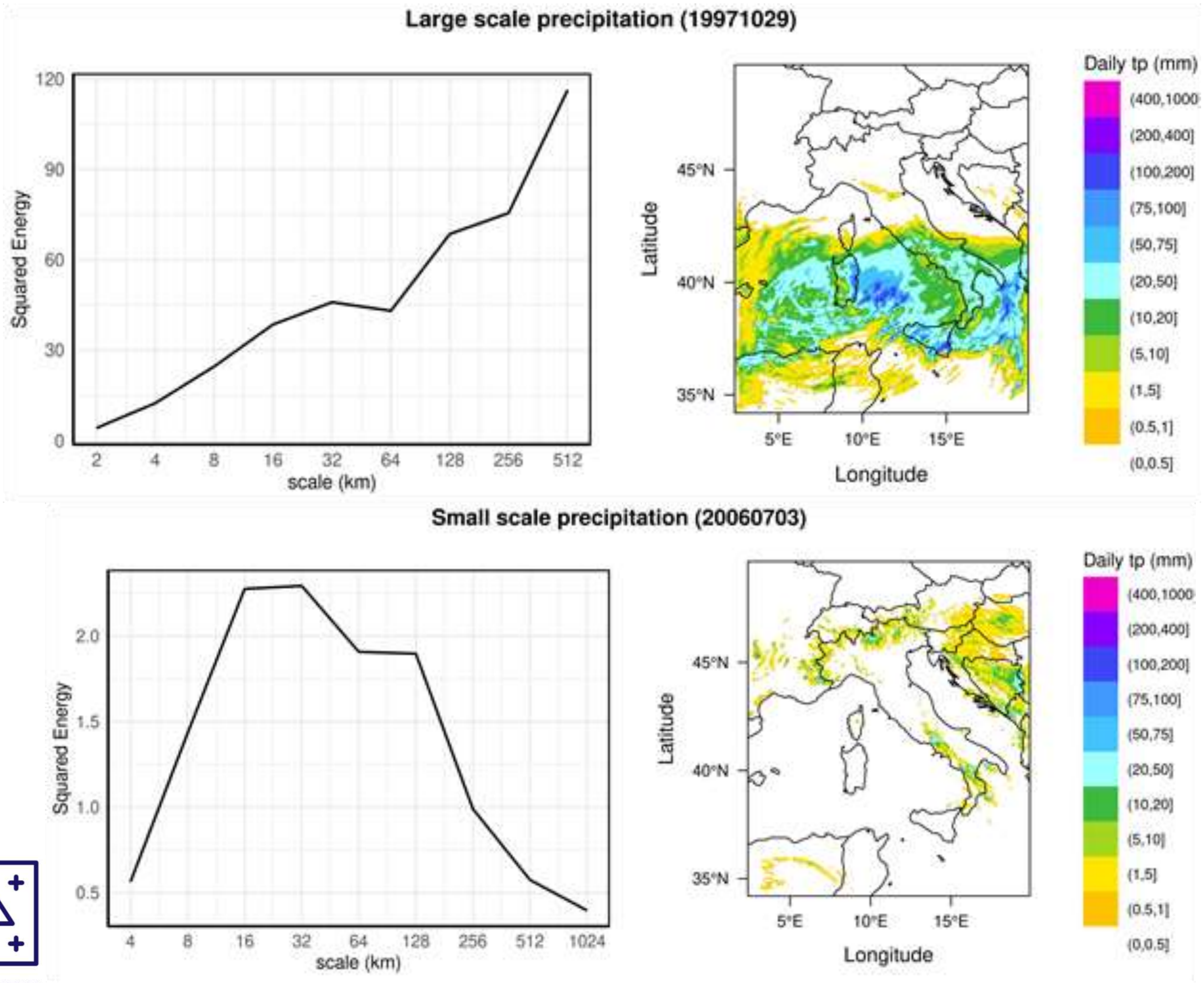
<u>Inter-comparison of daily reanalysis fields (both land and sea):</u>

1. Wavelet spectral decomposition

2. Frequency distributions

SCREEN CAPTURE WELCOME

# 1. Wavelets decomposition




Can show at which scale precipitation occurs. E.g.:

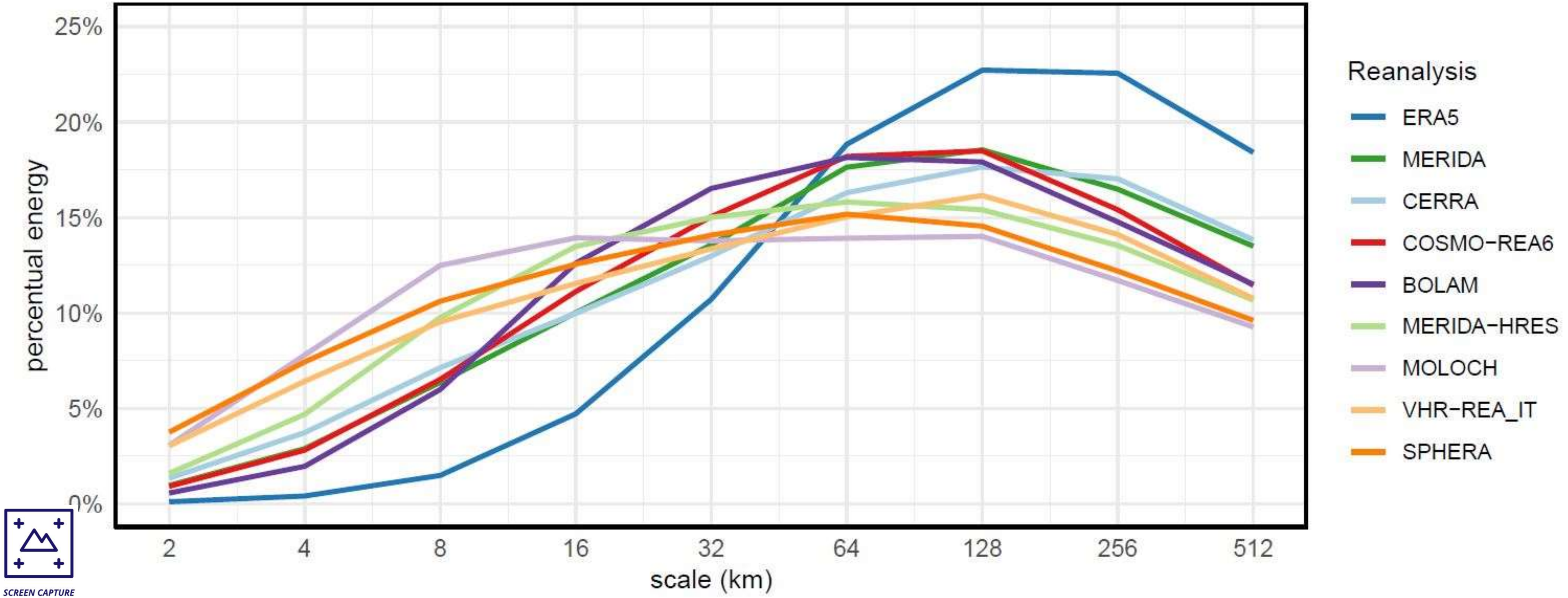
- synoptic: 100-500 km
- convective: < 20 km

→ value of the energy [$mm^2$] at each scale.

Averaged over a long period…

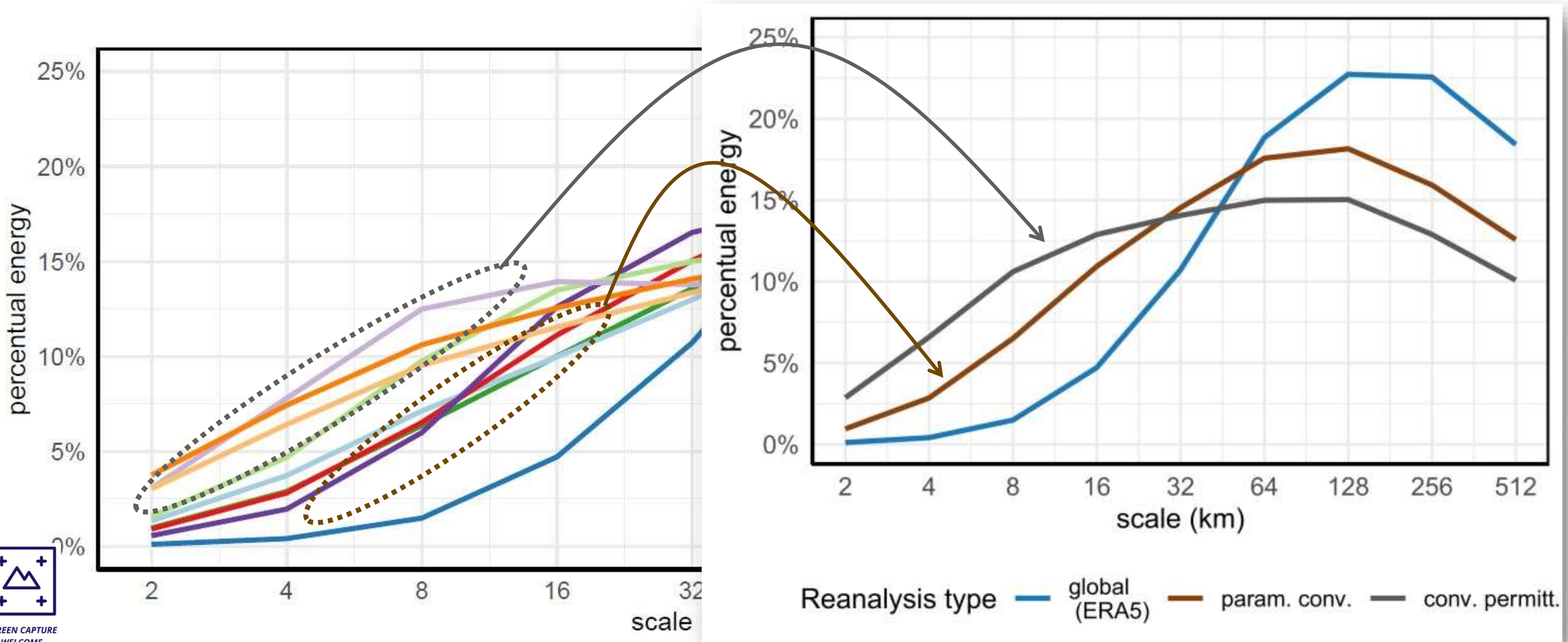
SCREEN CAPTURE WELCOME

# 1. Fraction of energy by spatial scale (1995-2019)



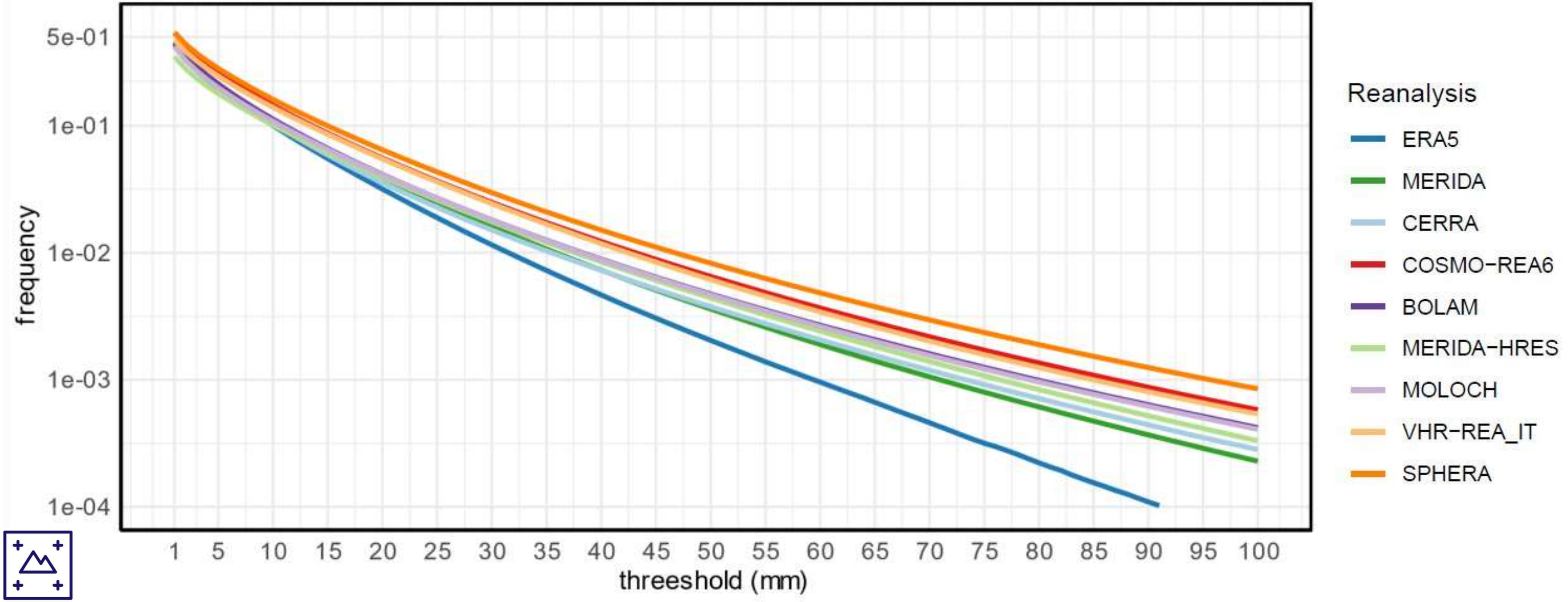

SCREEN CAPTURE WELCOME

# 1. Fraction of energy grouped by reanalysis type




SCREEN CAPTURE WELCOME

# 2. Distributions of daily intensity (1995-2019 average)




SCREEN CAPTURE WELCOME

3. daily spatial accuracy

4. climatological correctness

5. long-term time coherence

⇩

Validation against observations: ⇨

3. categorical daily skill against weather stations

4. systematic monthly deviations against gridded observational data

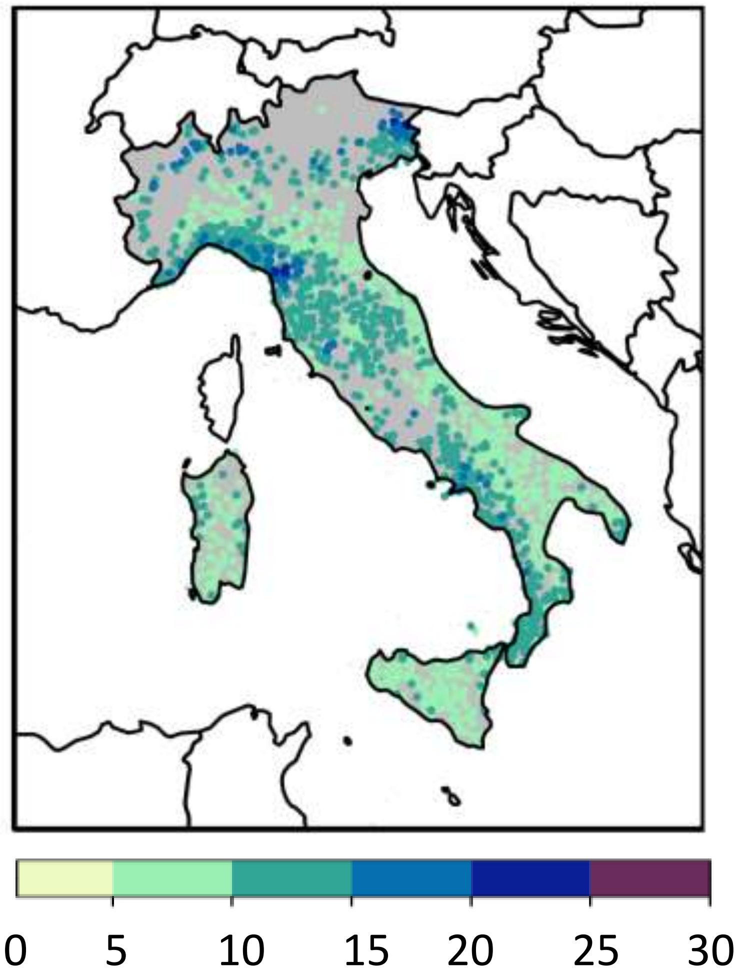
5. stability in time of the deviation in annual totals

# 3. categorical daily skill against weather stations

Evaluate the ability to distinguishing:

- Dry day (tp < 1 mm)
- Light rain
- Heavy rain

Threshold based on local obs. climatology:

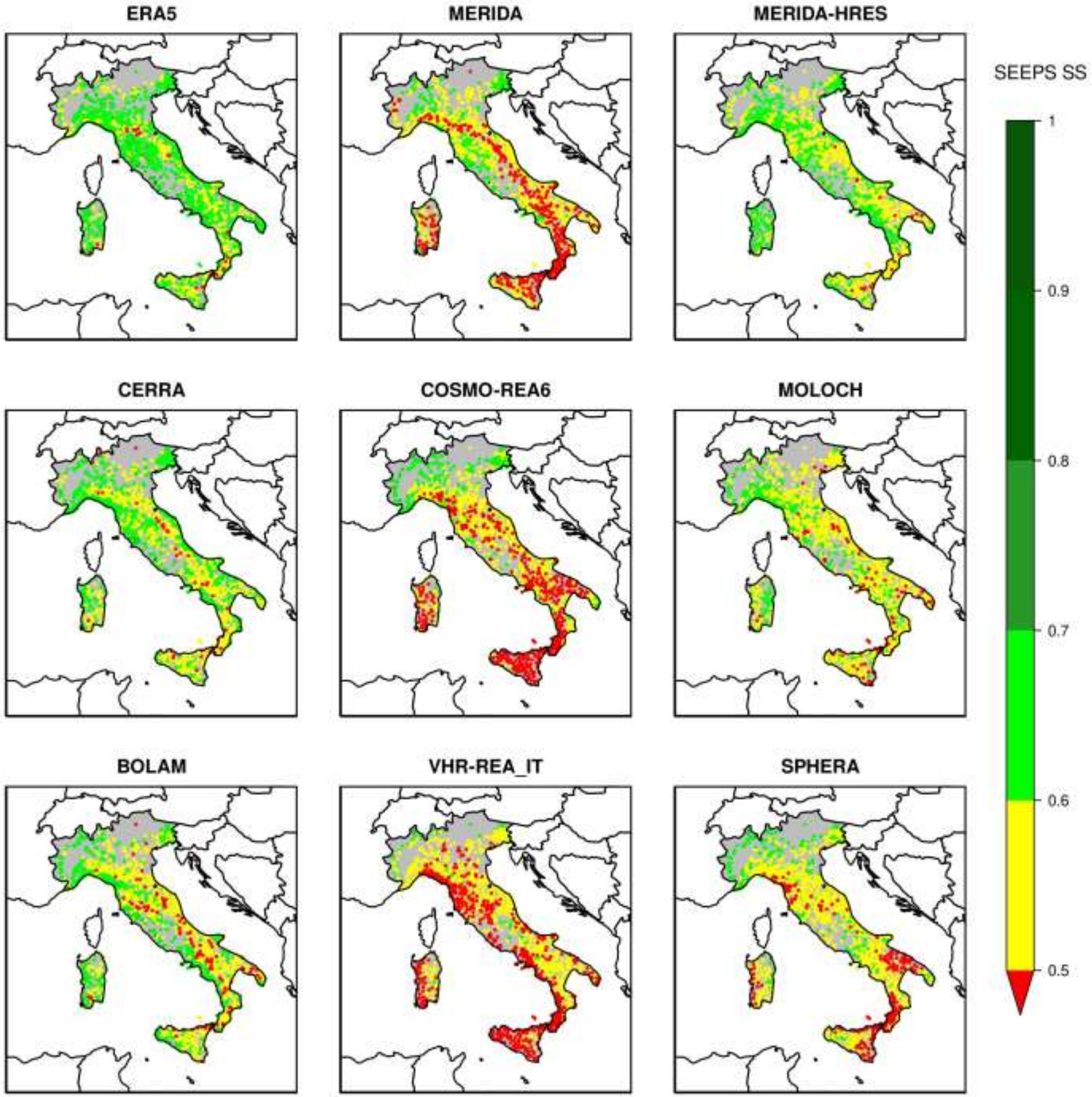



Employing a score also used by ECMWF:

Stable Equitable Error in Probability Space (SEEPS)

# SEEPS Skill Score (2016-2020 averaged)

| | DJF | MAM | JJA | SON |
|---|---|---|---|---|
| ERA5 | 0.67 | 0.65 | 0.49 | 0.65 |
| MERIDA | 0.59 | 0.58 | 0.41 | 0.55 |
| CERRA | 0.67 | 0.64 | 0.46 | 0.62 |
| COSMO-REA6 | 0.58 | 0.58 | 0.42 | 0.55 |
| BOLAM | 0.63 | 0.60 | 0.45 | 0.60 |
| MERIDA-HRES | 0.69 | 0.62 | 0.43 | 0.63 |
| MOLOCH | 0.64 | 0.58 | 0.41 | 0.61 |
| VHR_REA_IT | 0.57 | 0.54 | 0.42 | 0.54 |
| SPHERA | 0.57 | 0.59 | 0.47 | 0.58 |

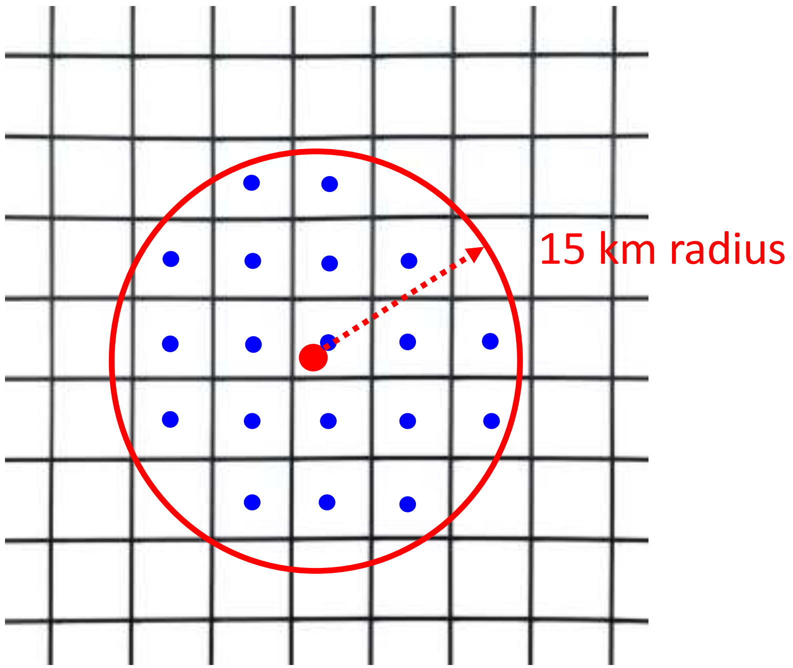



RSE Ricerca Sistema Energetico

ISAC

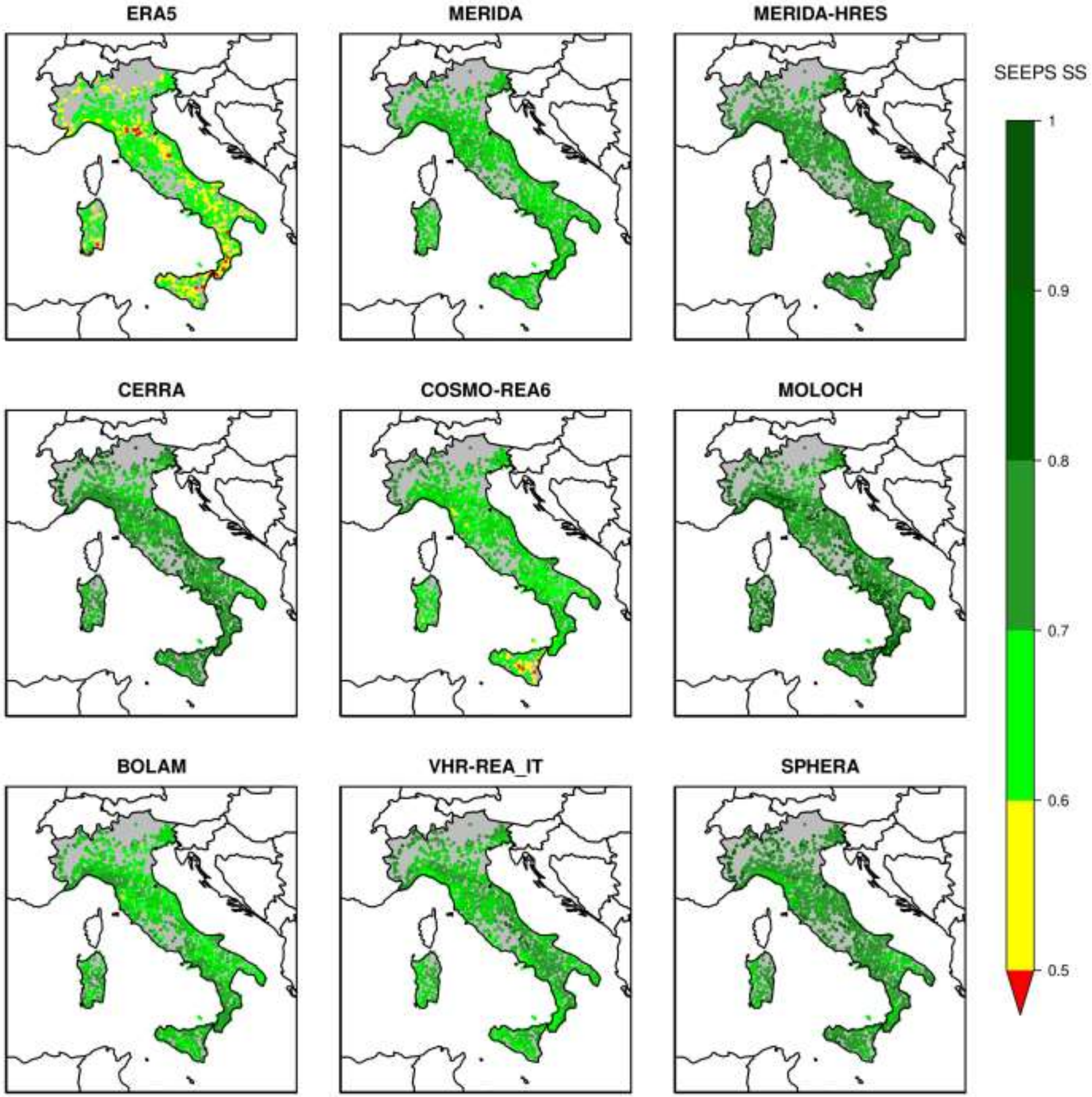
Norwegian Meteorological Institute

# Allowing for a 15 km misplacement

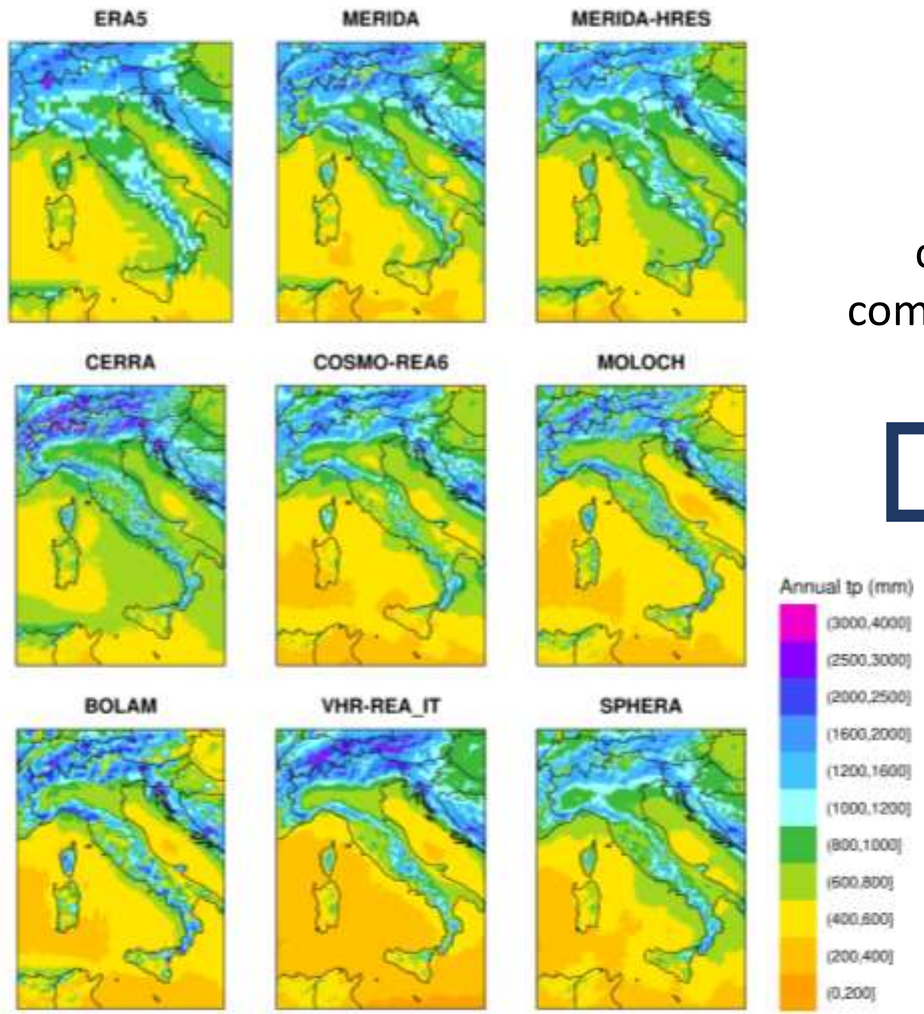



reanalysis cells central coordinates

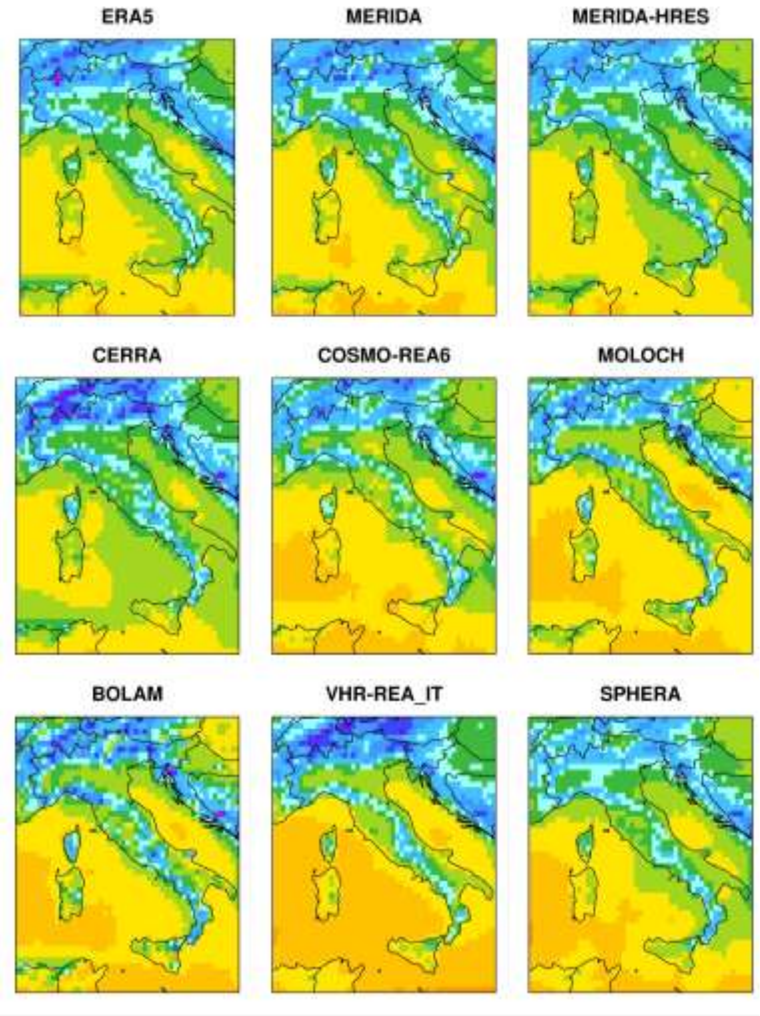
station position



# 4. Systematic deviations against gridded data

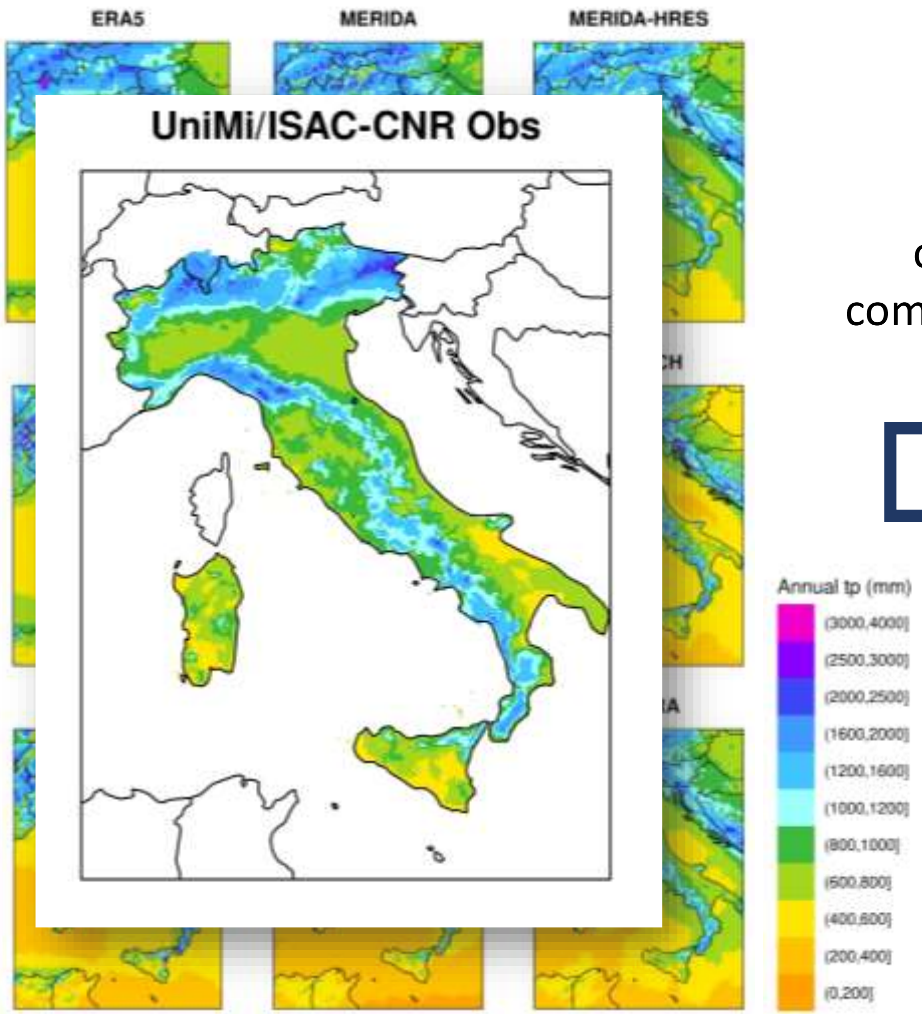



Conservative upscaling of climatological fields to the common ERA5 coarser resolution



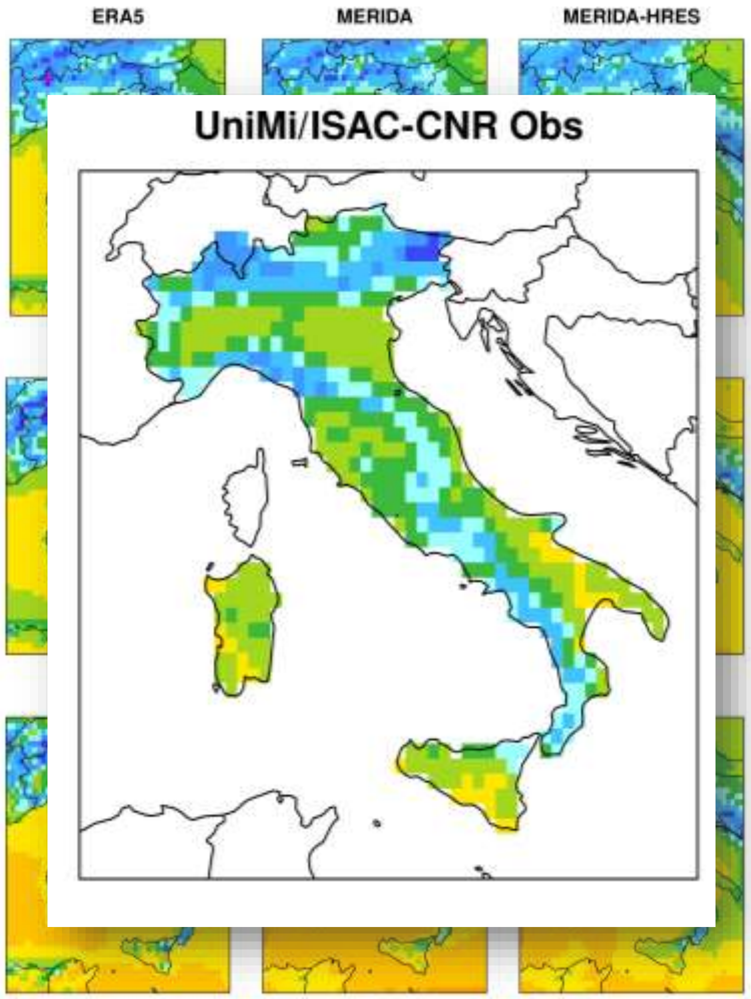

SCREEN CAPTURE WELCOME

# 4. Systematic deviations against gridded data




Conservative upscaling of climatological fields to the common ERA5 coarser resolution

Also gridded observations upscaled to the same grid



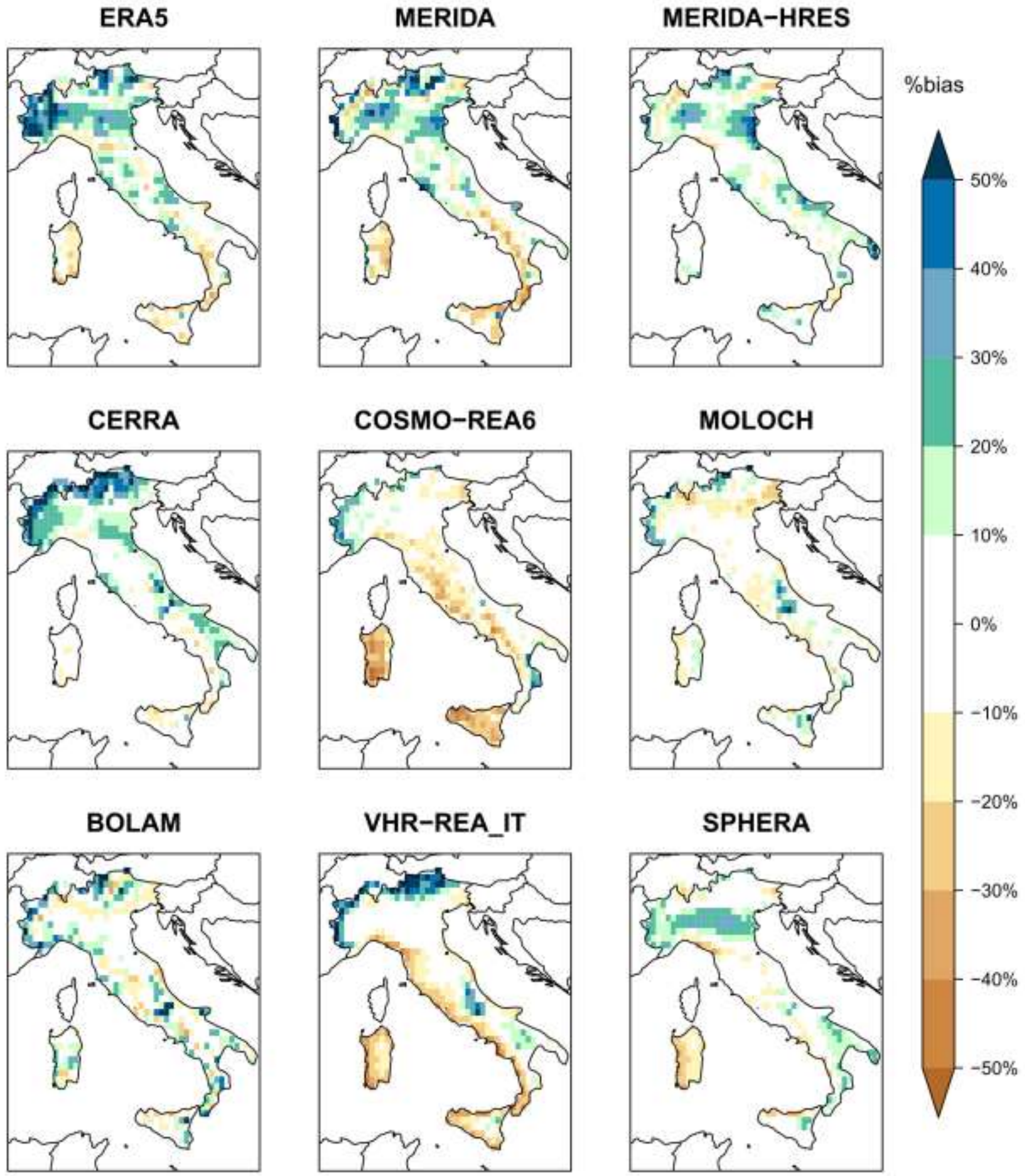

SCREEN CAPTURE WELCOME

Average yearly relative deviation:

$$\%\text{bias} = \frac{rean - obs}{obs}$$

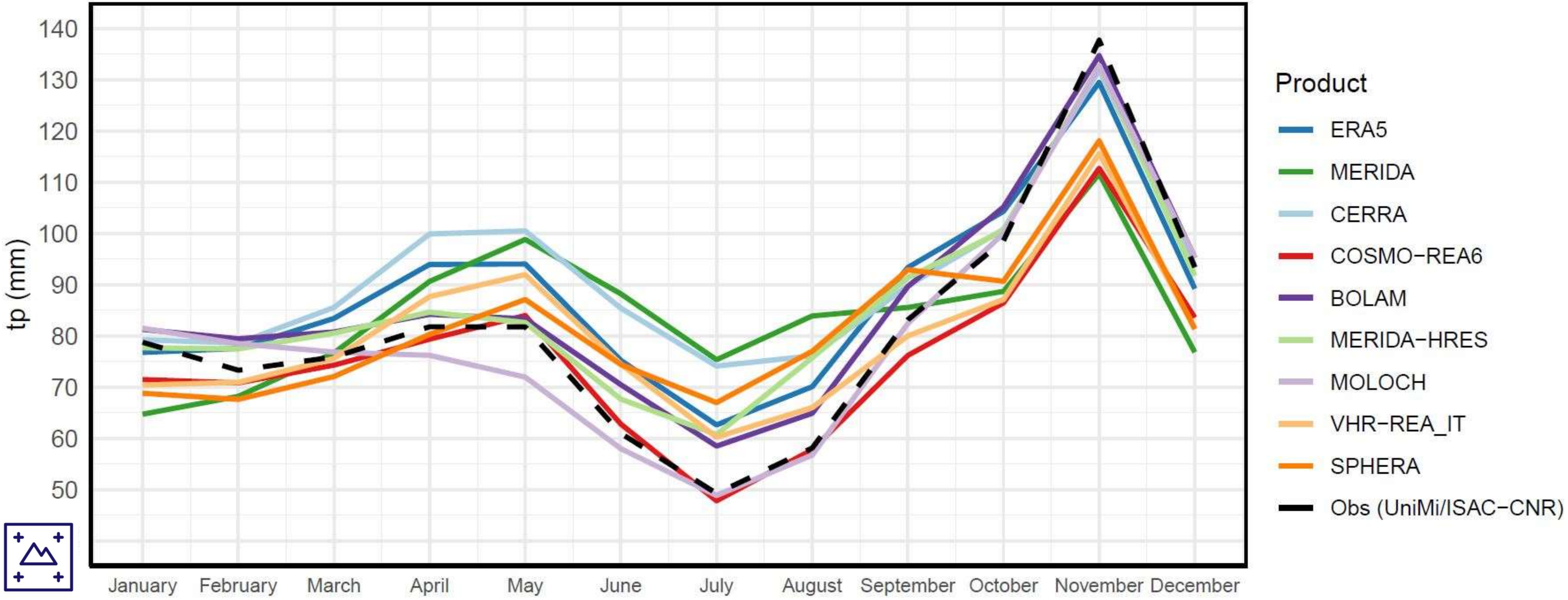
Systematic biases:

- Wet on the Alps and Po Valley
- Dry in Apennines, South Italy, West coast, Islands



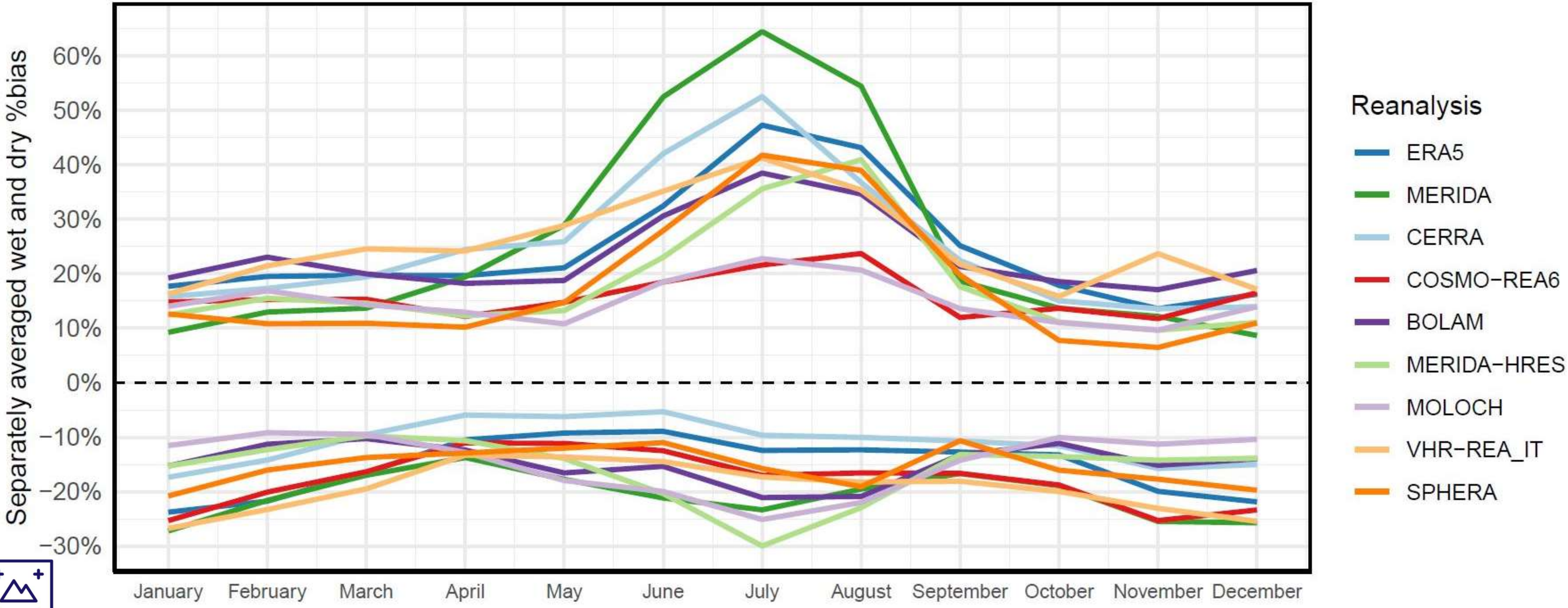

SCREEN CAPTURE WELCOME

# 4. Average monthly precipitations (1995-2019)




SCREEN CAPTURE WELCOME

# 4. Systematic average monthly deviations (1995-2019)




SCREEN CAPTURE WELCOME

# 5. Time consistence of annual totals

Annual total precipitation, averaged over the entire domain.

$$Rean.value \; - \; Obs.value \; = \; Rean.\ annual\ avg\ deviation$$

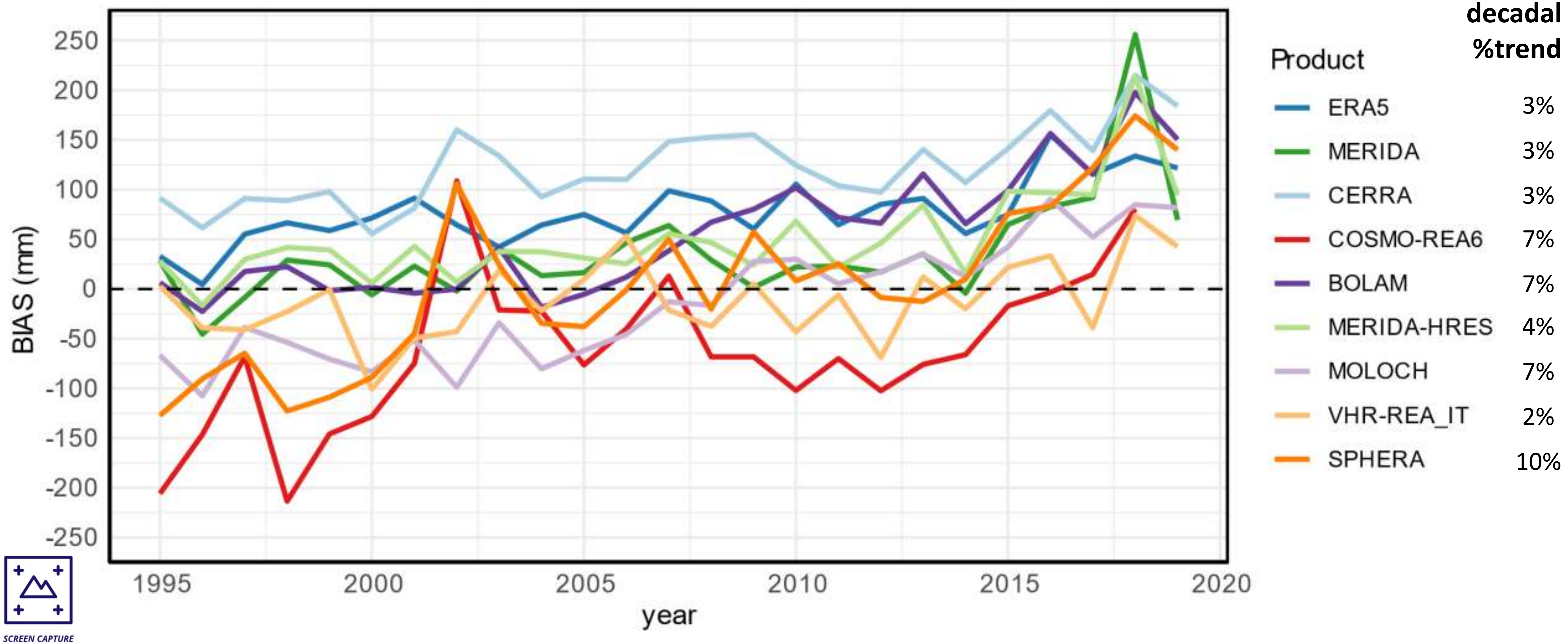
For each year, we get the annual deviation.
For each reanalysis, we get a series of annual deviations.

We expect fluctuations and an offset, but if reanalyses and observation represent the same long-term trend,

**zero trend should be detected in the series of their differences**

SCREEN CAPTURE WELCOME

# 5. Series of annual average deviations




SCREEN CAPTURE WELCOME

# 6. Key findings

SCREEN CAPTURE
WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**

SCREEN CAPTURE WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**
- **Wavelet Analysis**: effectiveness in capturing precipitation at various scales, distinguishing between global, parameterized, and convection-permitting models.

SCREEN CAPTURE WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**
- **Wavelet Analysis**: effectiveness in capturing precipitation at various scales, distinguishing between global, parameterized, and convection-permitting models.
- **ERA5 Limitations**: not enough energy at smaller spatial scales, and consequently smoothening of peaks: underestimates high-intensity precipitation (>20 mm/day).

SCREEN CAPTURE WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**
- **Wavelet Analysis**: effectiveness in capturing precipitation at various scales, distinguishing between global, parameterized, and convection-permitting models.
- **ERA5 Limitations**: not enough energy at smaller spatial scales, and consequently smoothening of peaks: underestimates high-intensity precipitation (>20 mm/day).
- **Small-Scale Events Misplacements**: comparison against weather stations reveal misplacements up to 15 km, especially in summer.

SCREEN CAPTURE WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**
- **Wavelet Analysis**: effectiveness in capturing precipitation at various scales, distinguishing between global, parameterized, and convection-permitting models.
- **ERA5 Limitations**: not enough energy at smaller spatial scales, and consequently smoothening of peaks: underestimates high-intensity precipitation (>20 mm/day).
- **Small-Scale Events Misplacements**: comparison against weather stations reveal misplacements up to 15 km, especially in summer.
- **Climatological Biases**: wet biases in Po Valley and Alps, dry biases in North-West coast, Apennines, and Southern Italy.

SCREEN CAPTURE WELCOME

- **Reanalysis products properly reproduce precipitation but need validation**
- **Wavelet Analysis**: effectiveness in capturing precipitation at various scales, distinguishing between global, parameterized, and convection-permitting models.
- **ERA5 Limitations**: not enough energy at smaller spatial scales, and consequently smoothening of peaks: underestimates high-intensity precipitation (>20 mm/day).
- **Small-Scale Events Misplacements**: comparison against weather stations reveal misplacements up to 15 km, especially in summer.
- **Climatological Biases**: wet biases in Po Valley and Alps, dry biases in North-West coast, Apennines, and Southern Italy.
- **Long-Term Trend**: annual precipitation deviations from observations show a trend, which should be considered when analyzing precipitation trends over Italy.

For full insights, see the preprint:
https://arxiv.org/abs/2407.11517

Under review for the publication on *Atmospheric Sciences* (Elsevier)

We acknowledge all Data Providers:

Simone Sperati (RSE), Mario Raffa (CMCC),
Valerio Capecchi (LaMMA), Davide Cesari (ARPAE),
Antonio Giordani (ARPAE; UniBo),
Ines Maria Luisa Cerenzia (ARPAE; RedRisk)


Multi-scale assessment of high-resolution reanalysis precipitation fields over Italy

Francesco Cavalleri[a,c,b,*], Cristian Lussana[b], Francesca Viterbo[c], Michele Brunetti[d], Riccardo Bonanno[c], Veronica Manara[a], Matteo Lacavalla[c], Simone Sperati[c], Mario Raffa[e], Valerio Capecchi[f], Davide Cesari[g], Antonio Giordani[h,g], Ines Maria Luisa Cerenzia[i,g], Maurizio Maugeri[a]

[a]*Environmental Science and Policy Department (ESP), University of Milan, Milan, 20133, Italy, Italy*
[b]*Division for Climate Services, the Norwegian Meteorological Institute, Oslo, 0313, Norway*
[c]*Sustainable Development and Energy Resources Department, Research on Electric Systems (RSE), Milan, 20134, Italy*
[d]*Institute of Atmospheric Sciences and Climate, National Research Council (CNR-ISAC), Bologna, 40129, Italy*
[e]*Euro-Mediterranean Center on Climate Change (CMCC), Caserta, 81100, Italy*
[f]*Environmental Monitoring and Modeling Laboratory (LaMMA), Sesto Fiorentino (FI), 50019, Italy*
[g]*Regional Agency for Environmental Prevention and Energy of Emilia-Romagna (ARPAE), Bologna, 40139, Italy*
[h]*Department of Physics and Astronomy (DIFA), University of Bologna, Bologna, 40127, Italy*
[i]*Risk Engineering + Development (RED), Pavia, 27100 , Italy*

**Abstract**

This study focuses on the validation of high-resolution regional reanalyses to understand their effectiveness in reproducing precipitation patterns over Italy, a climate change hotspot characterized by coastal sea-land interaction and complex orography. Nine reanalysis products were evaluated, with the ECMWF global reanalysis ERA5 serving as a benchmark. These included both European (COSMO-REA6, CERRA)

*Corresponding author
*Email addresses:* francesco.cavalleri@unimi.it (Francesco Cavalleri), cristianl@met.no (Cristian Lussana), viterbo.francesca@rse-web.it (Francesca Viterbo), m.brunetti@isac.cnr.it (Michele Brunetti), bonanno.riccardo@rse-web.it (Riccardo Bonanno), veronica.manara@unimi.it (Veronica Manara), lacavalla.matteo@rse-web.it (Matteo Lacavalla), sperati.simone@rse-web.it (Simone Sperati), mario.raffa@cmcc.it (Mario Raffa), capecchi@lamma.toscana.it (Valerio Capecchi), dcesari@arpae.it (Davide Cesari), antonio.giordani3@unibo.it (Antonio Giordani), ines.cerenzia@redrisk.com (Ines Maria Luisa Cerenzia), maurizio.maugeri@unimi.it (Maurizio Maugeri)

*Preprint submitted to Atmospheric Research* *July 11, 2024*

# Thank you for the attention!

SCREEN CAPTURE WELCOME

This work has been financed by the Research Fund for the Italian Electrical System under the Three-Year Research Plan 2022-2024 (DM MITE n. 337, 15.09.2022), in compliance with the Decree of April 16th, 2018.

# Essential references:


1. Kaiser-Weiss et al. (2019) Added value of regional reanalyses for climatological applications, Environ. Res. Commun. 1 071004

2. Hersbach et al. (2020) The ERA5 global reanalysis, Q J R Meteorol Soc.; 146: 1999–2049, https://doi.org/10.1002/qj.3803

3. Bonanno et al. (2019) A new high-resolution Meteorological Reanalysis Italian Dataset: MERIDA. Q J R Meteorol Soc.; 145: 1756-1779

4. Schimanke et al. (2021) CERRA sub-daily regional reanalysis data for Europe on model levels from 1984 to present, https://cds.climate.copernicus.eu/

5. Raffa et al. (2021) VHR-REA_IT Dataset: Very High-Resolution Dynamical Downscaling of ERA5 Reanalysis over Italy by COSMO-CLM, Data, 6(8)

6. Mitchell & Jones (2005) An improved method of constructing a database of monthly climate observations and associated high resolution grids, IJC, 25, 693–712

7. Vannucchi et al. (2021) Dynamical downscaling of ERA5 data on the north-western Mediterranean sea: From atmosphere to high-resolution coastal wave climate, Journal of Marine Science and Engineering 9, doi:10.3390/jmse902020

8. Bollmeyer et al. (2015) Towards a high-resolution regional reanalysis for the European CORDEX domain, Q J R Meteorol Soc.; 141, 1-15

9. Capecchi et al. (2023) A convection-permitting and limited-area model hindcast driven by ERA5 data: precipitation performances in Italy, CD 61, 1411–1437

10. Giordani et al. (2023) SPHERA, a new convection-permitting regional reanalysis over Italy: Improving the description of heavy rainfall, QJRMS 149(752), 781–808

11. Isotta et al. (2015) Evaluation of European regional reanalyses and downscalings for precipitation in the Alpine region, Meteorologische Zeitschrift, 24, 15-37

12. Casati et al. (2004) A new intensity scale approach for the verification of spatial precipitation forecasts, Meteorological Applications, 11, 141–154

13. Crespi et al. (2018) 1961–1990 high-resolution monthly precipitation climatologies for Italy, Int J Climatol, 38: 878-895

14. Italian Civil Protection Department, CIMA (2014) The Dewetra platform: a multi-perspective architecture for risk management during emergencies

15. Lavers et al. (2022) An evaluation of ERA5 precipitation for climate monitoring, Q J R Meteorol Soc. 2022;148:3152–3165

# Reanalysis specifics

| Name | Developing group | NWP Model | I.C. and B.C. | Grid spacing | Assimilated data | Convection-permitting |
|---|---|---|---|---|---|---|
| **ERA5** | ECMWF | IFS CY41R2 | / | 0.25° | see ERA5 User Guide | No |
| **CERRA** | ECMWF | ALADIN | ERA5 | 5.5 km | post-processed GNSS-RO (radio occultation) and GNSS-ZTD (zenith total delay) | No |
| **COSMO-REA6** | DWD | COSMO | ERA-Interim | 6 km | continuous nudging of radiosondes, aircraft measurements, wind profiler and station data | No |
| **MERIDA** | RSE | WRF-ARW v3.9 | ERA5 | 0.07° | spectral nudging of Φ, u and v wind components, and T. T2m observation nudging. | No |
| **BOLAM** | LaMMA | BOLAM | ERA5 | 0.07° | None | No |
| **MERIDA-HRES** | RSE | WRF | ERA5 | 0.04° | spectral nudging of Φ, u and v wind components, and T. T2m observation nudging. Assimilation of MERRA2 aerosol data. | Yes |
| **MOLOCH** | LaMMA | MOLOCH | BOLAM | 0.0247° | None | Yes |
| **VHR-REA_IT** | CMCC | COSMO-CLM v5.0 | ERA5 | 0.02° | None | Yes |
| **SPHERA** | ARPAE | COSMO v5.05 | ERA5 | 0.02° | continuous nudging of p, u and v wind components, hum. and T. | Yes |

# Observations interpolation

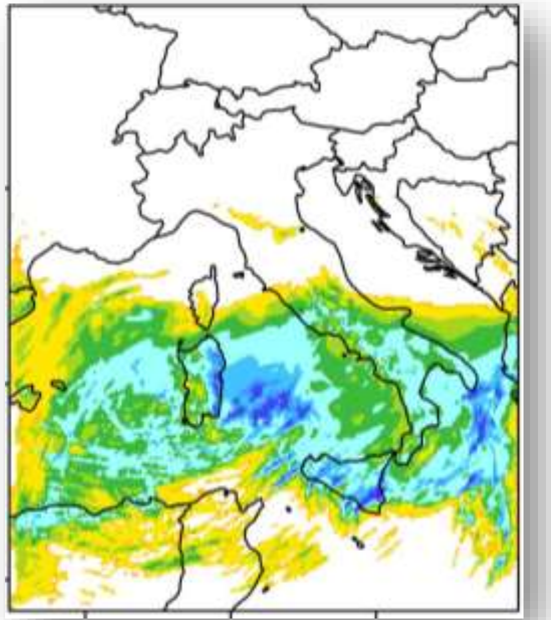
- Based on anomaly method [Mitchell & Jones, 2005]
- Climatologies
  - Method: weighted linear regression of precipitation vs. elevation [Crespi et al., 2021]
  - Station data: from 6134 weather stations evenly distributed over Italian territory
- Anomalies
  - Method: weighted angular mean [Gonzalez-Hidalgo et al., 2011]
  - Station data: from 1000 to 3000 stations depending on the period
- Reference person for observations interpolation: Michele Brunetti (ISAC-CNR)

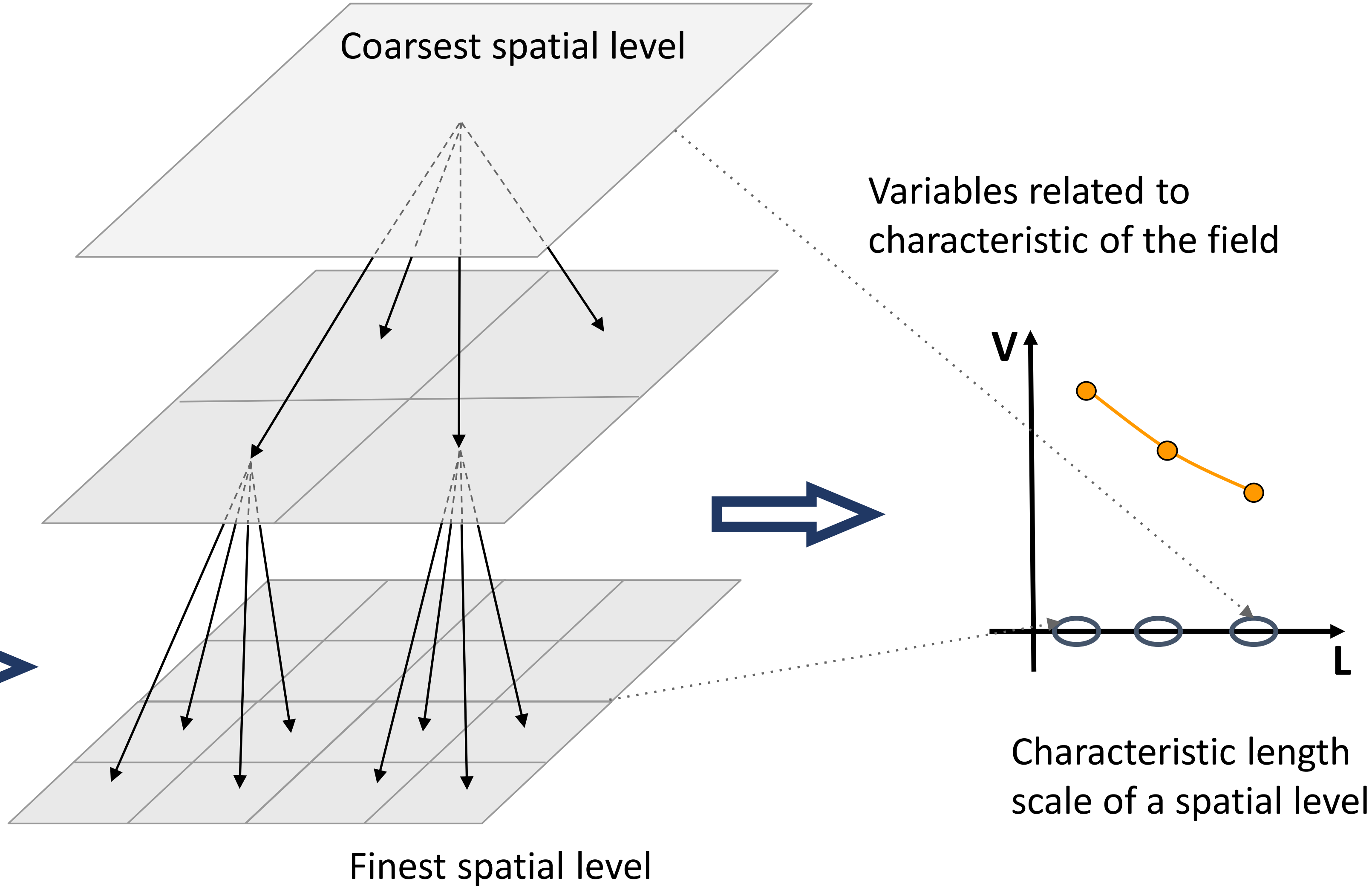
# 2d Haar wavelets [Casati et al., 2023]

Graphical elaboration from
EMS2022-181 UP3.6 (2022-9-7)
by Cristian Lussana et al.

Powerful way to look at data with different spatial scales of variation (multi-resolution decomposition)

Original field





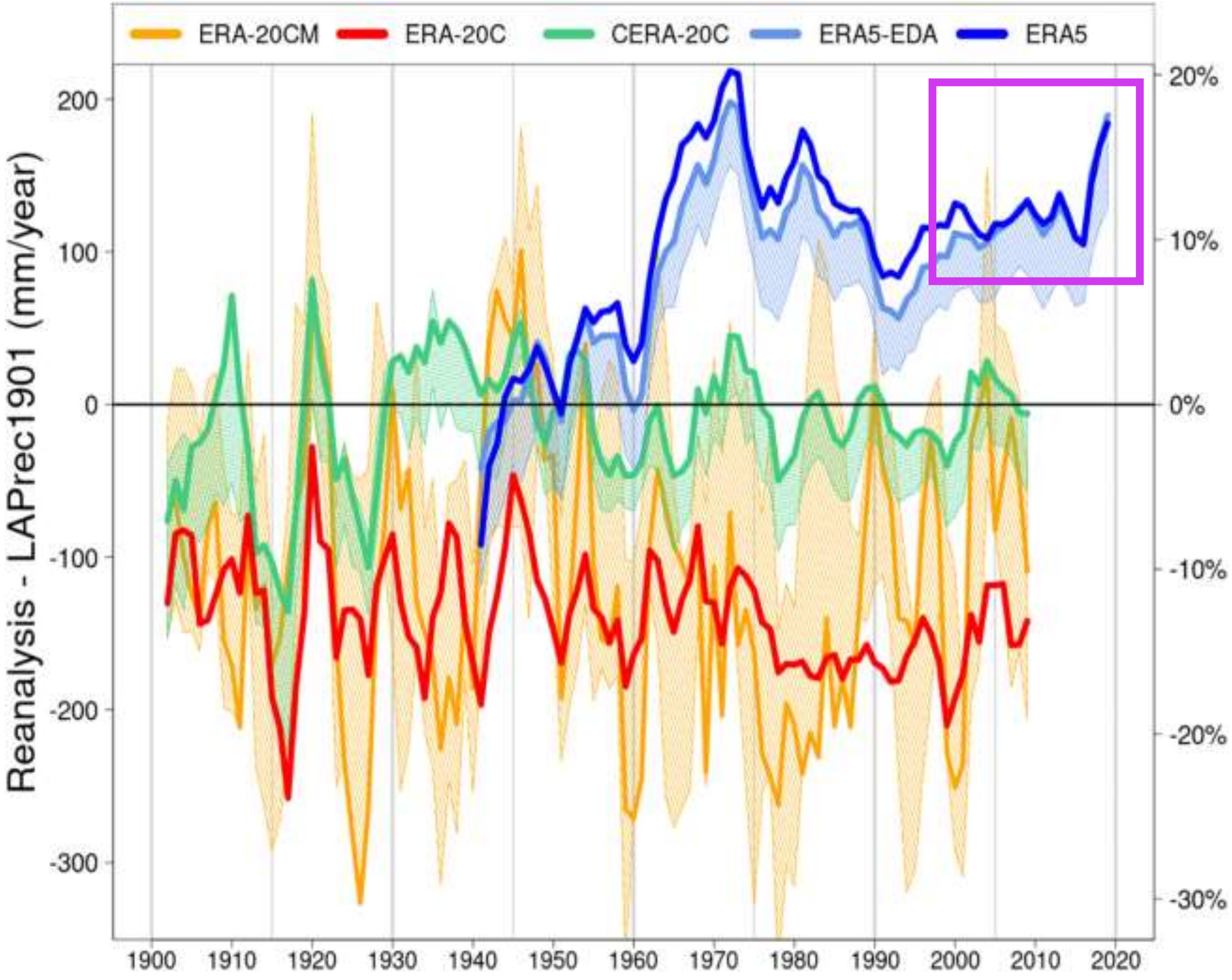
# SEEPS Skill Score [Haiden et al., 2012]

- $p_1$ = probability of at least 1 mm rain

$$
SS = 1 - \begin{matrix} \text{dry rean} \\ \text{light rean} \\ \text{heavy rean} \end{matrix}
\overset{\begin{matrix}\text{dry obs} & \text{light obs} & \text{heavy obs}\end{matrix}}{\begin{pmatrix} \dots & \dots & \dots \\ \dots & \dots & \dots \\ \dots & \dots & \dots \end{pmatrix}}
\cdot 1/2 \begin{pmatrix} 0 & \frac{1}{1-p_1} & \frac{4}{1-p_1} \\ \frac{1}{p_1} & 0 & \frac{3}{1-p_1} \\ \frac{1}{p_1} + \frac{3}{2+p_1} & \frac{3}{2+p_1} & 0 \end{pmatrix}
$$

- takes value 0 for no skill, 1 for perfect skill

# Time stability before 1995 [Lussana et al., 2024]




- Compared annual cumulates averaged over Alps against observations
- Other global reanalyses as reference
- ERA5 shows anomalous long-term trends against observations

→ becomes challenging to understand if precipitation trends from ERA5 are actually climatic signals or a result of data assimilation

Figure from: Lussana, C., Cavalleri, F. et al. (2024), *Evaluating long-term trends in annual precipitation: a temporal consistency analysis of ERA5 data in the Alps and Italy*, Atmospheric Sciences Letters, e1239, https://doi.org/10.1002/asl.1239