

# EFFECTS OF MODEL GRID RESOLUTION ON SIMULATING ATMOSPHERIC IMPACTS ON CULTURAL HERITAGE SITES

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# Introduction (1/3)

Climate change intensifies extreme events and alters microclimates, causing direct and indirect deterioration of monuments and their materials.

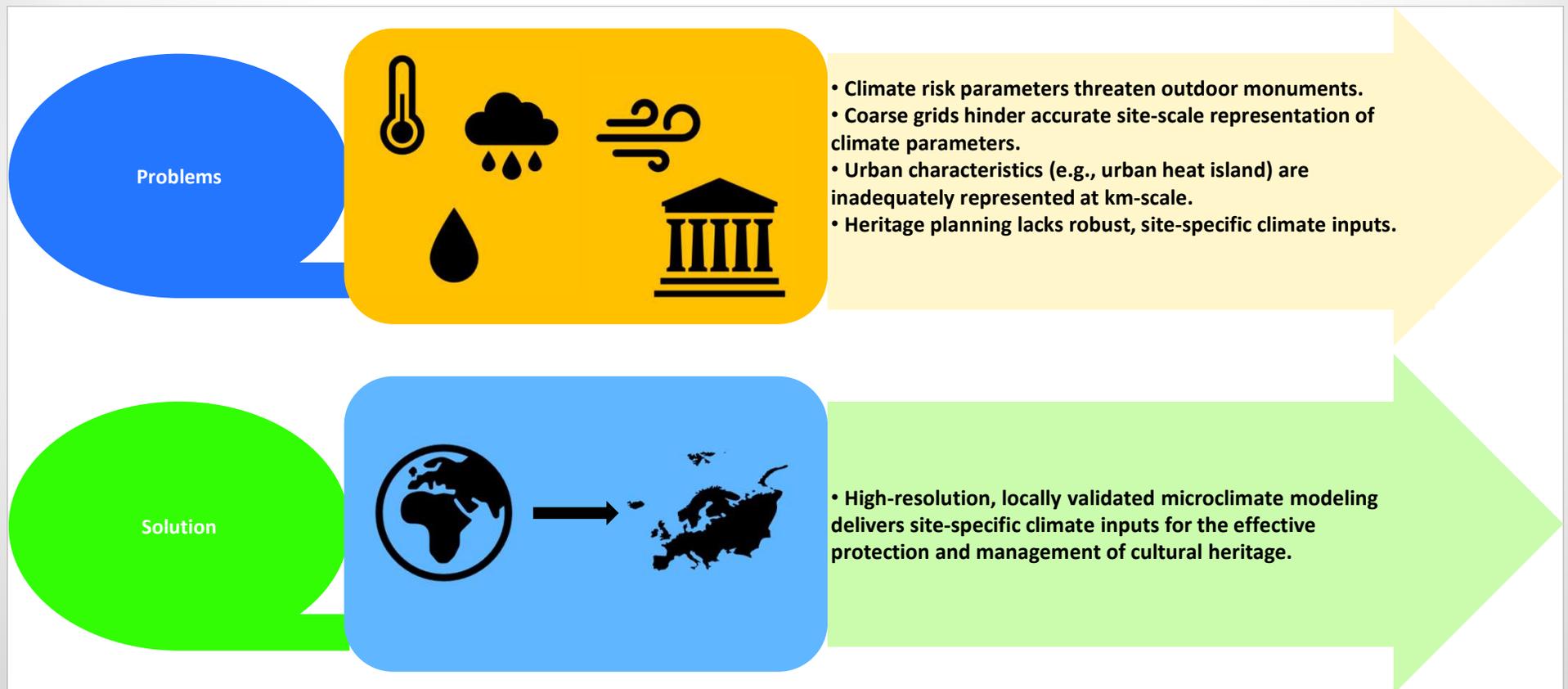
The cultural heritage of the Mediterranean - and Greece in particular - is especially vulnerable.



*Material degradation, Parthenon, Athens Acropolis*

# Introduction (2/3)

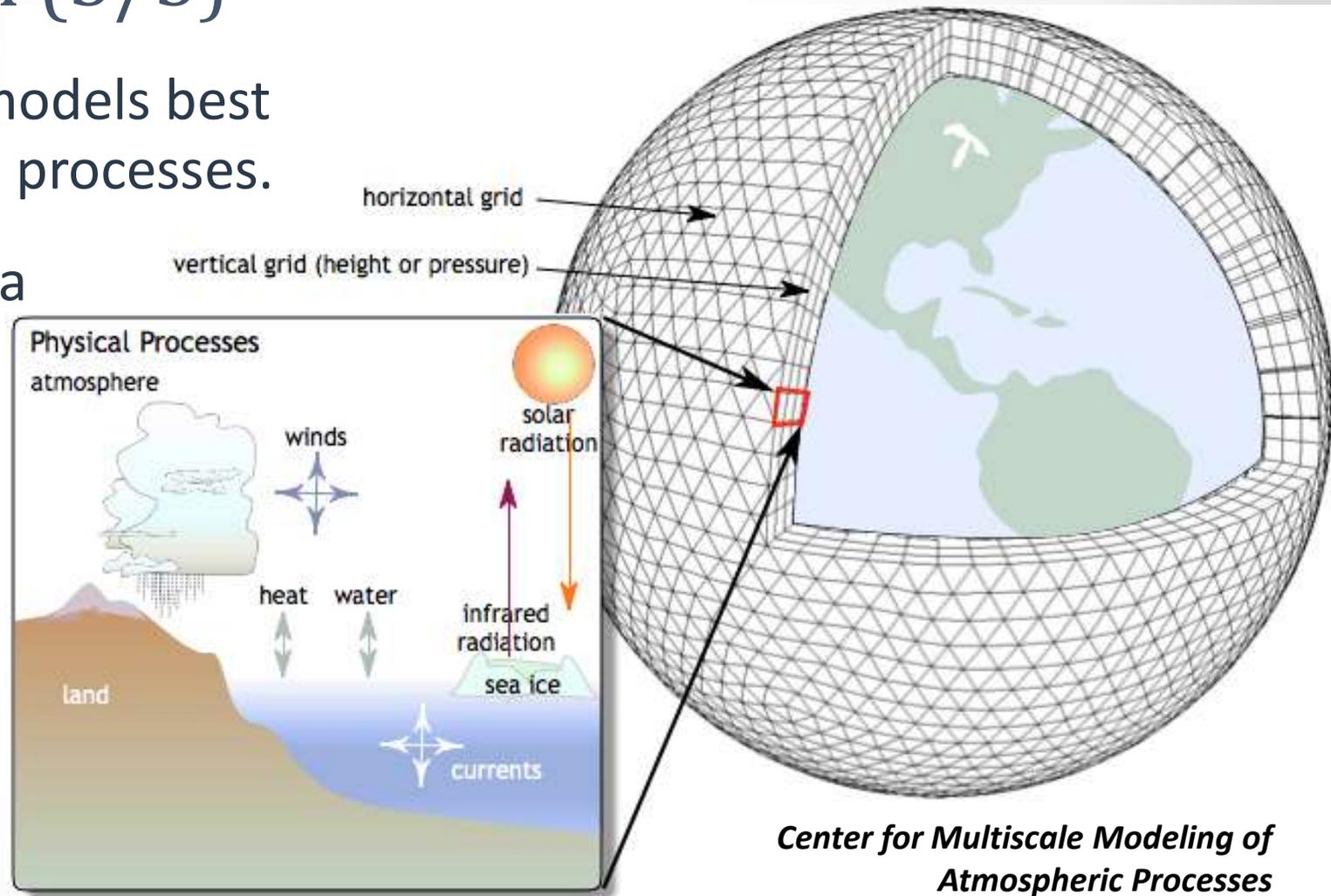
High-resolution modeling of climate parameters at cultural heritage sites is vital for more effective management.



# Introduction (3/3)

Meteorological models best describe physical processes.

They provide data at a high spatial and temporal resolution and capture local atmospheric processes that coarser datasets usually miss.

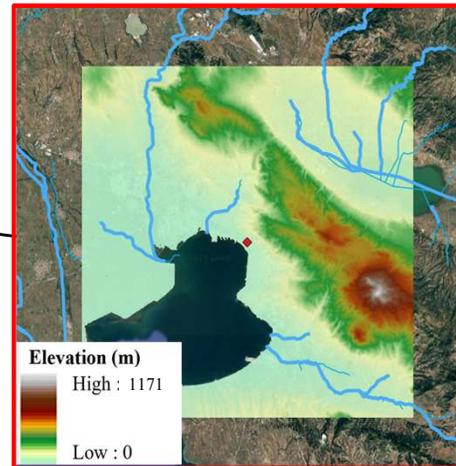


*Center for Multiscale Modeling of Atmospheric Processes*

# Studied regions

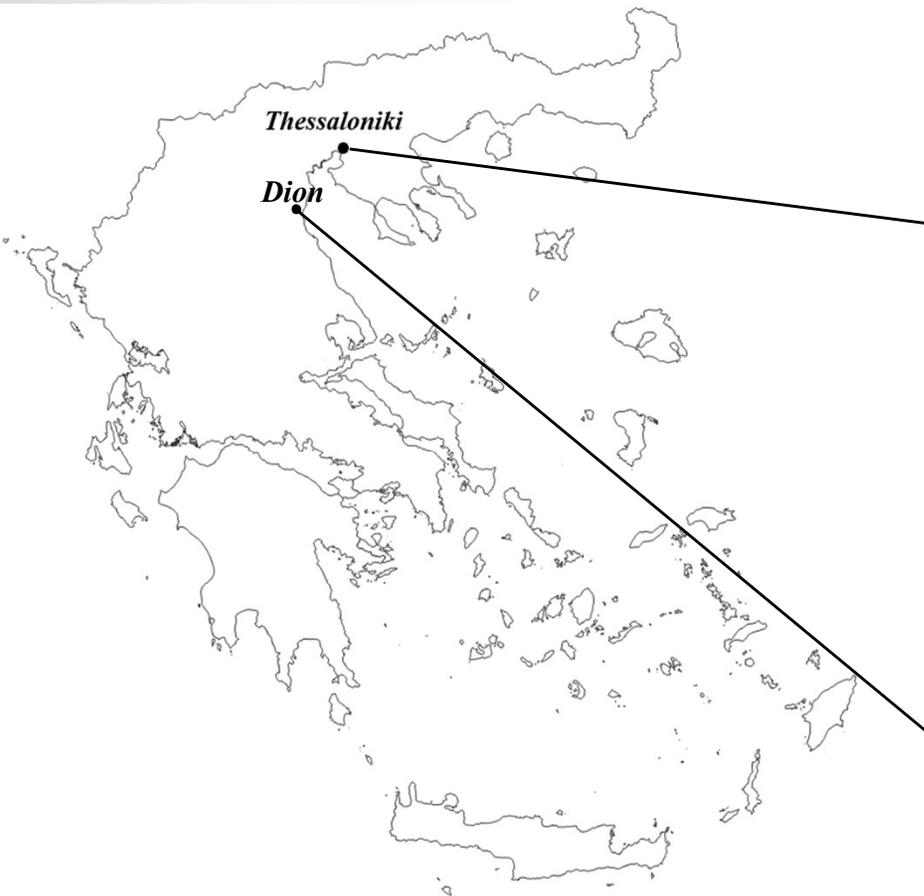
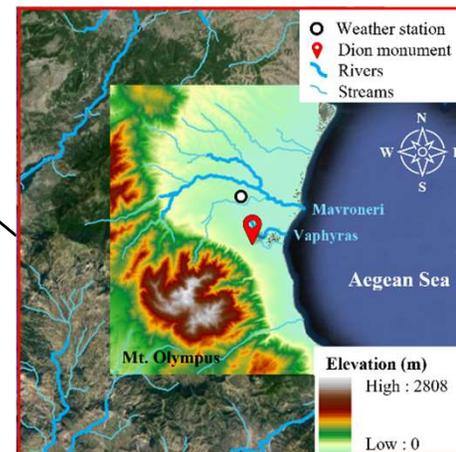
## Thessaloniki

**Dense urban fabric** (urban heat island) and heatwaves



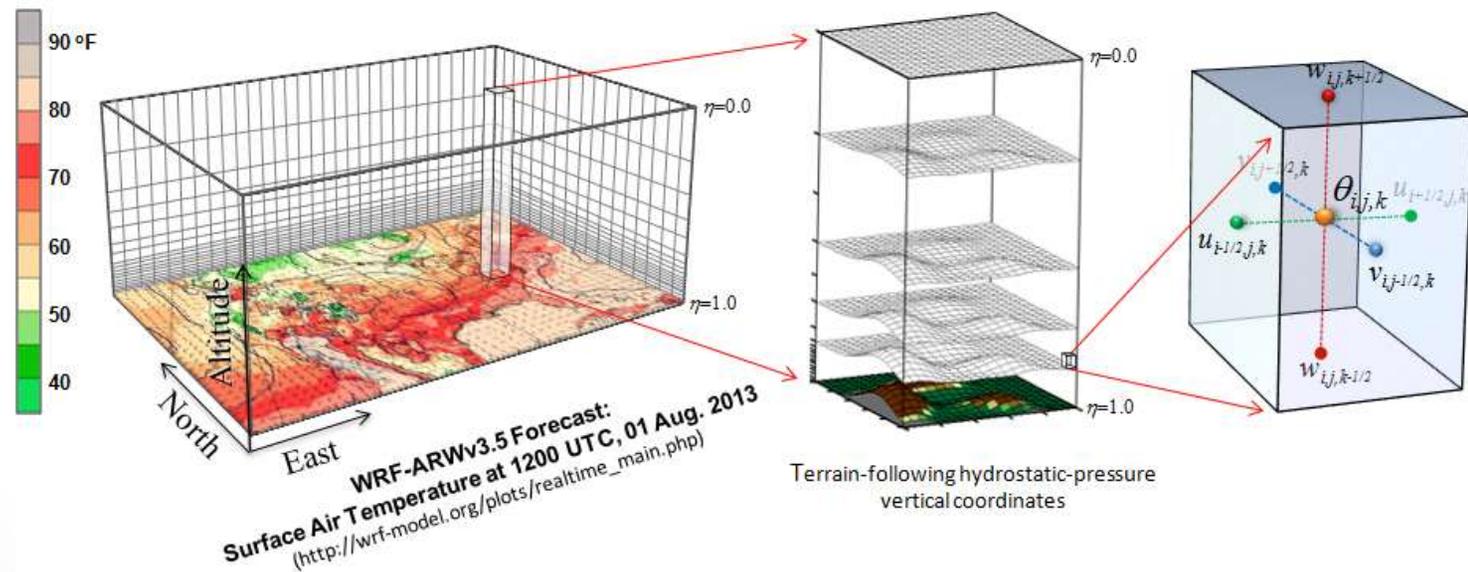
## Dion

**High relative humidity, dense stream network, pronounced temperature variability**



# Atmospheric models applied

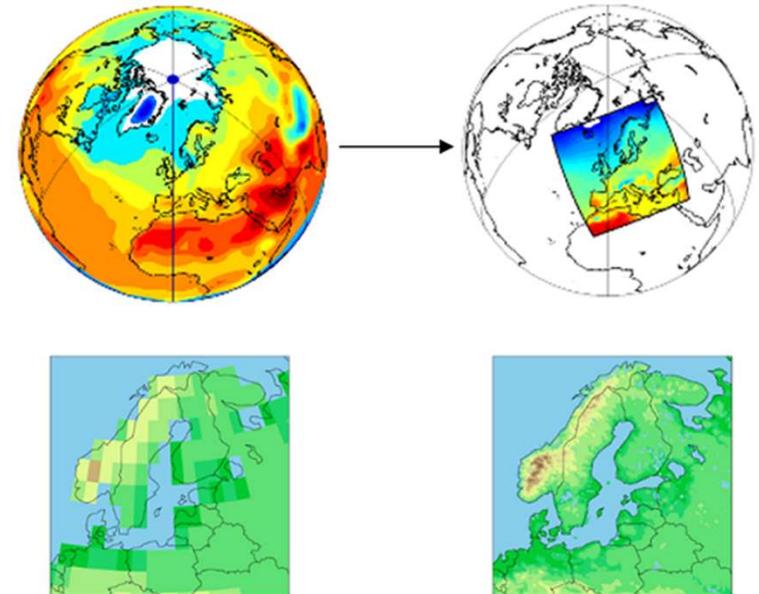
- **WRF** and **MEMO**, both ingesting initial and boundary conditions from **General Circulation Models** (GCMs) & **Regional Climate Models** (RCMs) and producing outputs with high spatial and temporal resolution.
- They use numerical methods to simulate atmospheric phenomena.
- The differential equations of the **meteorological variables** are solved numerically on a **3D computational grid**.
- Need for **Cluster**



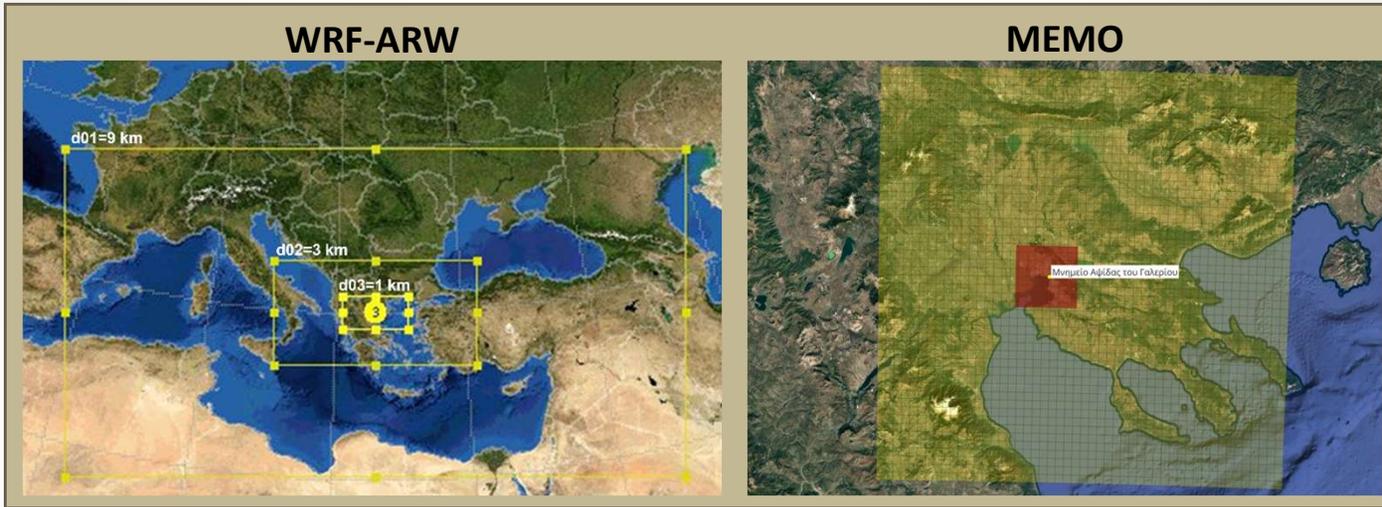
# Dynamical downscaling methodology

- Uses a high-resolution regional model nested in coarser GCM/RCM fields to resolve **local climate**.
- Driven by initial and lateral boundary conditions and using high-resolution **topography** and **land-use/ land-cover** data.
- Applies multi-domain, refining grids from coarse to fine scales.
- Captures **orography**, **urban canopy**, **urban heat island effects**, land-sea interactions, etc.
- Delivers **site-specific climate intelligence** to support **risk-informed adaptation** of heritage monuments.

**Global modelling**    **Regional modelling**



# Domain Specifications



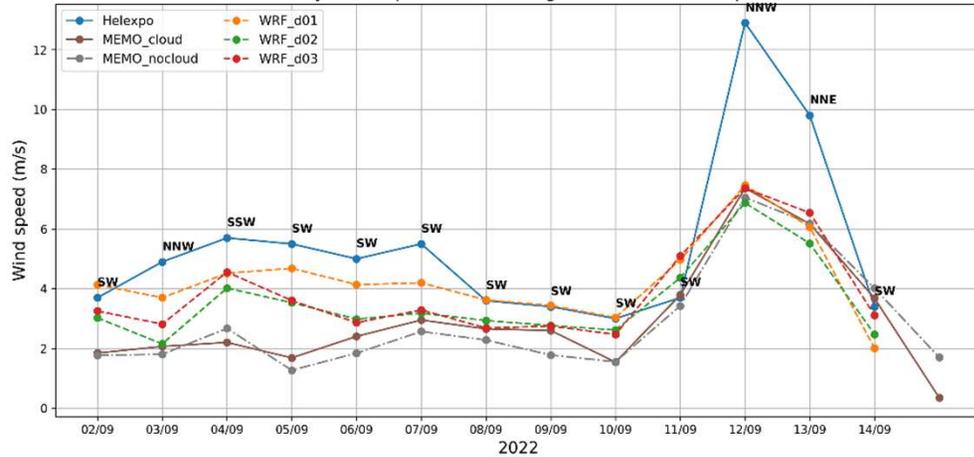
	WRF-ARW	MEMO
Input data	ERA5 reanalysis (0.25°×0.25°)	Radiosonde "Macedonia Airport"
Nesting Domains	One-way nesting d01 (9 km), d02 (3 km), d03 (1 km)	One-way nesting d01 (4 km), d02 (250 m)
Map projection	Lambert Conformal	UTM, north zone = 34
Vertical layer	31	25
Geographic data resolution	MODIS 30s	1 h
Microphysics	Thompson scheme	Diagnostic cloudiness, H <sub>2</sub> O, CO <sub>2</sub>
Longwave radiation	RRTMG scheme	Emissivity method
Shortwave radiation	RRTMG scheme	SONJA implicit scheme
Surface layer	Monin-Obukhov (Janjic)	Monin-Obukhov scheme
Land surface	Noah Unified model	7-layer surface categorization
Planetary boundary layer	Mellor-Yamada-Janjic (MYJ)	Non-hydrostatic, one-equation turbulence
Cumulus parameterization	Kain-Fritsch (new Eta)	-

- WRF and MEMO used multi-nesting grids with coarse domains enclosing higher-resolution nests.

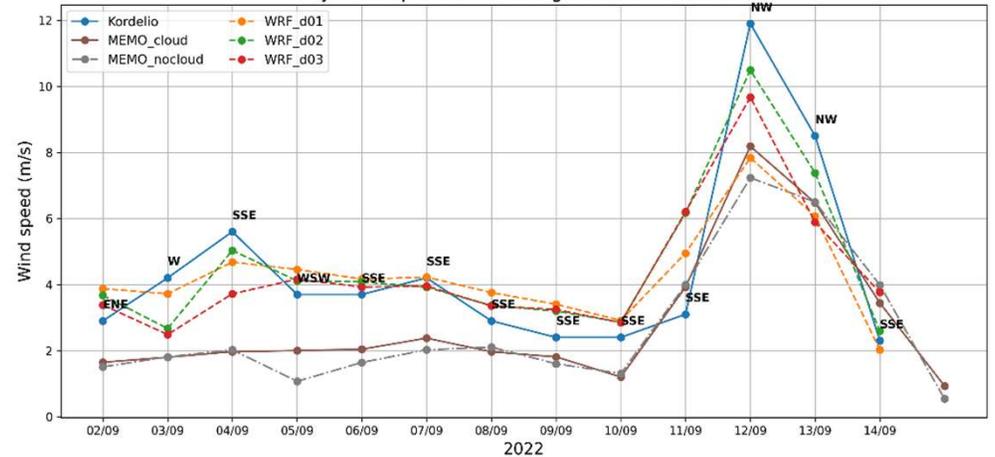
Model	Grid	Size (km)	Size (cells)	Resolution (m)
WRF-ARW	Coarse	20817	2313	9000
	Fine	2223	741	3000
	Fine	235	235	1000
MEMO	Coarse	480	120	4000
	Fine	30	120	250

# Comparison between WRF and MEMO results

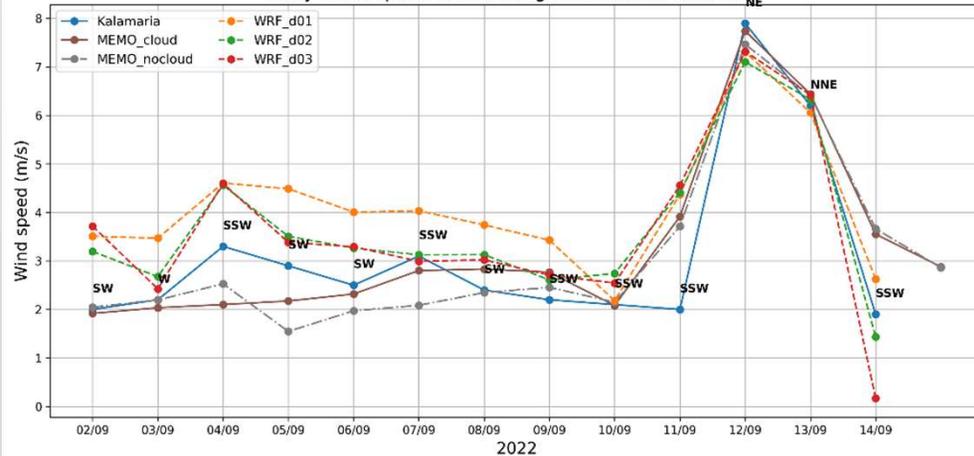
Daily Wind Speed & Prevailing Direction for Helexpo



Daily Wind Speed & Prevailing Direction for Kordelio

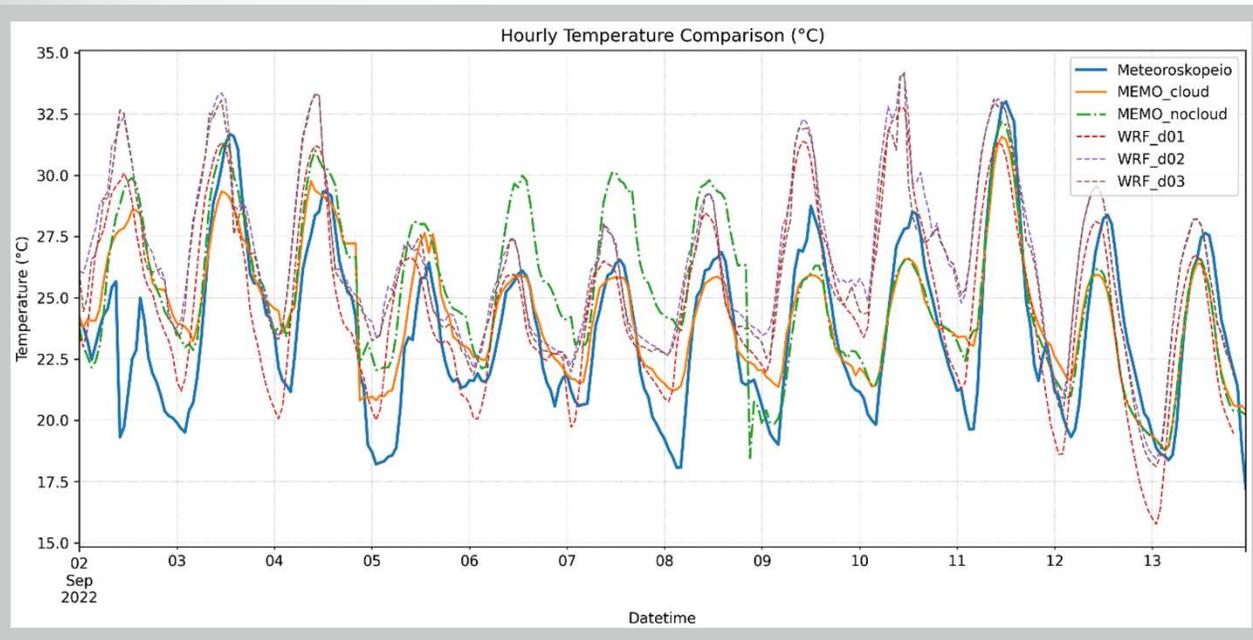


Daily Wind Speed & Prevailing Direction for Kalamaria



Both models generally **underestimate wind speed**, yet they **capture well the sharp increase on 12 September**; the Helexpo station is an exception, because the surface-roughness parameterization there proved to be not representative for the local conditions.

# Comparison between WRF & MEMO results



**“MEMO cloud”** showed the smallest diurnal temperature fluctuations & relatively higher nighttime minimum values, **indicating a more realistic representation of the urban heat island effect.**

This **advantage** over lower resolution simulations is **attributed to the very high spatial resolution (250 m)** within the urban fabric and the more accurate mapping of urban coverage, which **allows for a more realistic representation of the energy balance and aerodynamic resistance.**

# Validation of mesoscale results

Temperature (°C)					
Stations	WRF			MEMO	
	9 (km)	3 (km)	1 (km)	no cloud	cloud
	RMSE				
Chalastra	2.31	2.37	2.46	2.15	1.61
Eptapyrgio	1.91	2.71	2.03	2.72	1.53
Kalamaria	0.91	1.36	2.17	1.77	0.87
Noesis	1.01	2.59	1.83	2.03	0.97
Thessaloniki	1.06	1.6	2.33	1.62	0.76
Meteoroskopeio	1.79	2.69	2.36	2.36	1.68
MAE					
Chalastra	1.95	2.37	2.39	1.71	1.37
Eptapyrgio	1.5	2.47	1.82	2.19	1.35
Kalamaria	0.73	1.23	1.85	1.5	0.73
Noesis	0.8	2.33	2.23	1.67	0.84
Thessaloniki	0.83	1.51	2.07	1.31	0.59
Meteoroskopeio	1.38	2.39	2.12	1.9	1.1
Bias					
Chalastra	1.2	1.88	1.73	1.55	1.28
Eptapyrgio	0.96	2.32	1.56	2.17	1.35
Kalamaria	0.43	1.23	1.75	0.97	0.31
Noesis	0.72	2.23	1.15	1.14	0.44
Thessaloniki	0.7	1.51	2.05	0.87	0.25
Meteoroskopeio	0.6	2.35	2.05	1.57	0.92

- **Validation setup:** Thessaloniki (Sep 2022); **temperature** observations from 6 stations; comparison of **WRF** (9/3/1 km) and **MEMO** (250 m) with/without cloud parameterization.
- **Overall accuracy:** “MEMO cloud” delivered the best performance (**lowest RMSE/MAE and bias** across stations and the **highest IoA** at **4/6** stations) indicating the most accurate temperature values.

Pearson (r)					
Chalastra	0.73	0.84	0.84	0.44	0.68
Eptapyrgio	0.73	0.84	0.86	0.48	0.86
Kalamaria	0.79	0.89	0.89	0.32	0.74
Noesis	0.84	0.89	0.88	0.24	0.74
Thessaloniki	0.79	0.9	0.92	0.34	0.76
Meteoroskopeio	0.73	0.85	0.88	0.42	0.57
IoA					
Chalastra	0.69	0.69	0.69	0.55	0.69
Eptapyrgio	0.73	0.63	0.73	0.53	0.76
Kalamaria	0.84	0.74	0.65	0.55	0.84
Noesis	0.84	0.62	0.75	0.52	0.83
Thessaloniki	0.81	0.69	0.62	0.58	0.86
Meteoroskopeio	0.74	0.61	0.66	0.56	0.7

- **Time-series agreement:** WRF (**3** and **1 km**) achieved **higher r** at **3/6** and **5/6** stations - better timing/ variability despite larger magnitude errors.

# Validation of mesoscale models

Wind speed (m/s)					
Stations	WRF			MEMO	
	9 (km)	3 (km)	1 (km)	no cloud	cloud
RMSE					
Chalastra	3.09	2.70	2.45	3.02	3.01
Eptapyrgio	2.55	2.77	2.49	2.60	2.39
Kalamaria	1.25	0.94	1.06	0.93	0.89
Noesis	4.00	4.64	4.86	4.32	4.19
Thessaloniki	6.59	6.82	6.56	5.30	5.28
Meteoroskopeio	3.19	2.51	2.88	2.15	2.33
MAE					
Chalastra	2.72	2.42	2.13	2.71	2.69
Eptapyrgio	1.58	1.87	1.65	2.11	1.90
Kalamaria	1.09	0.73	0.80	0.71	0.66
Noesis	3.53	4.24	4.43	3.97	3.84
Thessaloniki	4.53	4.98	4.66	3.98	3.98
Meteoroskopeio	3.06	2.36	2.67	1.69	1.97
Bias					
Chalastra	-2.72	-2.42	-2.13	-2.71	-2.69
Eptapyrgio	-1.12	-1.44	-1.06	-1.50	-1.33
Kalamaria	0.97	0.52	0.39	0.07	0.24
Noesis	-3.53	-4.24	-4.43	-3.97	-3.84
Thessaloniki	-4.53	-4.98	-4.66	-3.98	-3.98
Meteoroskopeio	3.06	2.36	2.67	1.69	1.97

- **Validation setup:** Thessaloniki (Sep 2022); **wind-speed** observations from 6 stations; comparison of **WRF** (9/3/1 km) & **MEMO** (250 m) with/without cloud parameterization.
- **Overall accuracy:** “MEMO cloud” delivered the best performance (**lowest RMSE/MAE & bias** across stations & the **highest IoA** at **3/6** stations) indicating the most accurate wind-speed values.

	Pearson (r)				
	9 (km)	3 (km)	1 (km)	no cloud	cloud
Chalastra	0.82	0.86	0.88	0.77	0.77
Eptapyrgio	0.90	0.84	0.85	0.80	0.83
Kalamaria	0.91	0.90	0.85	0.86	0.88
Noesis	0.91	0.84	0.87	0.87	0.89
Thessaloniki	0.86	0.84	0.80	0.90	0.91
Meteoroskopeio	0.90	0.89	0.90	0.83	0.85
IoA					
Chalastra	0.51	0.62	0.66	0.57	0.57
Eptapyrgio	0.73	0.69	0.76	0.79	0.83
Kalamaria	0.86	0.92	0.91	0.93	0.93
Noesis	0.55	0.51	0.49	0.52	0.53
Thessaloniki	0.51	0.52	0.52	0.68	0.69
Meteoroskopeio	0.31	0.39	0.36	0.47	0.44

- **Time-series agreement:** **WRF (9 km)** achieved **higher r** at **4/6** stations - better timing/variability despite larger magnitude errors.

# Validation of WRF results

- **Validation setup:** Dion (Oct 2009, Nov 2019); **relative humidity** from a local station; WRF evaluated at 9/3/1 km.
- **Resolution impact (errors):** 9 → 3 km nearly halves both RMSE and MAE; moving to 1 km yields no meaningful additional improvement.
- **Systematic bias:** Coarse grid underestimates RH; bias  $\approx -14\%$  at 9 km, almost eliminated at 3 km, marginally improved at 1 km.
- Clear diminishing returns beyond 3 km for RH at Dion; **3 km emerges as the best trade-off between skill and computational cost.**
- **Pearson correlation:** Moderate in Oct 2009 ( $r \approx 0.55-0.59$ ) and weak in Nov 2019 ( $r \approx 0.20-0.30$ ) across resolutions.

Relative humidity (%)						
	WRF					
	9 km		3 km		1 km	
metrics	Oct. 2009	Nov. 2019	Oct. 2009	Nov. 2019	Oct. 2009	Nov. 2019
RMSE	20.33	17.09	13.27	7.93	13.19	7.22
MAE	17.04	14.43	10.08	6.31	10.05	5.98
Bias	-14.49	-13.89	0.10	-3.07	0.27	-2.67
Pearson r	0.59	0.20	0.55	0.20	0.56	0.30

# Conclusions

- The selected parameterizations reproduced station observations across all spatial analyses, with deviations remaining within acceptable limits.
- In WRF, the 3 km resolution achieved the best balance of spatial detail, numerical accuracy (RMSE, MAE, Bias, r), and computational cost for relative humidity, temperature, and wind speed.
- In MEMO, the 250 m resolution delivered the highest numerical accuracy and captured local phenomena such as the urban heat island.
- For cultural heritage protection and management in both urban and non-urban areas, high-resolution modeling is required to obtain detailed and reliable climatic assessments.

## *Acknowledgements*

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***Thank you for your attention!***