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STRENGTHENING THE RESEARCH CAPACITIES
FOR EXTREME WEATHER EVENTS IN ROMANIA

SUMMER SCHOOL ON AI USE FOR CLIMATE EXTREMES 2026

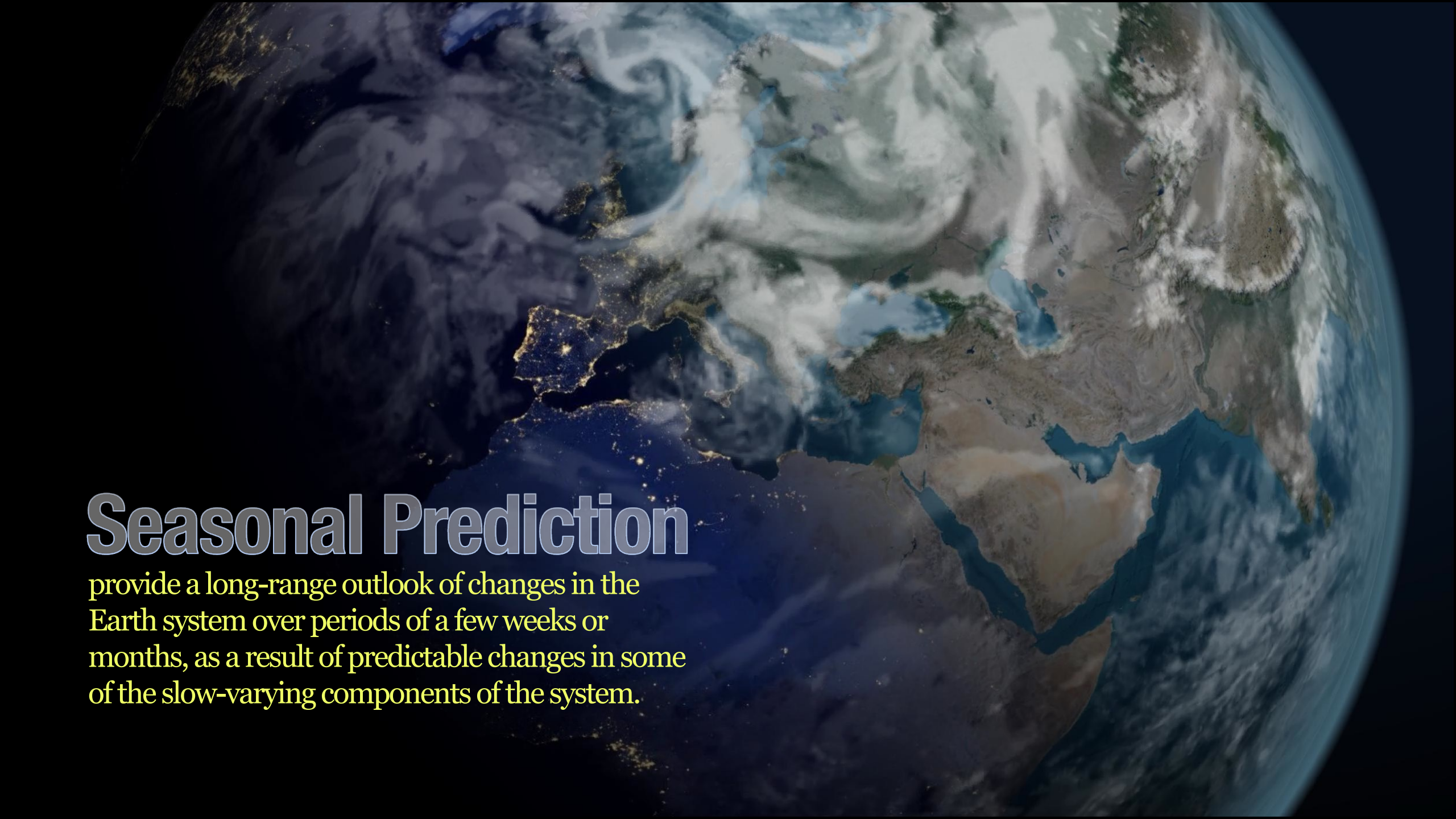
STATISTICAL DOWNSCALING USING MACHINE LEARNING TECHNIQUES

Bridging global seasonal forecast knowledge with local decision-making processes

Leonardo Aragão[1], Andrea Borrelli[2] & Silvio Gualdi[1]

CMCC Foundation - Euro-Mediterranean Center on Climate Change
[1]Earth SYstem modeling and Data Assimilation (ESYDA)
[2]CLImate VAriability and Predictions (CLIVAP)

Funded by the European Union
Grant Agreement 101159497



Seasonal Prediction

provide a long-range outlook of changes in the Earth system over periods of a few weeks or months, as a result of predictable changes in some of the slow-varying components of the system.



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to forecast ✗ to predict

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weather climate

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weather — climate

product — process

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to forecast		to predict
weather		climate
product		process
time-stamped		outlook

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to forecast		to predict
weather		climate
product		process
time-stamped		outlook
short-range		long-range

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to forecast		to predict
weather		climate
product		process
time-stamped		outlook
short-range		long-range
event		slow-varying

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to forecast		to predict
weather		climate
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event		slow-varying
deterministic model	✗	Earth system

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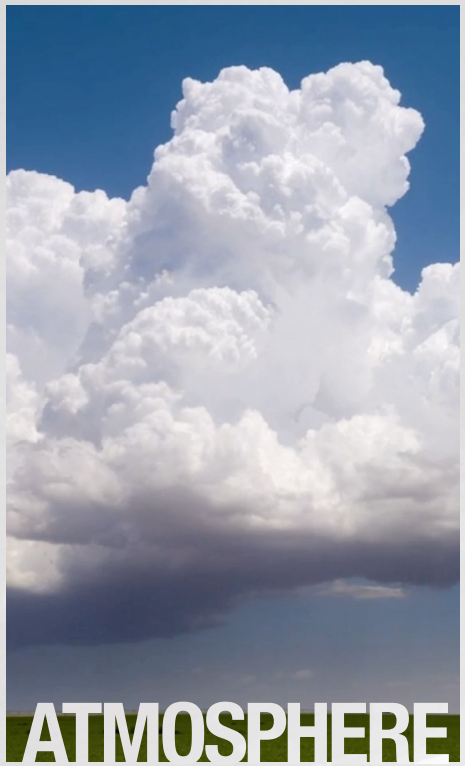


EARTH SYSTEM

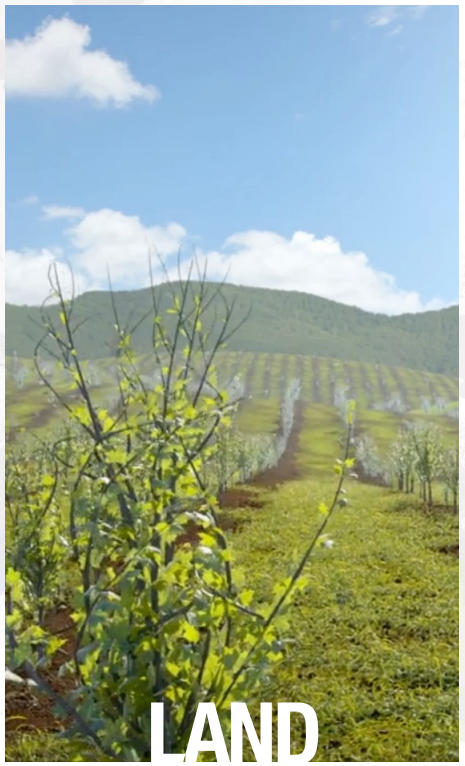
EARTH SYSTEM MODELS

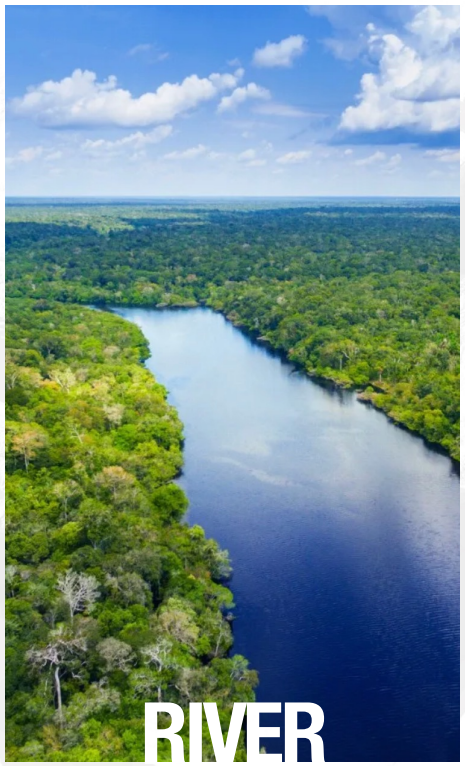
CMCC Seasonal Prediction System v4

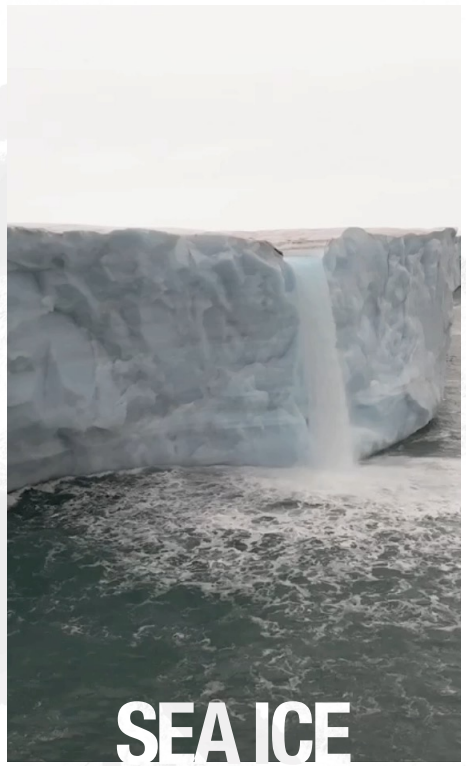
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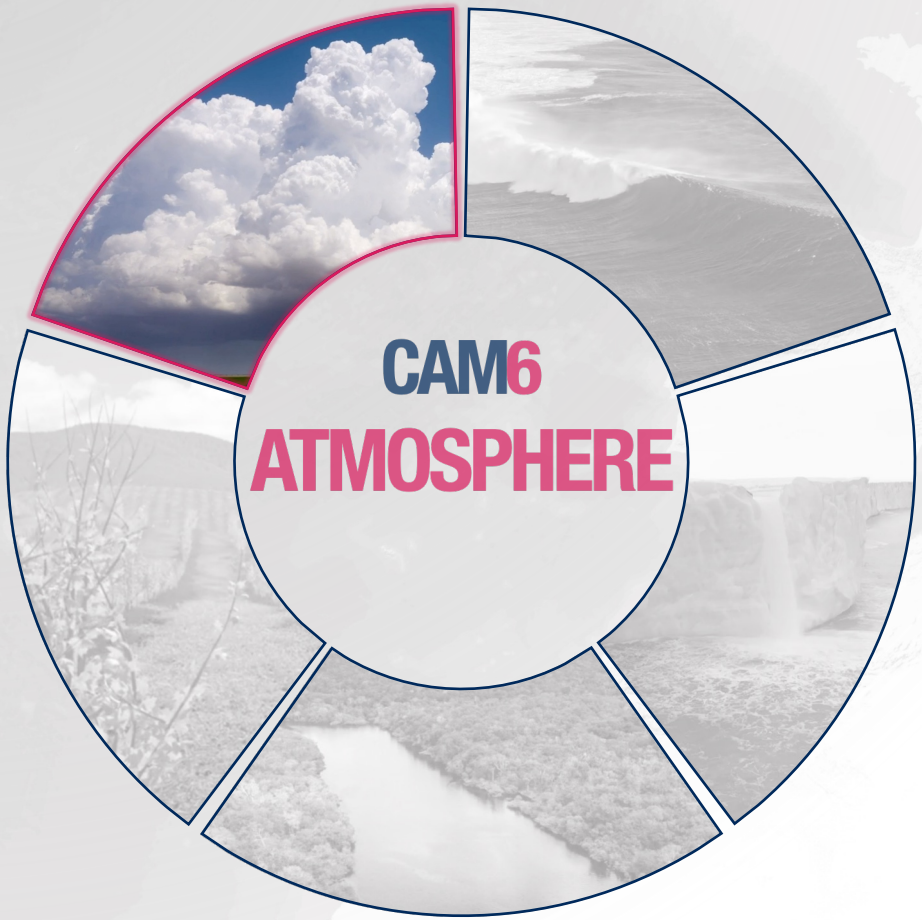


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EARTH SYSTEM MODELS

CMCC Seasonal Prediction System v4 (v3.5)

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Community Atmosphere Model version 6 (5.3)

Craig *et al.* (2021)

- Atmospheric component of the NCAR's Community Earth System Model (CESM)
- Regular grid of 0.47° (latitude) × 0.63° (longitude)
- 83 vertical hybrid levels
- Troposphere and Stratosphere up to 0.01 hPa

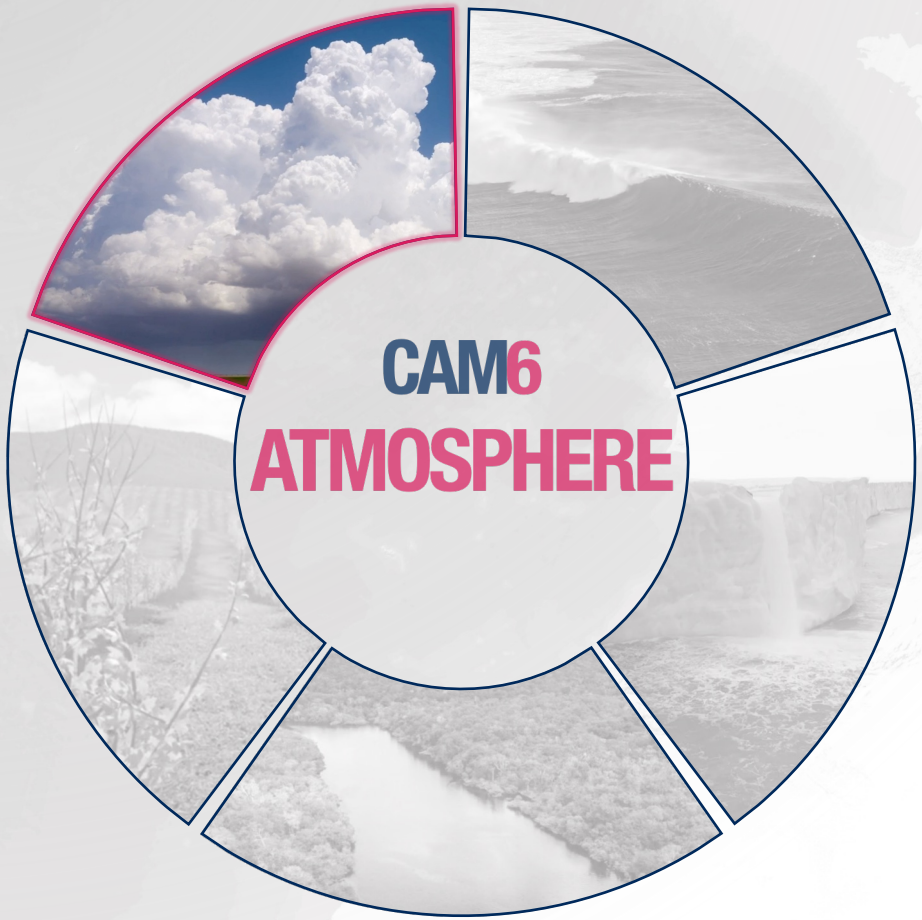
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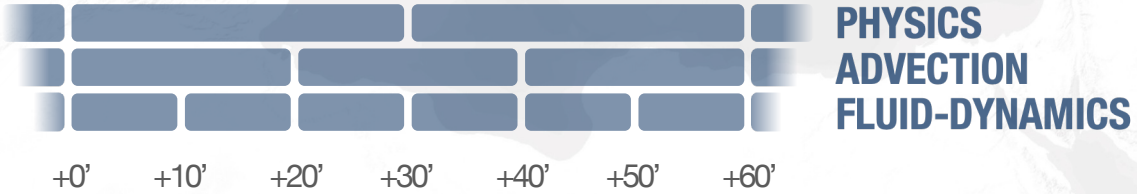


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Time-steps:



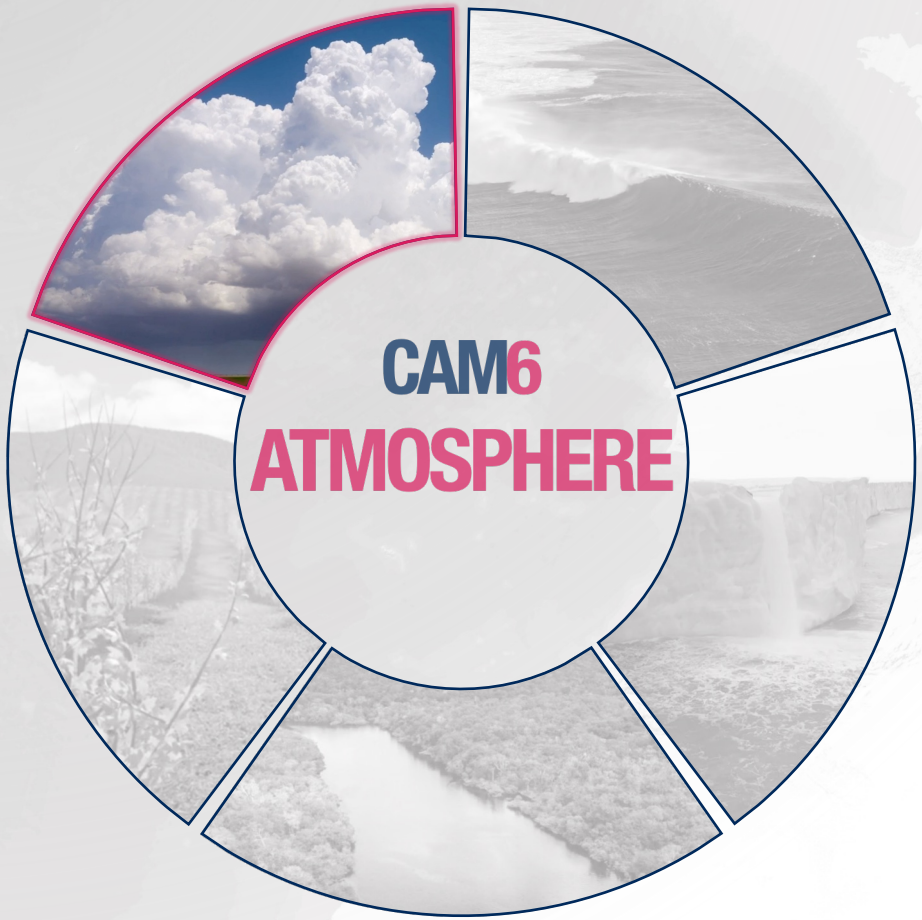
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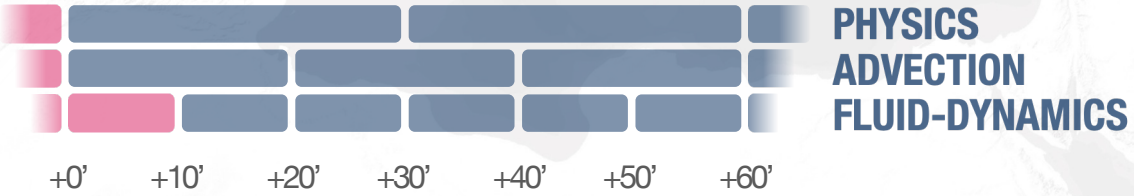


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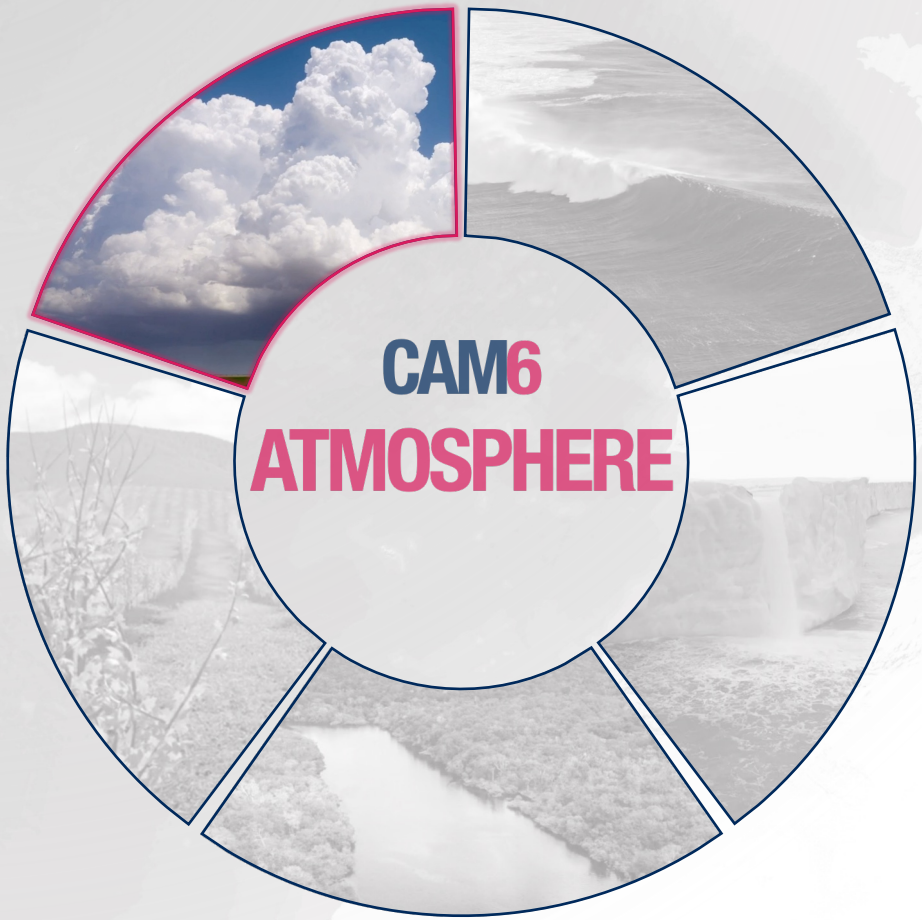
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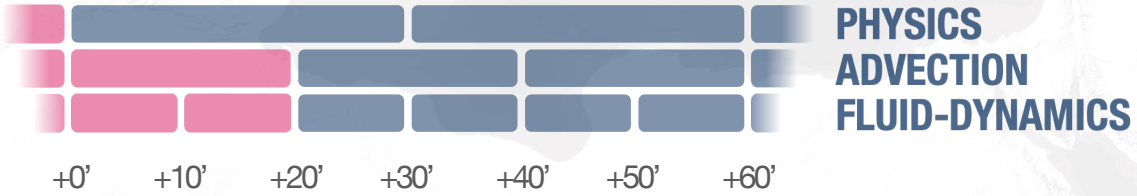


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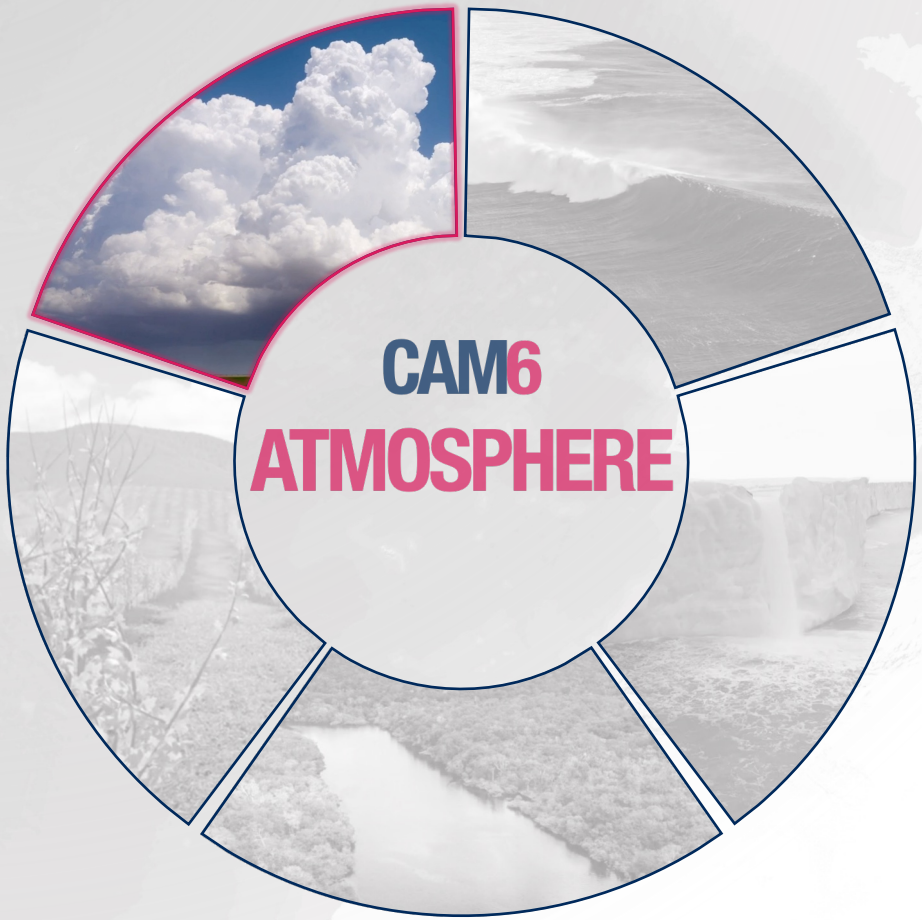
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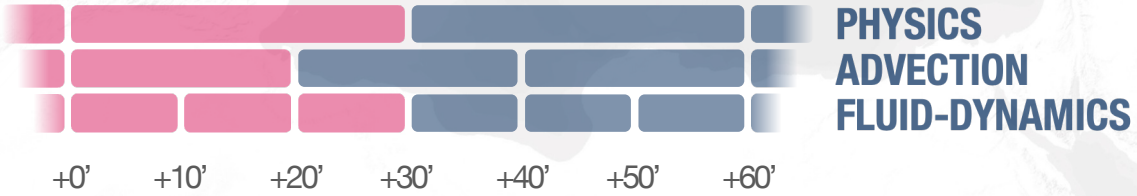


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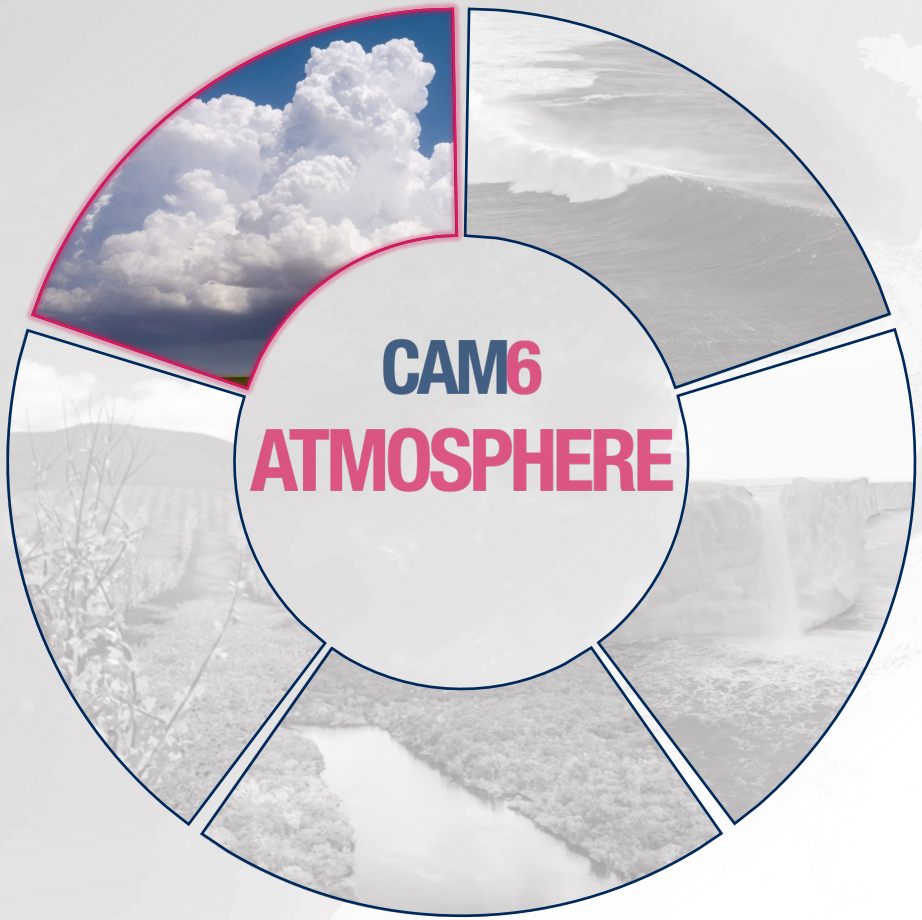
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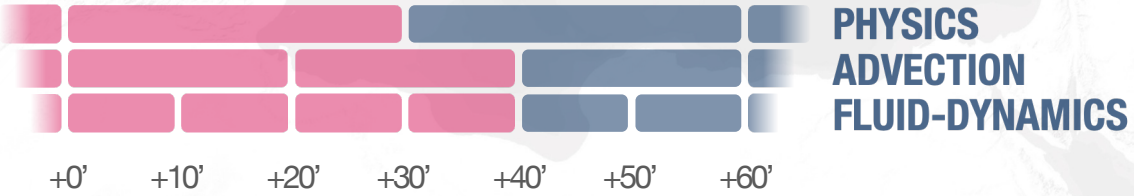


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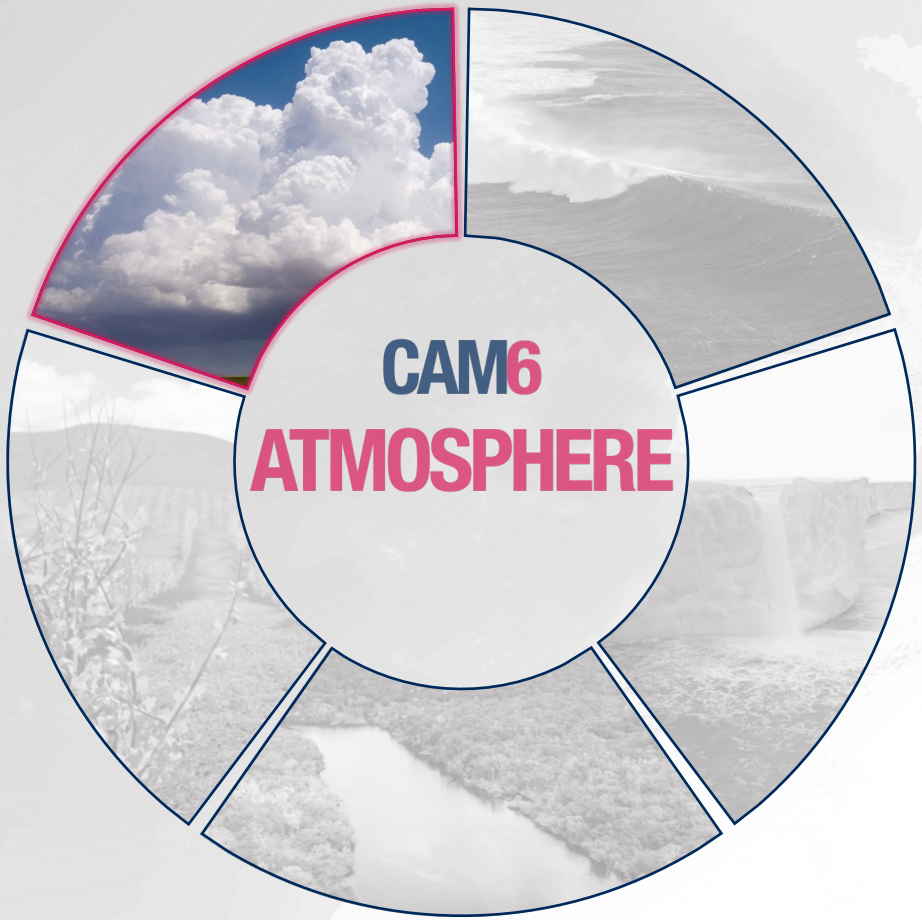
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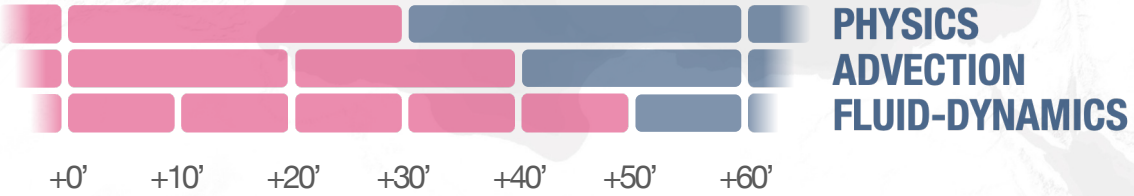


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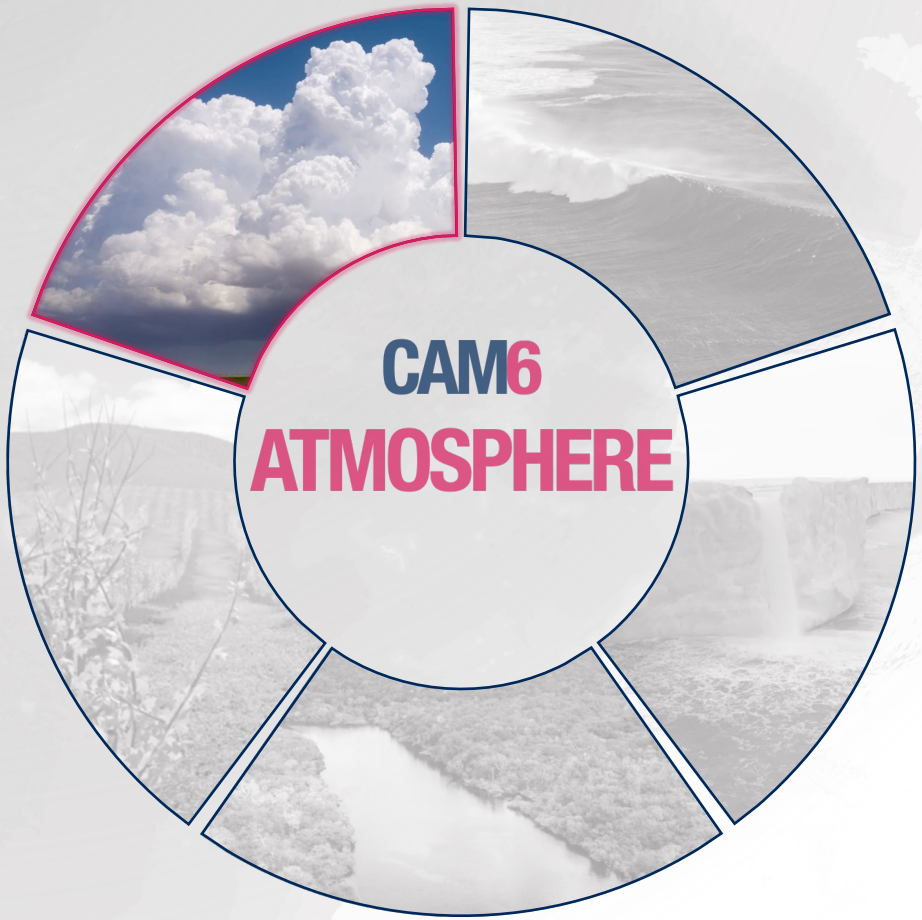
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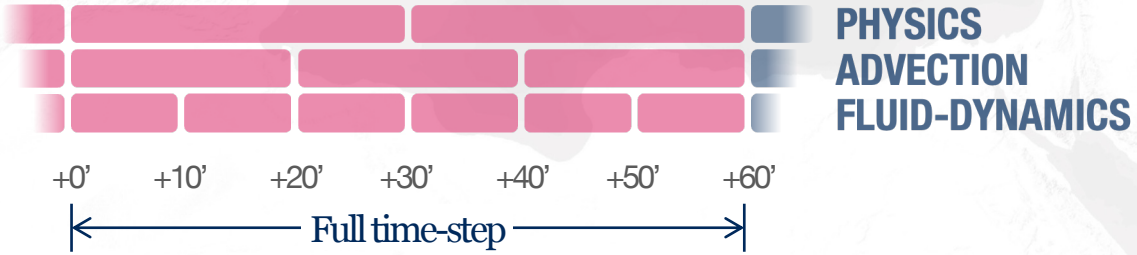


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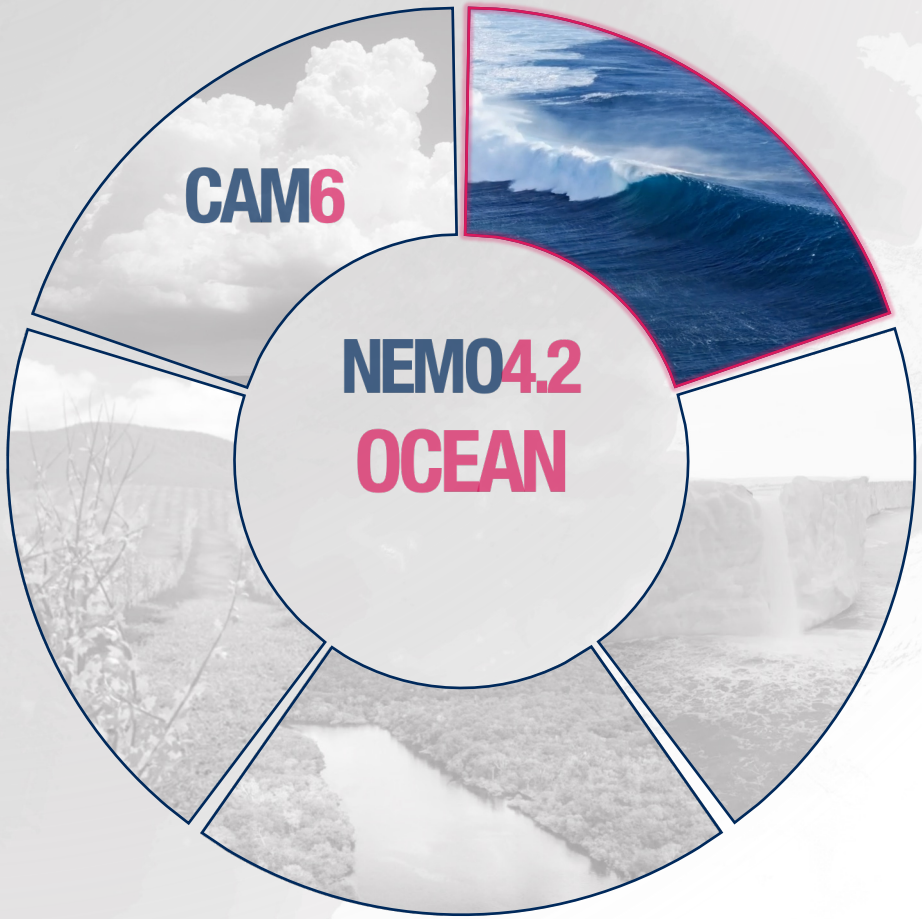
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EARTH SYSTEM MODELS

CMCC Seasonal Prediction System v4 (v3.5)

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Nucleus for European Modelling of the Ocean model version 4.2 (3.4)

Madec *et al.* (2022)

- Tripolar ORCA grid of 0.25 °
- 75 vertical levels
- 20-minute time-step
- Prognostic variables: three velocity components, the sea surface height, the potential temperature, and salinity

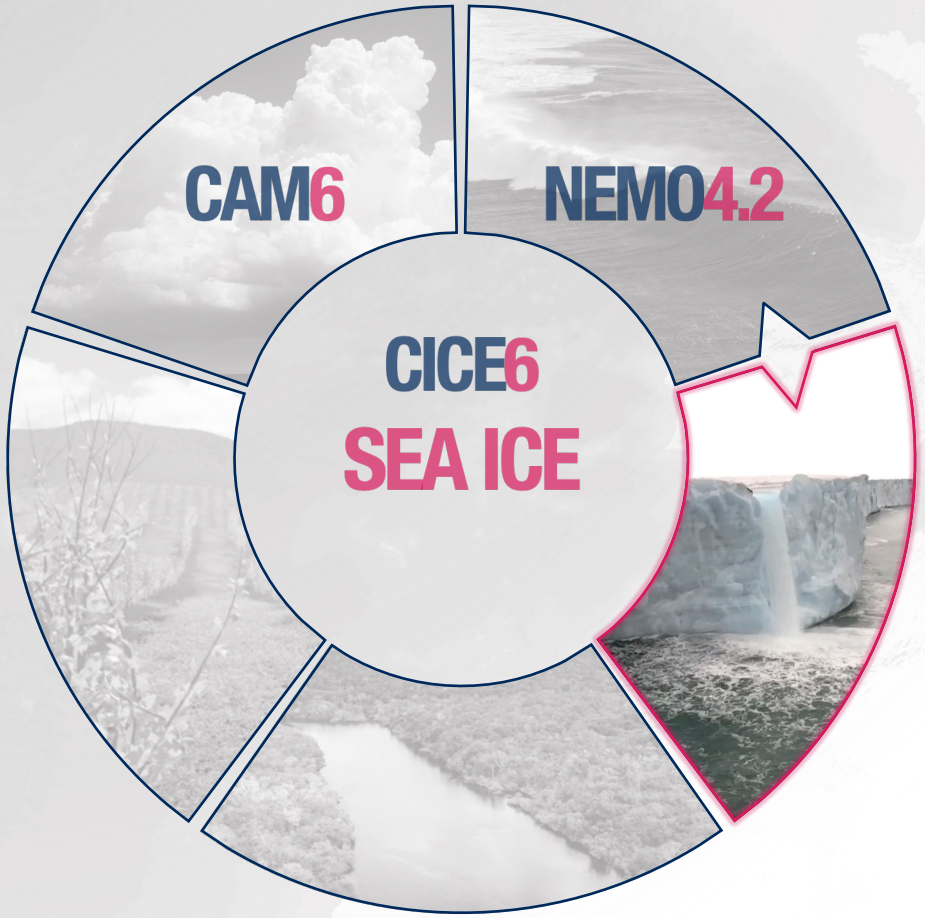
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EARTH SYSTEM MODELS

CMCC Seasonal Prediction System v4 (v3.5)

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Los Alamos sea ICE model version 6 (4)

Hunke *et al.* (2018)

- Consortium ICE
- Integrated with NEMO (coupled): Tripolar ORCA grid of 0.25°
  20-minute time-step
- 8 ice layers
- 3 snow layers
- 5 ice categories (single)
- No wave model

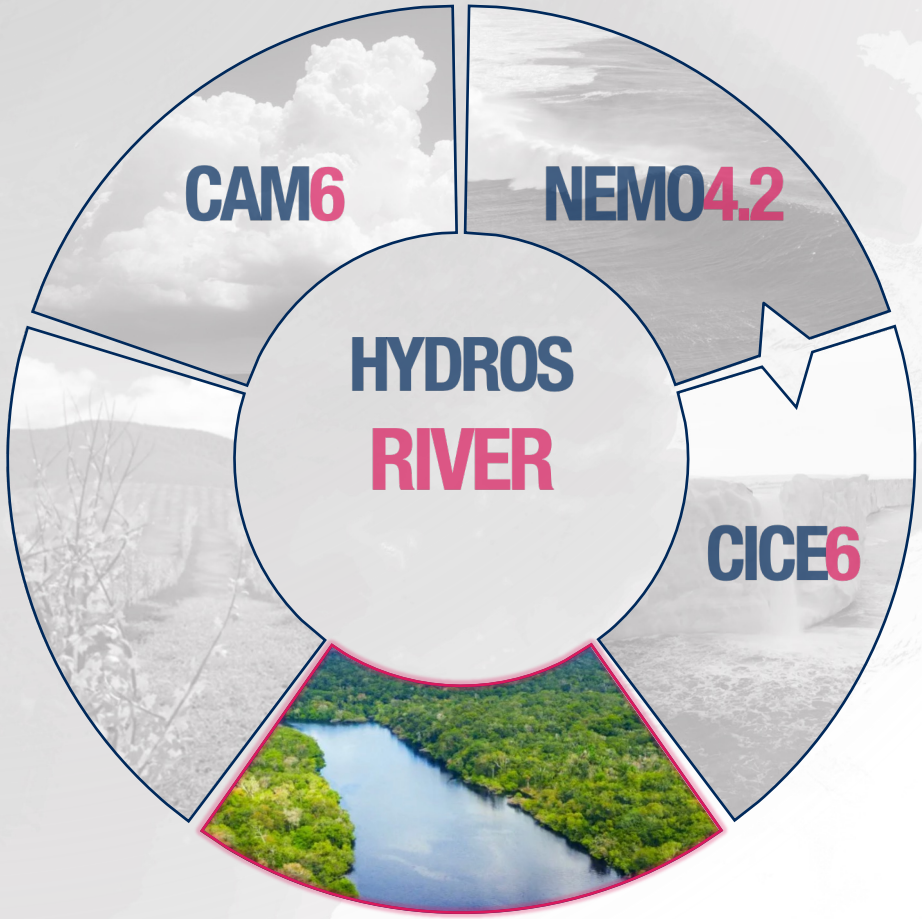
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HYdro-Dynamic ROuting Scheme (RTM)

Materia *et al.* (2020)

- Replaces the River Transport Model (RTM, Graham *et al.* 1999)
- A more complex scheme for computing the flow velocity
- Generates time-dependent flow velocity influenced by orography and water availability
- Regular grid of 0.5°
- 3-hour time step
- Receive input data from the land surface model

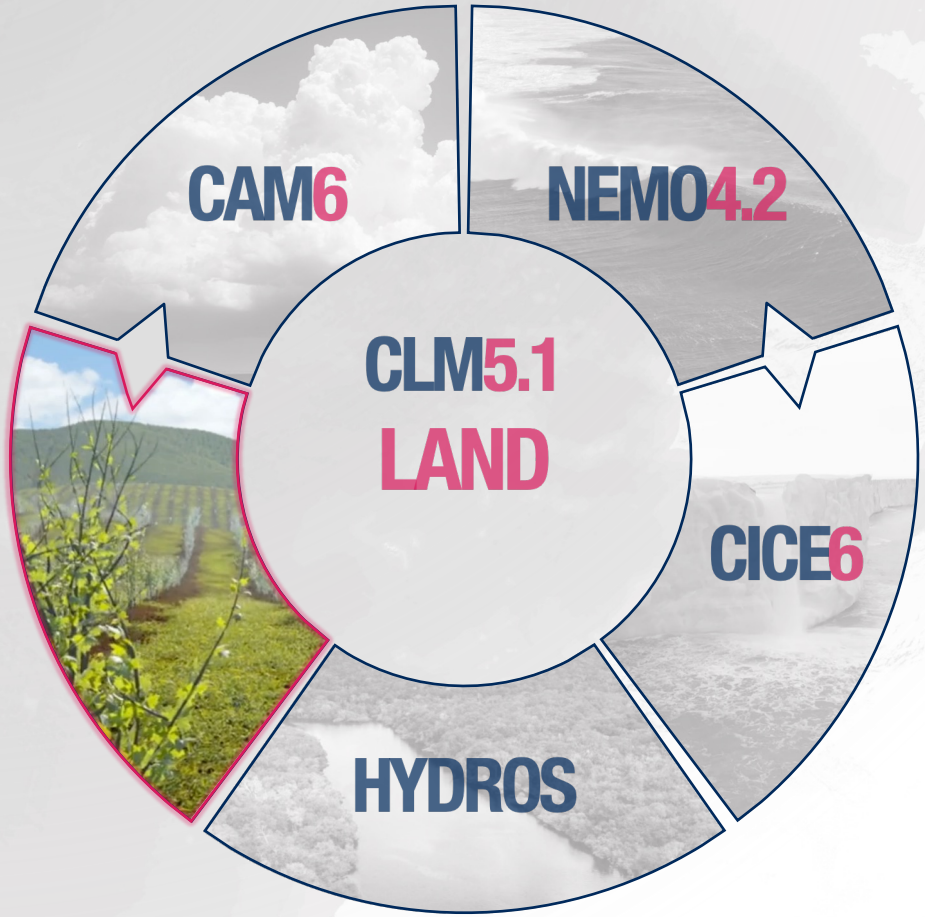
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EARTH SYSTEM MODELS

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Community Land Model version 5.1 (4.5)

Lawrence *et al.* (2019)

- Land/Surface component of the NCAR's Community Earth System Model (CESM)
- Integrated with CAM6 (coupled): Regular grid of 0.47° (latitude) × 0.63° (longitude)
  30-minute time step
- 20 soil layers (down to 20 m)
- 5 bedrock layers (down to 42 m)
- Snow density parameterisation accounting for a tuning factor to adjust the snow ageing
- Biogeochemical cycles included

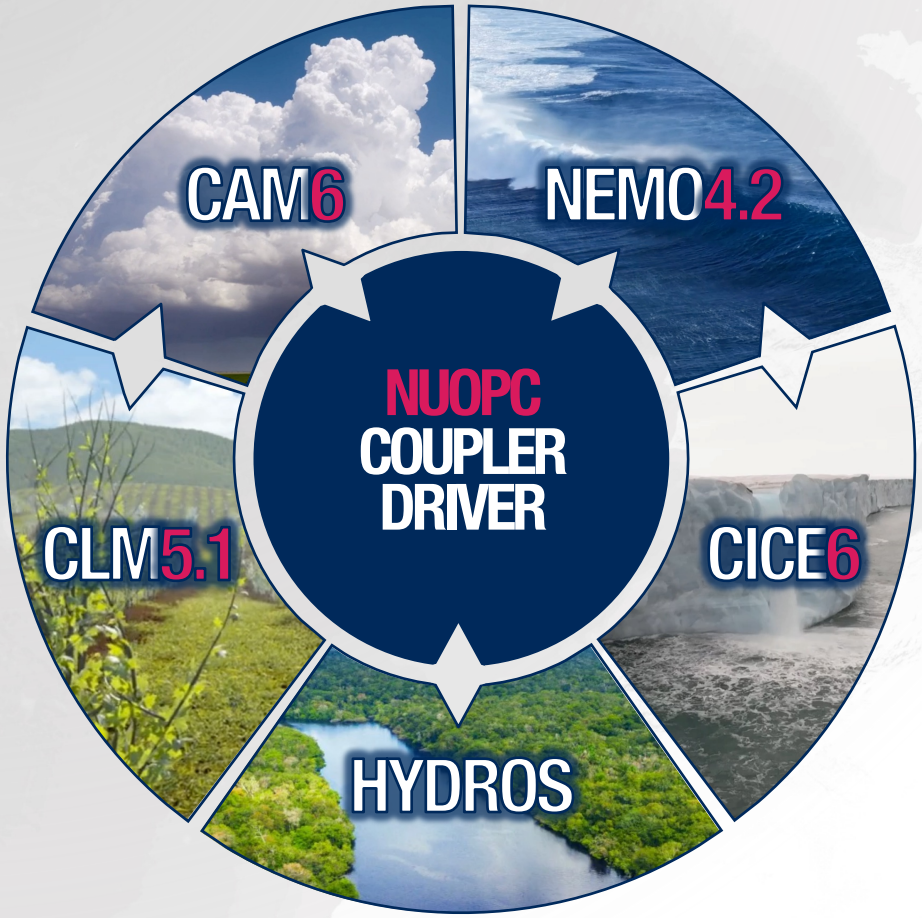
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EARTH SYSTEM MODELS

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National Unified Operational Prediction Capability

Earth System Modelling Framework

- Coupler component of the NCAR's Community Earth System Model (CESM)
- Atmosphere-Ocean 60 minutes (full time-step of the atmospheric model)
- Atmosphere-Land 30 minutes (internally in CAM6)
- Ocean-Sea Ice 20 minutes (internally in NEMO4.2)
- Land-River 180 minutes (3x full time-step of the atmospheric model)

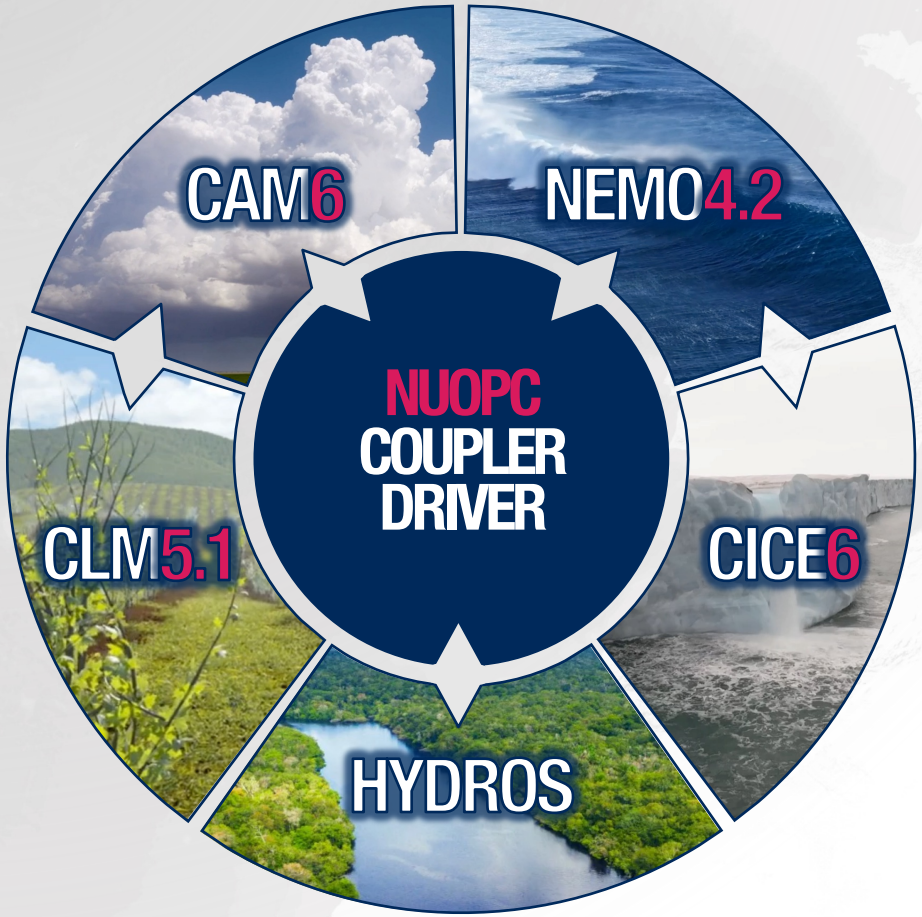
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EARTH SYSTEM MODELS

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INITIALISATIONS & ENSEMBLE

Copernicus Climate Change Services (C3s) framework

Perturbed Initial Conditions

10 Atmosphere x **3** Land x **9** Ocean = **270** Possibilities

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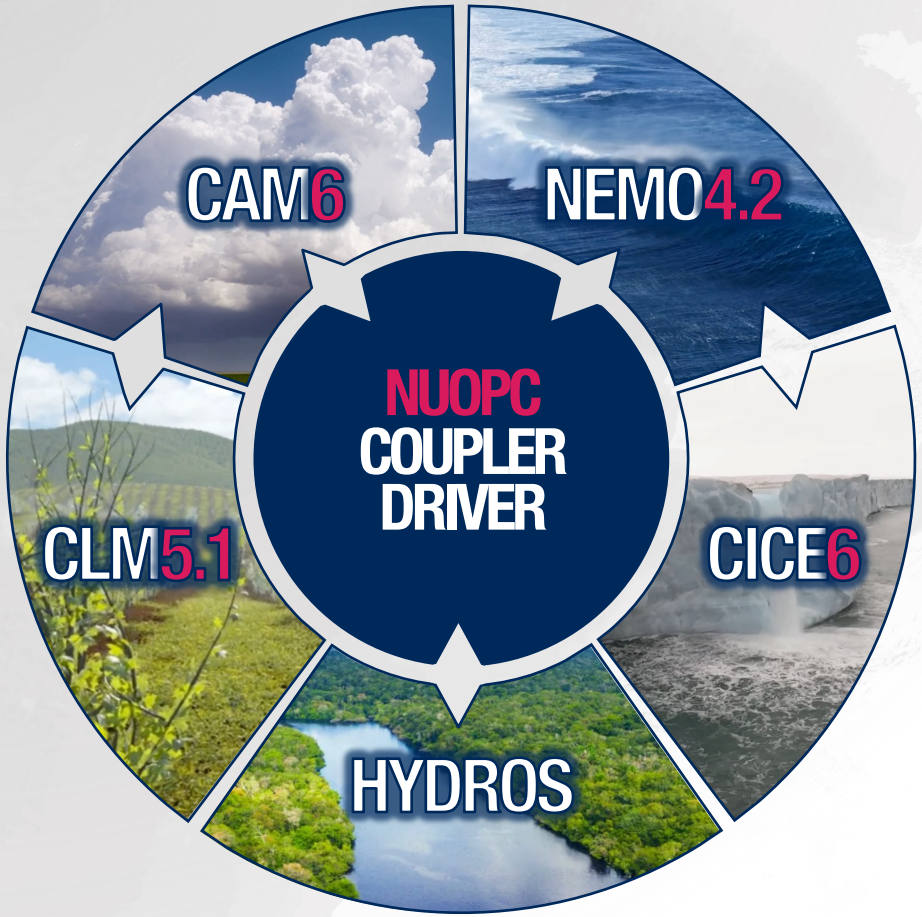
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INITIALISATIONS & ENSEMBLE

Copernicus Climate Change Services (C3s) framework

270 Possibilities

Random Selection

50 Ensemble Members*

*Hindcast mode (30 in forecast mode).

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EARTH SYSTEM MODELS

CMCC Seasonal Prediction System v4 (v3.5)

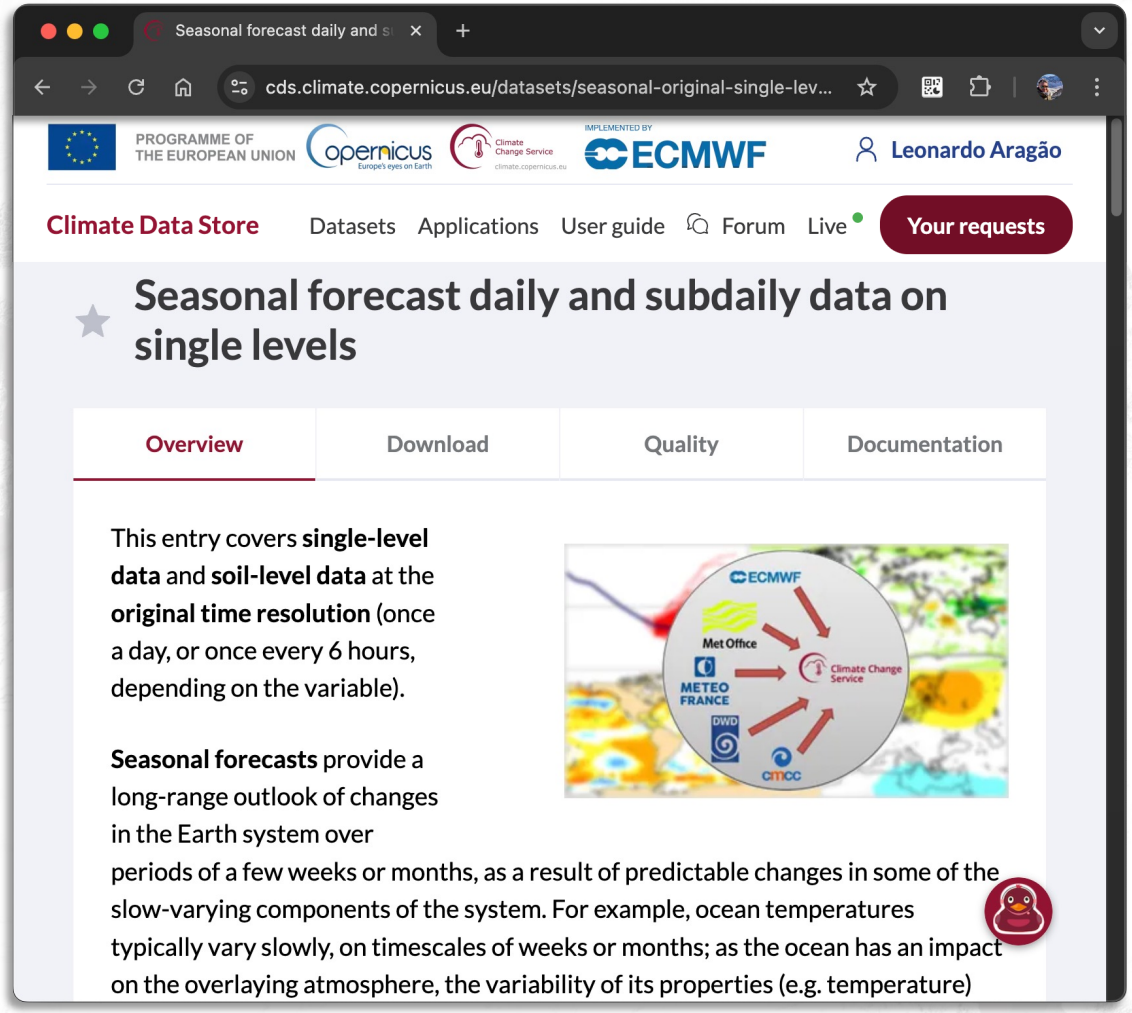
INITIALISATIONS & ENSEMBLE

Copernicus Climate Change Services (C3s) framework

270
Possibilities

Random Selection

50
Ensemble Members*



*Hindcast mode (30 in forecast mode).

More information in: Sanna *et al.* (2025) // DOI 10.25424/cmcc-dkcv-fs25

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CMCC Seasonal Prediction System v4 (v3.5)

SCEWERO

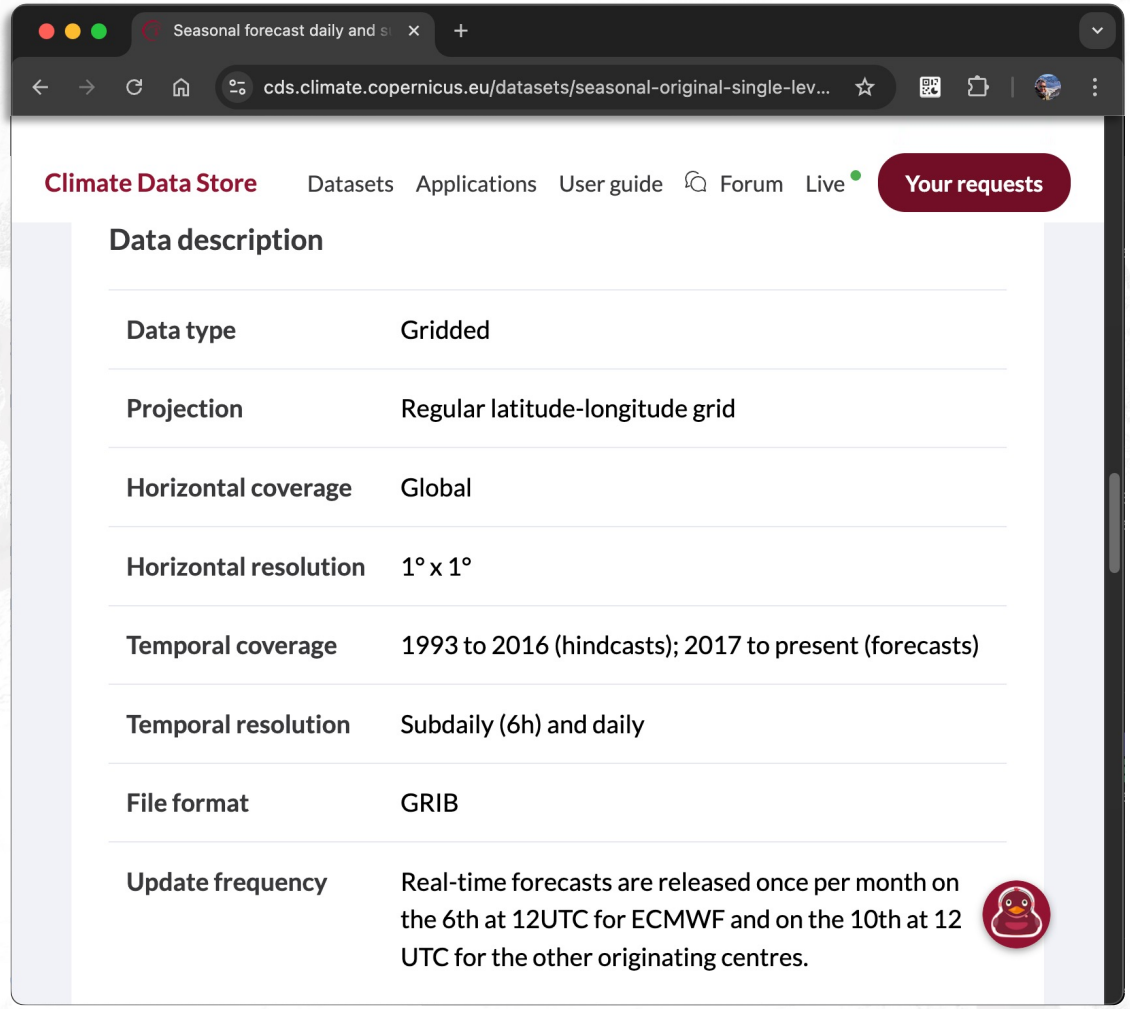
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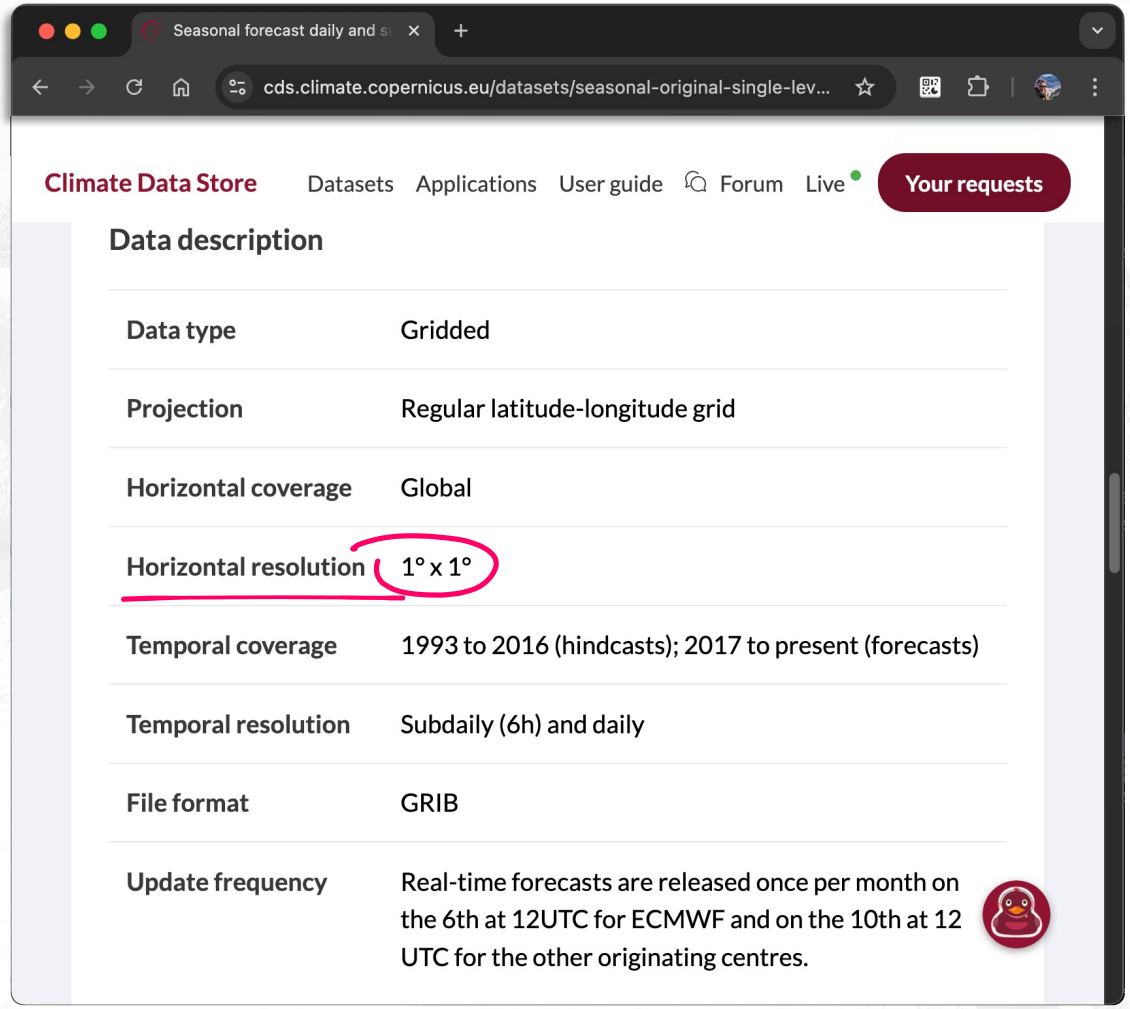
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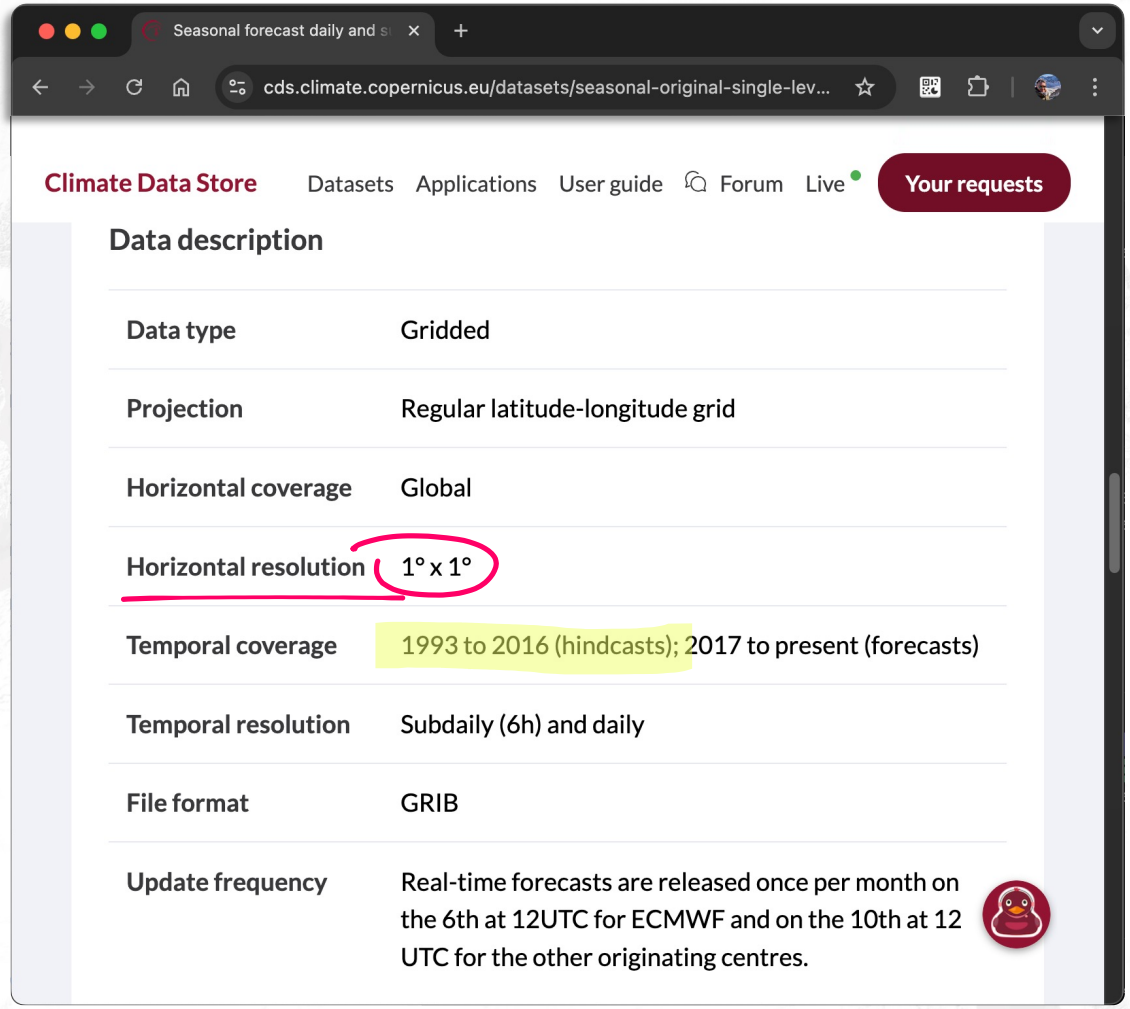
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STATISTICAL DOWNSCALING

SCEWERO

OUR SCOPE

"The general objective is to develop a computational algorithm in Python language that allows downscaling low-resolution meteorological data (historical or forecast) using machine learning techniques."

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EXPERIMENT

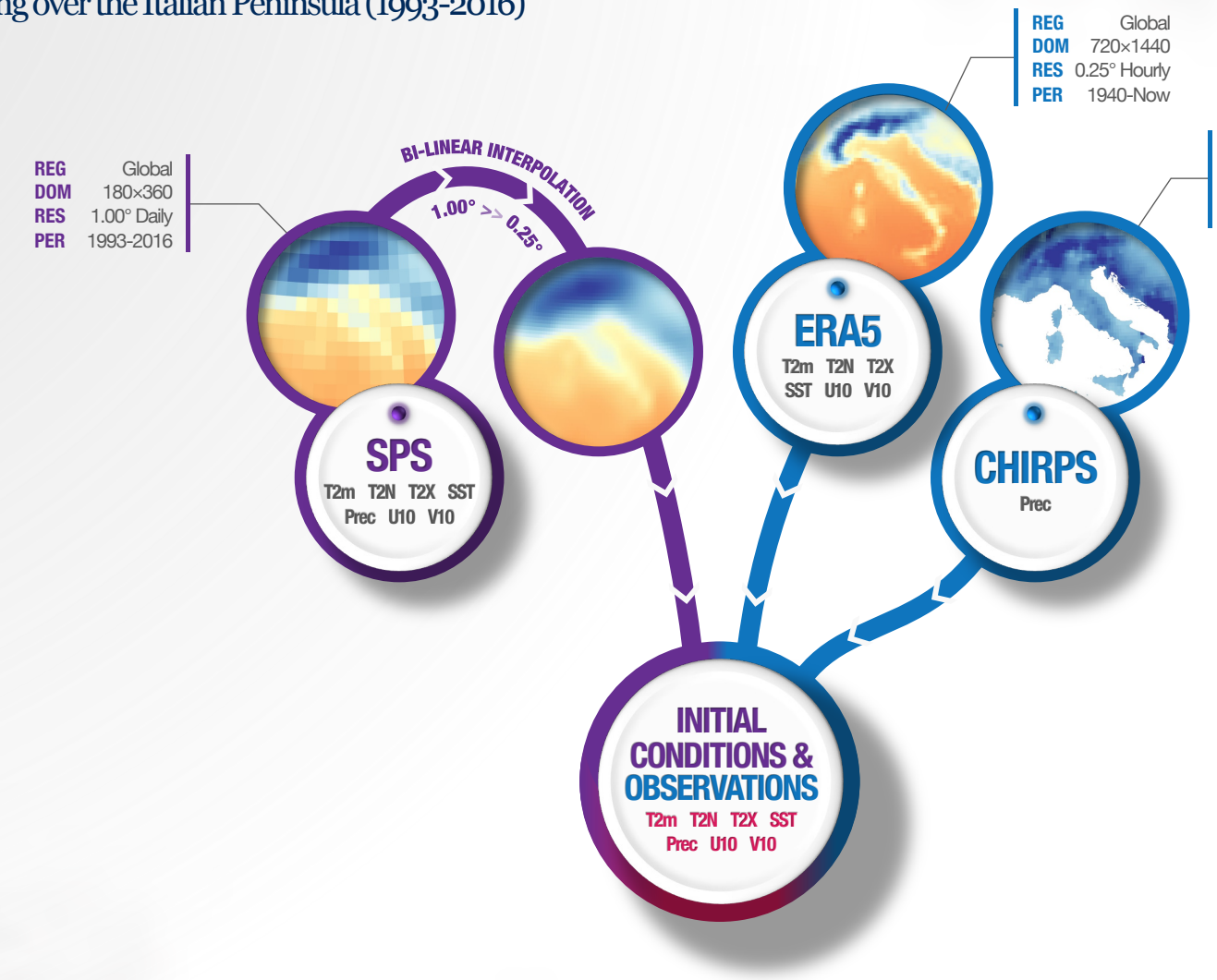
"To evaluate two different machine learning methods, Empirical Quantile Mapping (EQM) and k-Nearest Neighbours (kNN), in downscaling seven meteorological fields over the Italian Peninsula based on the 24-year hindcasts (1993-2016) of the CMCC Seasonal Prediction System v3.5 (SPS)."

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DATA & METHODS

SPS3.5 statistical downscaling over the Italian Peninsula (1993-2016)

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T2m	Daily average 2m Temperature
T2N	Daily minimum 2m Temperature
T2X	Daily maximum 2m Temperature
SST	Daily average Sea Surface Temperature
Prec	Daily Precipitation (accumulated)
U10	Daily average zonal wind component
V10	Daily average meridional wind component

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DATA & METHODS

SPS3.5 statistical downscaling over the Italian Peninsula (1993-2016)

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REG 50°N – 50°S
DOM 2000×7200
RES 0.05° Daily
PER 1981-Now

CHIRPS
Prec

REG Global
DOM 720×1440
RES 0.25° Hourly
PER 1940-Now

ERA5
T2m T2N T2X
SST U10 V10

BI-LINEAR INTERPOLATION
1.00° >> 0.25°

REG Global
DOM 180×360
RES 1.00° Daily
PER 1993-2016

SPS
T2m T2N T2X SST
Prec U10 V10

INITIAL CONDITIONS & OBSERVATIONS
T2m T2N T2X SST
Prec U10 V10

28-49°N / 03-22°E REG
85×77 DOM
0.25° Daily RES
1993-2016 PER
HOMOGENISED
to the Italian Peninsula

DIMENSIONS
345×5
$(w.p - w_{IC}) \times n$

n = 5 Predictors
p = 24 years (1993-2016)
w = 14+1 Days Window

Initial Condition window (w_{IC}) removed for Cross-Validation

WEATHER GENERATOR VARIABLES >>>
+T2N
+T2X

FEATURE VECTOR
T2m Prec SST
U10 V10

Euclidean Distance

k Analog Days

Proportional to Observational Time-series Length
$k = \sqrt{(w+1)p - 1} \approx 19$

BISQUARE WEIGHT FUNCTION

EACH DAY AVAILABLE IN EVERY HINDCAST START-DATE

kNN
T2m T2N T2X SST
Prec U10 V10

F_{SPS}
185 days
by start-date

F_{Obs}
185 Days
× 24 years

EMPIRICAL CUMULATIVE DISTRIBUTION FUNCTIONS
for each variable

q

QUANTILES' IDENTIFICATION

q

INVERSE FUNCTION

EQM
T2m T2N T2X SST
Prec U10 V10

$$M(x_{SPS}) = F_{Obs}^{-1}(F_{SPS}(x_{SPS}))$$

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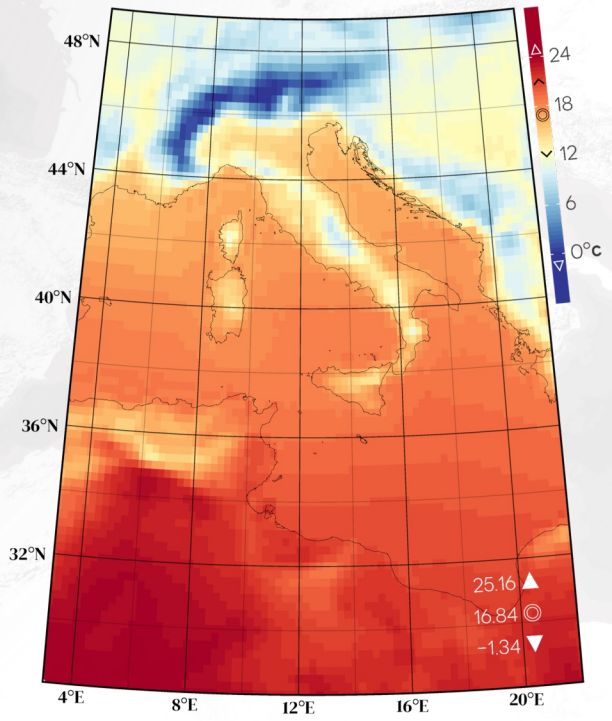
SUMMARISED RESULTS

SUMMARISED RESULTS

Ensemble annual mean (lead month 1) for the daily average 2m temperature (1993-2016)

SCEWERO

ERA5

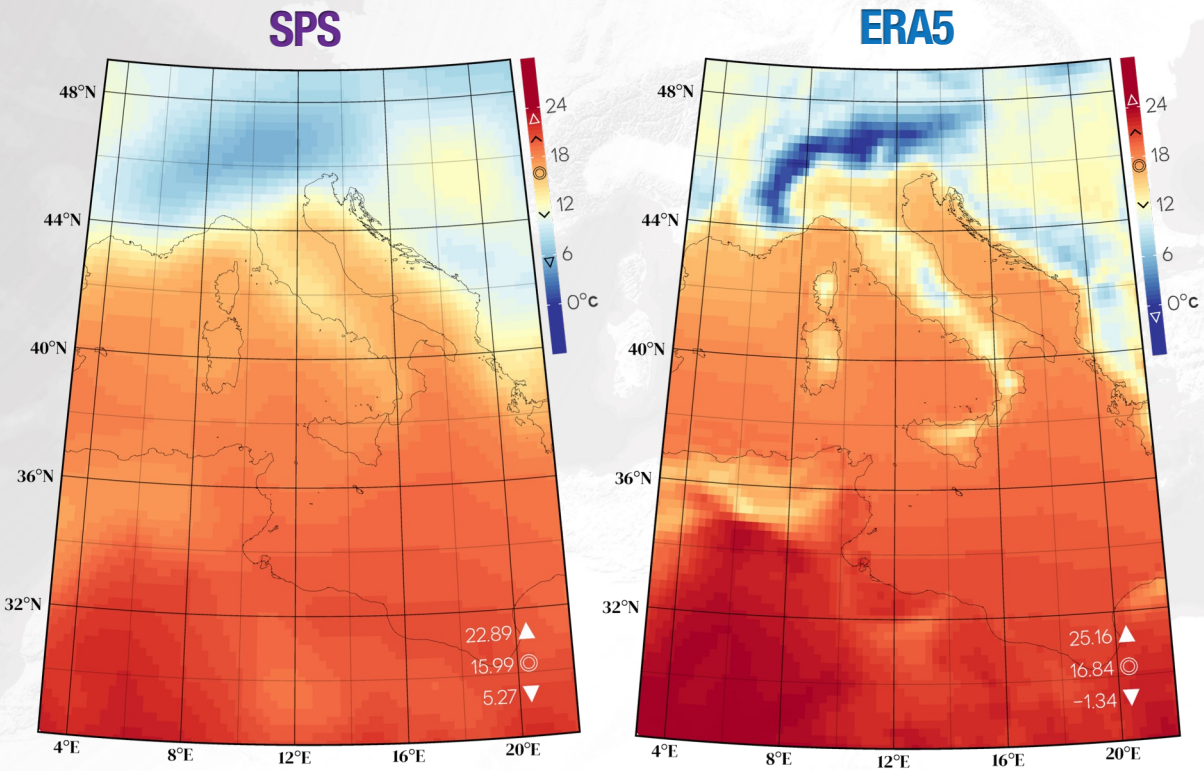


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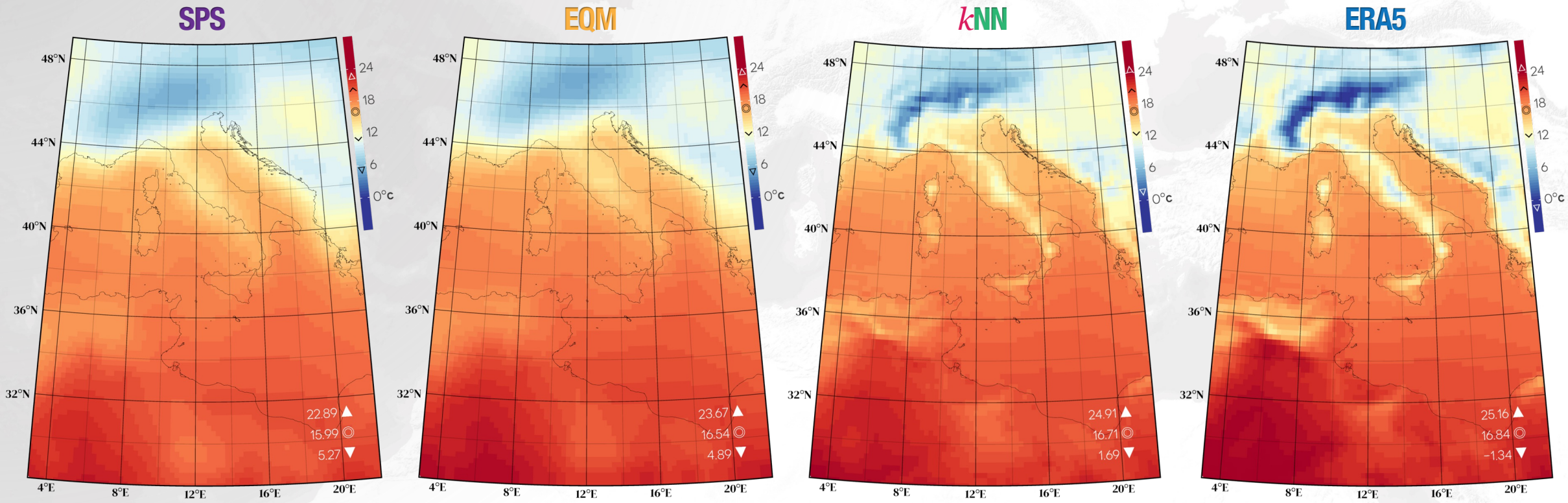


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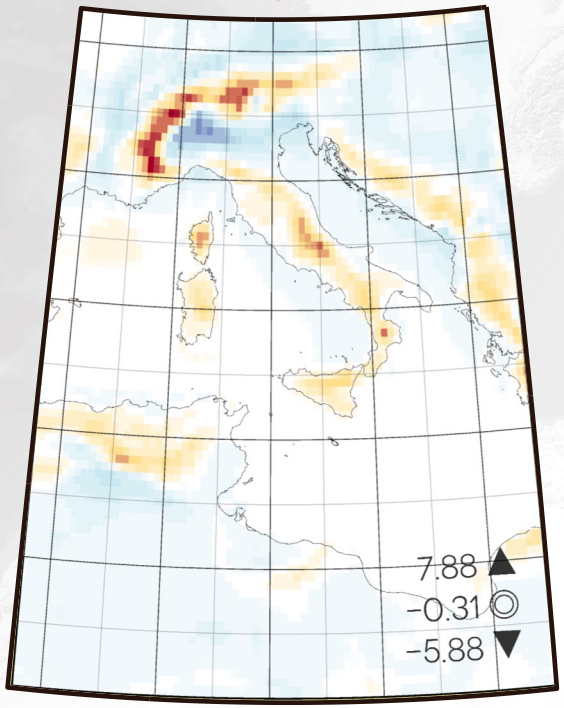
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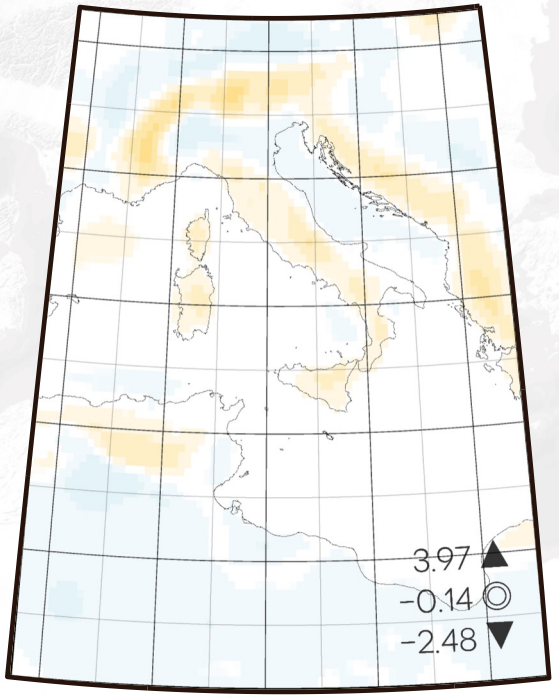
Ensemble annual mean (lead month 1) for the daily average 2m temperature Bias (1993-2016)

SCEWERO

EQM



*k*NN

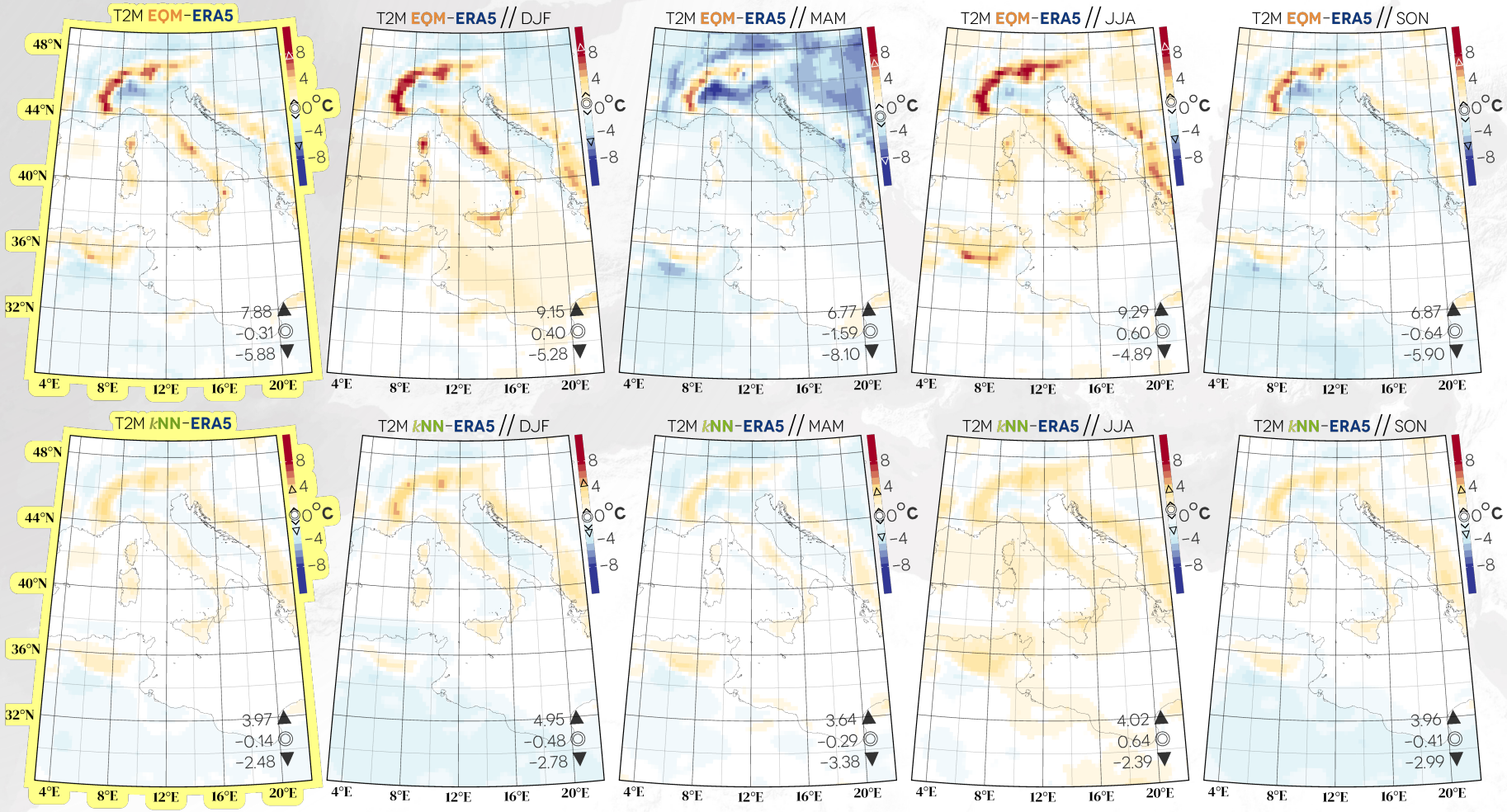


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SUMMARISED RESULTS

Ensemble Seasonal mean (lead month 1) for the daily average 2m temperature Bias (1993-2016)

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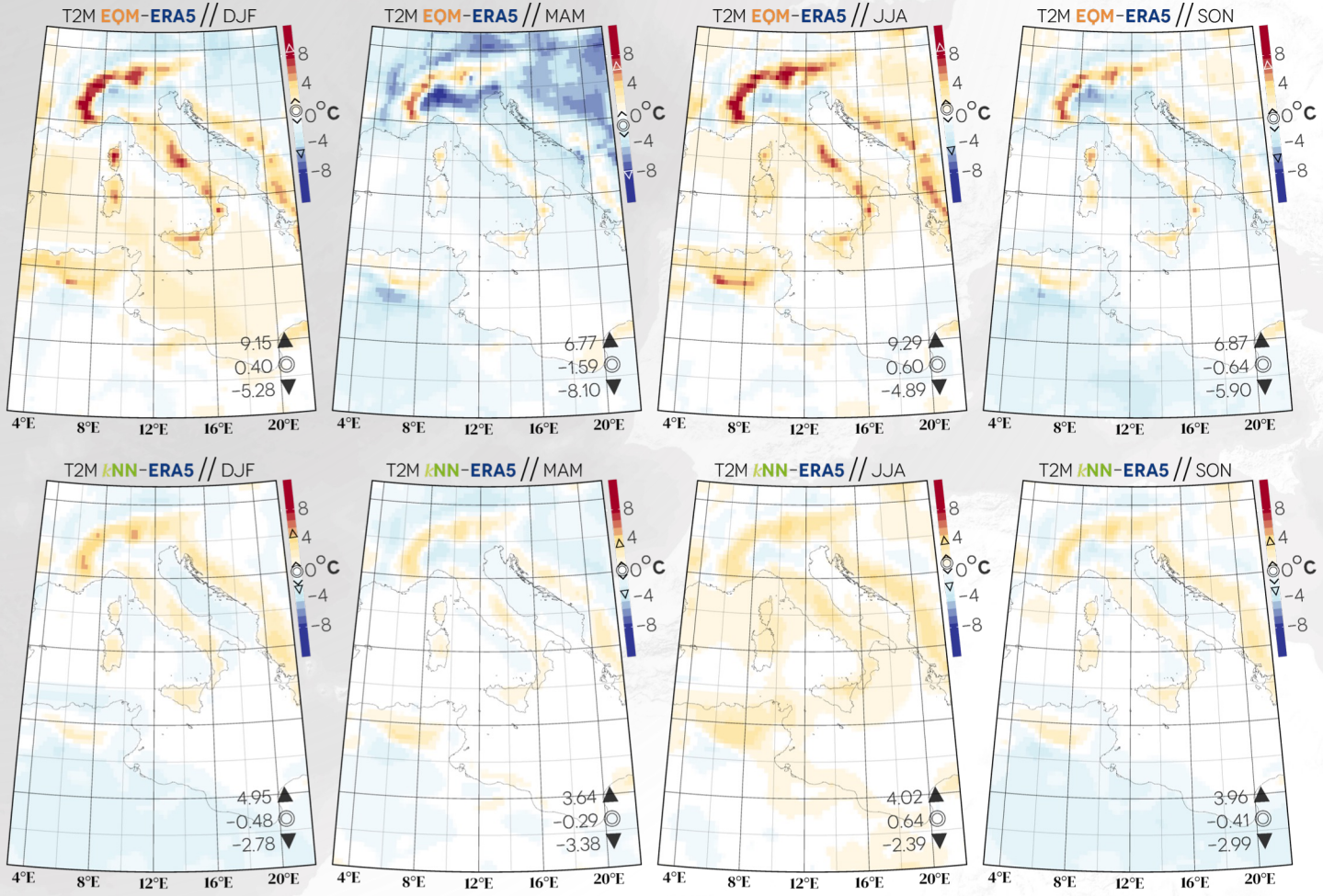


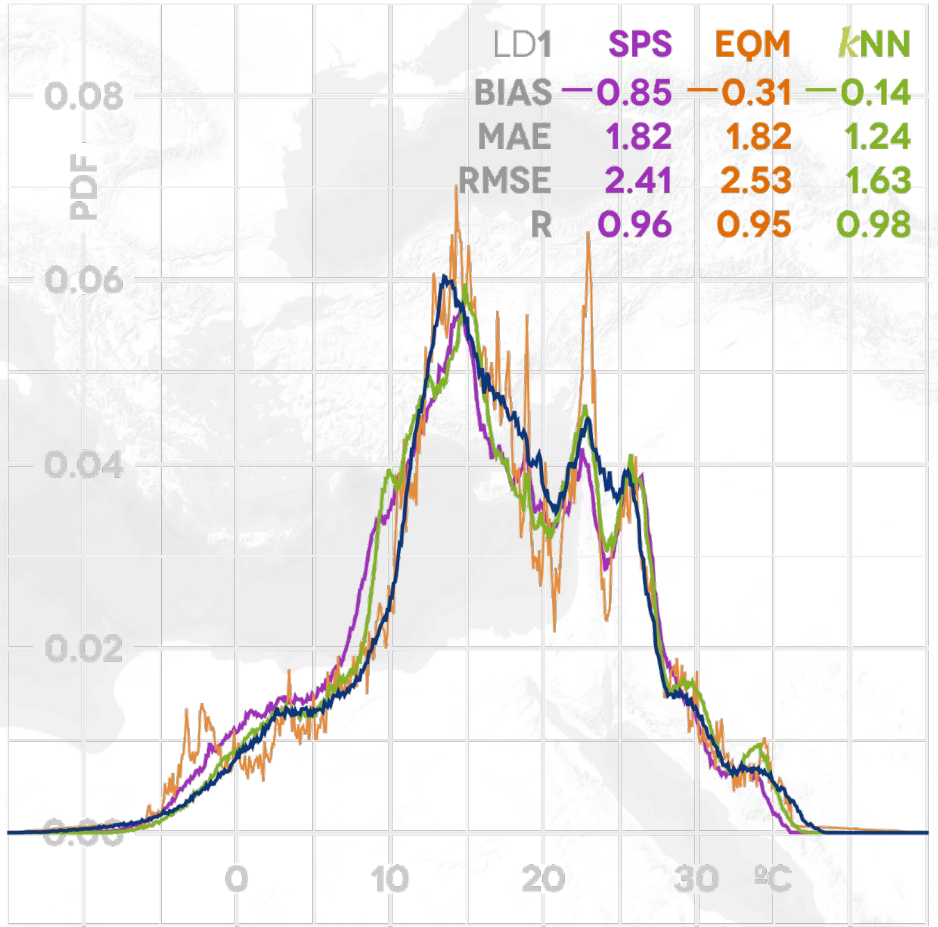
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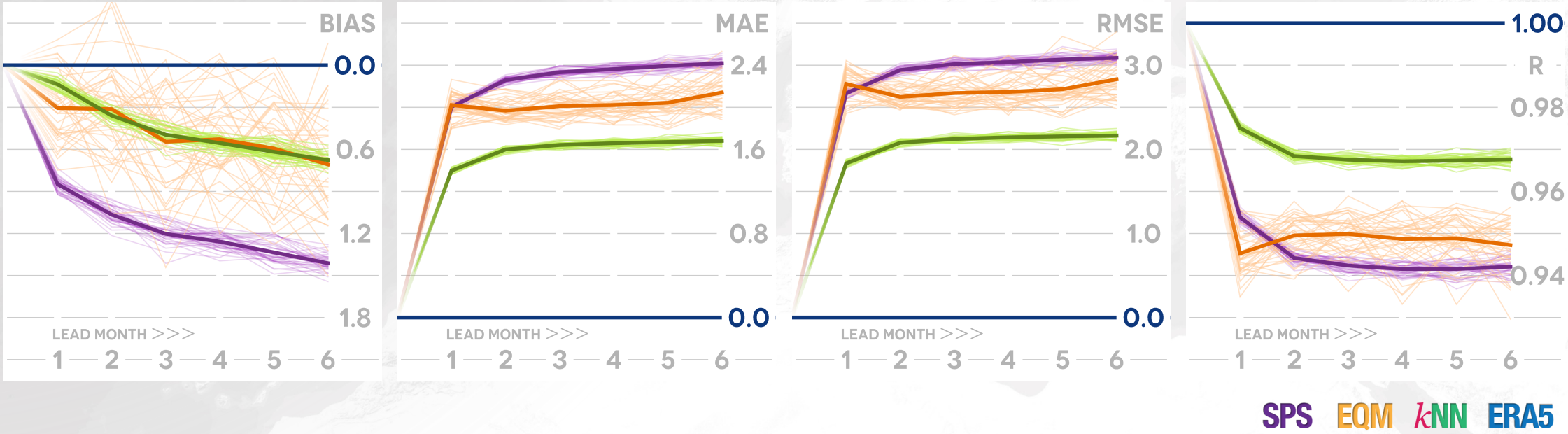


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SUMMARISED RESULTS

Statistical indices by lead month of the daily average 2m temperature (1993-2016)

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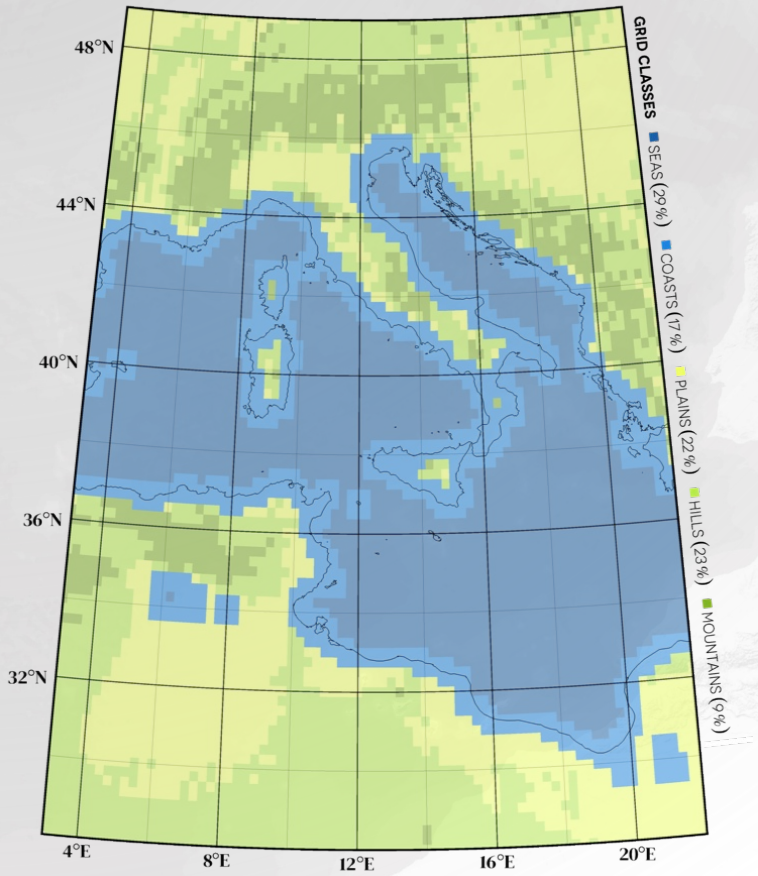


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SUMMARISED RESULTS

Statistical indices by environment (lead month 1) of the daily average 2m temperature (1993-2016)

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		DOMAIN	SEAS	COASTS	PLAINS	HILLS	MOUNTAINS
Bias	SPS	−0.85	−0.7	−1.12	−1.65	−1.03	1.66
	EQM	−0.31	−0.07	−0.25	−1.25	−0.62	1.96
	*k*NN	−0.14	−0.08	0.04	−0.72	−0.41	1.48
MAE	SPS	1.82	1.15	2.06	2.12	1.94	2.49
	EQM	1.82	1.03	1.67	2.22	2.11	3.05
	*k*NN	1.24	0.69	1.1	1.49	1.52	1.98
RMSE	SPS	2.41	1.67	2.74	2.66	2.38	3.15
	EQM	2.53	1.36	2.16	3.06	2.75	3.79
	*k*NN	1.63	0.9	1.39	1.84	1.89	2.44
R	SPS	0.96	0.97	0.94	0.98	0.98	0.95
	EQM	0.95	0.96	0.94	0.96	0.96	0.93
	*k*NN	0.98	0.98	0.98	0.98	0.98	0.97

SEAS
Gridpoints at the sea level (Altitude $h = 0$m)

COASTS
Gridpoints at the sea level ($h = 0$m) surrounded by at least one gridpoint with $h > 0$m, plus those surrounded by gridpoints at the sea level.

PLAINS
Gridpoins with $0\text{m} < h \leq 300\text{m}$

HILLS
Gridpoins with $300\text{m} < h \leq 800\text{m}$

MOUNTAINS
Gridpoins with $h > 800$m

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SUMMARISED RESULTS

Cross-validation of the ensemble mean within the SPS3.5 hindcast period over the Italian domain (1993-2016)

SCEWERO

		T2m	Prec	SST	U10	V10	T2N	T2X
Bias	SPS	-0.85	-4.39	-0.44	0.15	-0.04		
	EQM	-0.31	8.76	0.45	-0.06	0.13	-0.44	-0.20
	*k*NN	-0.14	-20.48	0.06	0.01	-0.06	-0.24	-0.08
MAE	SPS	1.82	19.89	0.78	0.81	0.72		
	EQM	1.82	27.35	0.89	0.86	0.78	1.92	1.95
	*k*NN	1.24	24.72	0.49	0.73	0.63	1.23	1.33
RMSE	SPS	2.41	33.81	1.15	1.09	0.95		
	EQM	2.53	42.91	1.12	1.17	1.05	2.62	2.74
	*k*NN	1.63	41.45	0.65	1.01	0.86	1.63	1.79
R	SPS	0.96	0.76	0.97	0.74	0.61		
	EQM	0.95	0.68	0.97	0.69	0.52	0.95	0.95
	*k*NN	0.98	0.73	0.99	0.77	0.69	0.98	0.98

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CONCLUSIONS & NEXT STEPS

CONCLUSION

SCEWERO

The analysis of spatial variability shows that kNN produces more detailed and realistic T2m fields across Italy than EQM. Unlike EQM's smooth and generalised fields, kNN captures key geographic features like the Po Valley and the Alps, aligning closely with ERA5. Statistically, kNN achieves better performance with a 0.98 correlation and 1.63°C RMSE, outperforming EQM.

T2m seasonal bias assessment reveals that EQM has higher winter biases (up to 8°C in the Alps), while kNN shows smoother and more accurate seasonal cycles. kNN better reflects ERA5 data across all seasons, especially in marine regions. EQM's apparent low marine bias is misleading, caused by seasonal over- and underestimations balancing each other.

Environmental analysis across Italy shows that kNN outperforms EQM in all regions, especially in coastal and mountainous areas where EQM fails to capture contrasts. Both methods perform better over marine areas, but kNN shows lower errors inland. The persistent bias in mountainous zones indicates challenges in representing cold extremes.

In seasonal forecasting (up to 6 months), kNN shows lower bias and RMSE than EQM and SPS, preserving initial signals while improving local-scale detail. EQM's bias correction introduces uncertainty due to inter-member spread. kNN's ensemble is more consistent, offering better reliability for climate-sensitive applications.

Expanding these analyses to other variables yields a similar scenario. While kNN tries to align with ERA5, preserving the initial conditions from SPS, EQM shows greater spread and less physical coherence, abruptly forcing SPS towards the observations. Thus, kNN better replicates observed variability in spatially structured environments.

Precipitation downscaling remains difficult for statistical methods. EQM overestimates light rain and misses seasonal variability, especially in cold months and orographic zones. kNN better captures spatial patterns in spring and autumn but underrepresents convective summer extremes. These challenges demand more sophisticated inputs and frameworks.

Due to analogs averaging, kNN struggles with extremes, often underestimating cold days and intense summer precipitation, especially in mountainous regions. Minor errors in analogs selection lead to significant rainfall underestimations. Hybrid methods and convective indices could enhance kNN's ability to capture such extremes.

When used as a weather generator, kNN accurately reproduces daily temperature extremes (T2N and T2X), aligning closely with ERA5 in terms of spread and skewness, unlike EQM. These results confirm the value of kNN's multivariate coherence and spatial sensitivity. However, improving its treatment of extremes remains key for broader applicability.

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CONCLUSION

> *Due to analogs averaging, kNN struggles with extremes, often underestimating cold days and intense summer precipitation, especially in mountainous regions.*

CONCLUSION

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The analysis of spatial variability shows that kNN produces more detailed and realistic T2m fields across Italy than EQM. Unlike EQM's smooth and generalised fields, kNN captures key geographic features like the Po Valley and the Alps, aligning closely with ERA5. Statistically, kNN achieves better performance with a 0.98 correlation and 1.63°C RMSE, outperforming EQM.

T2m seasonal bias assessment reveals that EQM has higher winter biases (up to 8°C in the Alps), while kNN shows smoother and more accurate seasonal cycles. kNN better reflects ERA5 data across all seasons, especially in marine regions. EQM's apparent low marine bias is misleading, caused by seasonal over- and underestimations balancing each other.

Environmental analysis across Italy shows that kNN outperforms EQM in all regions, especially in coastal and mountainous areas where EQM fails to capture contrasts. Both methods perform better over marine areas, but kNN shows lower errors inland. The persistent bias in mountainous zones indicates challenges in representing cold extremes.

In seasonal forecasting (up to 6 months), kNN shows lower bias and RMSE than EQM and SPS, preserving initial signals while improving local-scale detail. EQM's bias correction introduces uncertainty due to inter-member spread. kNN's ensemble is more consistent, offering better reliability for climate-sensitive applications.

Expanding these analyses to other variables yields a similar scenario. While kNN tries to align with ERA5, preserving the initial conditions from SPS, EQM shows greater spread and less physical coherence, abruptly forcing SPS towards the observations. Thus, kNN better replicates observed variability in spatially structured environments.

Precipitation downscaling remains difficult for statistical methods. EQM overestimates light rain and misses seasonal variability, especially in cold months and orographic zones. kNN better captures spatial patterns in spring and autumn but underrepresents convective summer extremes. These challenges demand more sophisticated inputs and frameworks.

Due to analogs averaging, kNN struggles with extremes, often underestimating cold days and intense summer precipitation, especially in mountainous regions. Minor errors in analogs selection lead to significant rainfall underestimations. Hybrid methods and convective indices could enhance kNN's ability to capture such extremes.

When used as a weather generator, kNN accurately reproduces daily temperature extremes (T2N and T2X), aligning closely with ERA5 in terms of spread and skewness, unlike EQM. These results confirm the value of kNN's multivariate coherence and spatial sensitivity. However, improving its treatment of extremes remains key for broader applicability.

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NEXT STEPS

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SCIENTIFIC PUBLICATION

The full version of this experiment considering the whole set of variables, analysis and discussions

OPERATIONAL VERSION

Integrate the ***k*****NN** *tool to* **SPS4** *to provide statistical downscaled predictions monthly*

MedCORDEX DOMAIN

6 times faster is not enough

TOWARDS EXTREMES

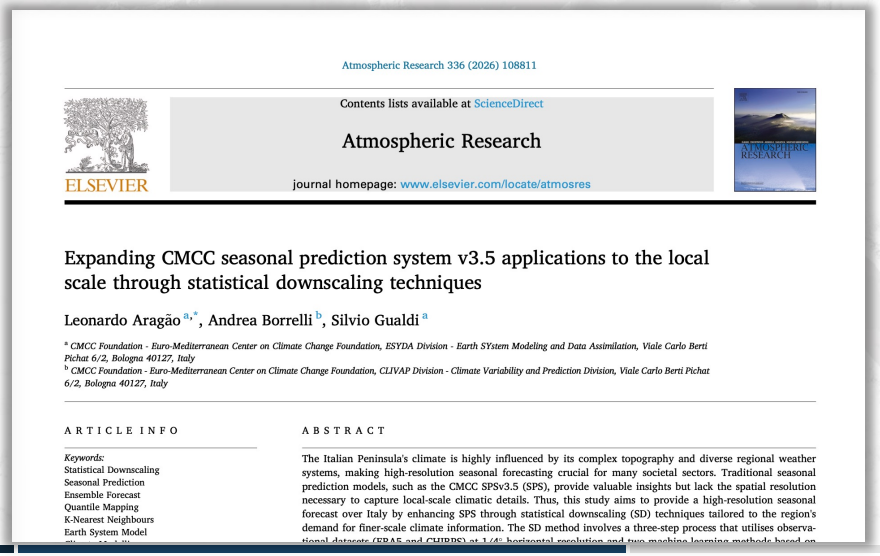
Review the list of predictors to include large-scale variables and enhance the ***k*****NN** *skill to a daily level*

ARAGÃO, Borrelli & Gualdi (2025)

CMCC Seasonal Prediction System v3.5 hindcasts downscaled from 1-degree to 0.25-degree using Empirical Quantile Mapping and k-Nearest Neighbours.
CMCC Data Delivery System, DOI 10.25424/cmcc-4brr-ym18

ARAGÃO, Borrelli & Gualdi (2026) ▫ **Bright NEW!!!**

Expanding CMCC Seasonal Prediction System v3.5 applications to the local scale through statistical downscaling techniques.
Atmospheric Research, DOI 10.1016/j.atmosres.2026.108811



Atmospheric Research 336 (2026) 108811

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Expanding CMCC seasonal prediction system v3.5 applications to the local scale through statistical downscaling techniques

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ABSTRACT

The Italian Peninsula's climate is highly influenced by its complex topography and diverse regional weather systems, making high-resolution seasonal forecasting crucial for many societal sectors. Traditional seasonal prediction models, such as the CMCC SPSv3.5 (SPS), provide valuable insights but lack the spatial resolution necessary to capture local-scale climatic details. Thus, this study aims to provide a high-resolution seasonal forecast over Italy by enhancing SPS through statistical downscaling (SD) techniques tailored to the region's demand for finer-scale climate information. The SD method involves a three-step process that utilises observa-

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STRENGTHENING THE RESEARCH CAPACITIES
FOR EXTREME WEATHER EVENTS IN ROMANIA

SUMMER SCHOOL ON AI USE FOR CLIMATE EXTREMES 2026

STATISTICAL DOWNSCALING USING MACHINE LEARNING TECHNIQUES

Bridging global seasonal forecast knowledge with local decision-making processes

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Thank you!

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