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

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Abstract: The present study evaluates the impact of spatial grid resolution of numerical models (WRF-ARW and MEMO) on the simulation accuracy of critical microclimatic variables (relative humidity, temperature, and wind speed) at two culturally significant sites in Northern Greece: the archaeological site of Dion and the urban area of Thessaloniki. Using dynamical downscaling techniques and multi-grid nesting (WRF: 9, 3, 1 km; MEMO: 4 km, 250 m), simulations were compared against observational data from meteorological stations. Results highlight that increasing grid resolution notably improves model accuracy. Specifically, WRF simulations at 3 km provided an optimal balance between accuracy and computational efficiency, while MEMO at 250 m effectively captured detailed urban phenomena, such as the urban heat island effect. The findings emphasize that high spatial resolution modeling is essential for accurate climate assessments, supporting more effective strategies for protecting cultural heritage sites against climate change impacts.

Key words: *atmospheric models, dynamical downscaling, spatial grid resolution, atmospheric stressors*

INTRODUCTION

Climate change affects the intensity and frequency of extreme weather events, such as heavy rainfall, floods, droughts, and sea level rise (Sesana et al., 2021). These phenomena directly impact monuments and indirectly influence them through changes in the surrounding natural environment, causing deterioration of their structural materials. Consequently, climate change represents a multidimensional threat to cultural heritage, amplifying existing risks from natural and anthropogenic factors (Cox et al., 2010).

The Mediterranean basin, particularly vulnerable to climate change impacts, frequently experiences intense rainfall, significant temperature fluctuations, and high humidity levels (Kapsomenakis et al., 2023). Greece, due to its geographical diversity and rich cultural heritage, is particularly exposed to climatic challenges. Although future climate impacts on cultural heritage have been assessed in various studies (Tringa and Tolika, 2023), few of them employed high resolution numerical simulations, which are essential for accurately capturing local microclimatic conditions.

This study evaluates the effect of spatial resolution of numerical grids in two atmospheric models on simulating critical microclimatic parameters - relative humidity, temperature, and wind speed - in two important sites of Northern Greece: the archaeological site of Dion and the city of Thessaloniki. Dion has a complex microclimate, due to its proximity to Mount Olympus and its extensive water system, while Thessaloniki experiences the urban heat island effect, characterized by limited diurnal temperature fluctuations and strong winds. The study aims to highlight the importance of high spatial resolution in achieving reliable simulations to enhance climate change adaptation strategies for cultural heritage protection.

METHODOLOGY

This study employs dynamical downscaling, a method in which low resolution global model data are used as initial and boundary conditions for high resolution numerical models to simulate local climatic conditions. Dynamical downscaling is particularly crucial in regions with complex geography, such as Greece, where detailed climate assessment is essential for cultural heritage conservation.

Atmospheric models, such as WRF-ARW and MEMO used in this study, simulate past and future atmospheric conditions (Katopodis et al., 2020) through physical modeling of fundamental processes occurring in the troposphere and lower stratosphere. Differential equations governing meteorological variables are numerically solved on a three-dimensional computational grid. This approach captures large-scale air movements in the atmosphere, adhering to physical principles including the conservation of momentum, mass, energy, and moisture. Simultaneously, processes such as turbulent flow and cloud formation are simulated, employing parameterizations where necessary, thus enhancing the understanding of atmospheric complexity. Consequently, atmospheric models are computationally demanding and typically require high-performance computing systems.

Both WRF-ARW and MEMO models employed a multi-nesting grid technique, in which coarse domains encompassed higher resolution nested domains. Specifically, the WRF model employed three domains with resolutions of 9 km (parent), 3 km, and 1 km, while the MEMO model utilized two domains at 4 km (parent) and 250 m (nested) resolution.

The Weather Research and Forecasting – Advanced Research WRF (WRF-ARW) model is a non-hydrostatic, three-dimensional numerical weather prediction system designed for research and operational forecasting (Skamarock et al., 2021). Similarly, the MEMO model (Moussiopoulos et al., 2012), developed by Aristotle University of Thessaloniki (AUTh) in collaboration with the Karlsruhe Institute of Technology (KIT), is also a non-hydrostatic mesoscale atmospheric model.

This study utilized WRF-ARW version 4.4, incorporating significant technical improvements. Basic simulation settings for both models are summarized in Table 1. Simulations of past conditions were validated against meteorological data from stations managed by the National Observatory of Athens and Aristotle University of Thessaloniki.

Table 1. Simulation settings and computational parameters for WRF and MEMO.

	WRF-ARW	**MEMO**
Input data	ERA5 reanalysis (0.25°×0.25°)	Radiosonde "Macedonia Airport"
Nesting	One-way nesting	One-way nesting
Domains	d01 (9 km), d02 (3 km), d03 (1 km)	d01 (4 km), d02 (250 m)
Map projection	Lambert Conformal	UTM, north zone = 34
Vertical layers	31	25
Geographic data resolution	MODIS 30s	1 h
Microphysics	Thompson scheme	Diagnostic cloudiness, H_2O, CO_2
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 discretization
Planetary boundary layer	Mellor-Yamada-Janjic (MYJ)	Non-hydrostatic, one-equation turbulence
Cumulus parameterization	Kain-Fritsch (new Eta)	-

Below, results are presented for three specific cases: (1) calculation of error metrics for relative humidity at Dion using WRF at three grid resolutions for two past periods, (2) comparison of hourly temperature timeseries between the WRF and MEMO models at a monitoring station in Thessaloniki during a past period, and (3) calculation of error metrics for wind speed at multiple stations in Thessaloniki using both the WRF and MEMO models for a past period.

RESULTS

Dion is characterized by high humidity due to the presence of water in the area (surface and groundwater as well as frequent rainfall). Relative humidity levels are quite high for the Dion area; typically, in November 2019, the station recorded values mostly between 70 and 95% throughout the day.

Table 2 compares the error metrics in the relative humidity values at the Dion station with the three WRF resolutions for the periods 10/2009 and 11/2019. The transition from 9 km to 3 km reduces both the RMSE and the MAE by almost half, while the 1 km resolution does not bring about any further significant improvement. The WRF model appears to underestimate relative humidity, especially at the lowest resolution. Thus, the bias is initially strongly negative at around -14% at 9 km, while at 3 km it is almost eliminated and improves marginally at 1 km. The correlation coefficient r is 0.55 in October 2009 and decreases to 0.2-0.3 in November 2019.

Table 2. Relative humidity errror metrics for October 2009 and November 2019 at the Dion station compared with WRF simulations at three spatial resolutions.

	Relative humidity (%)					
	9 km		**3 km**		**1 km**	
metrics	**10/2009**	**11/2019**	**10/2009**	**11/2019**	**10/2009**	**11/2019**
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

The hourly comparison of temperature timeseries from the WRF and MEMO models was performed for the period 2-15 September 2022 (Figure 1), during which two thunderstorm episodes with dense cloud cover occurred on 2 and 5 September in Thessaloniki. In the MEMO sensitivity analysis, inclusion of cloud cover ("MEMO cloud" case) brought the hourly temperature values into closer agreement with observations from the meteorological station, yielding the smallest deviations in both daily maximum and nighttime minimum values. By contrast, the "MEMO no cloud" configuration exhibited the largest discrepancies on cloudy days (5-8 September), while on clear days (9-10 and 12-13 September) it systematically underestimated peak temperatures - likely reflecting limitations of even very high spatial resolution to capture localized thermal features around the station.

Moreover, "MEMO cloud" showed the smallest diurnal temperature fluctuations and 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. In contrast, the higher resolutions of WRF d02 (3 km) and d03 (1 km) follow the maximum temperatures but exhibited a systematic positive bias (day and night) due to the sensitivities of the parameterizations near the surface.

Finally, it is important to note that dynamical downscaling with very high resolution (as in the case of MEMO) may overestimate surface roughness in areas where detailed land-use/land-cover input data are lacking, since the lack of information leads to the assumption of maximum urban roughness everywhere. Figure 1 shows that nighttime minimum temperatures are overestimated, which translates into an underestimation of relative humidity (see Table 1) and, specifically, underestimation of nighttime maximum relative humidity values. This confirms the close interdependence between errors reproduction of minimum temperatures and deviations in relative humidity peaks.

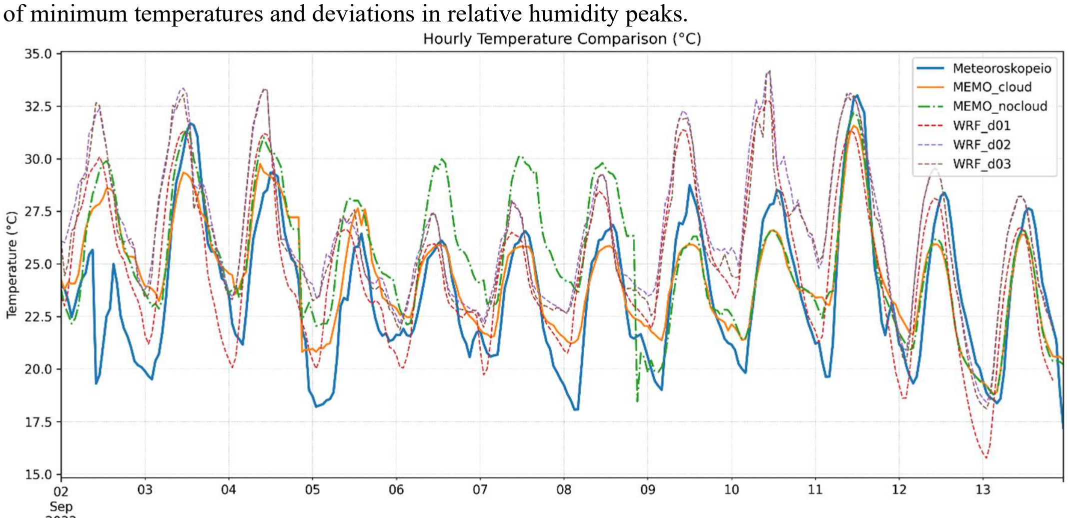

Figure 1. Temperature timeseries from MEMO, three spatial resolutions of WRF, and the meteorological station near the city center (Meteoroskopeio).

The comparison of error metrics for the wind variable during the period of September 2022 in the Thessaloniki area, between the three WRF analyses (9 km, 3 km, 1 km) and MEMO (with and without cloud cover) at five meteorological stations (see Table 3) showed that “MEMO cloud” has the best overall performance. Specifically, it has the lowest RMSE and MAE values as well as bias, while at least three of the six stations also have the highest values of the index of agreement (IoA), proving that it renders wind values with greater accuracy. In contrast, the Pearson correlation coefficient (r) is systematically higher for WRF analyses, mainly at 9 km, where four stations confirm its superiority in representing wind dynamics over time.

At the station level, the locations of Thessaloniki, Noesis, Meteoroskopeio, and Chalastra showed the largest error metrics, with systematic underestimation of wind speed by both models. The Thessaloniki station is in an open coastal area, while the Noesis and Chalastra stations are located outside the urban area. The Meteoroskopeio, although adjacent to the city center, is located within the university campus, near a park, and is not characterized by dense construction. Therefore, it is possible that the surface roughness attributed by the models, based on the urban coverage category from the land use maps, does not adequately represent the actual conditions on the surface, thus leading to errors in the prediction of wind intensity.

Table 3. Wind speed error metrics for September 2022, comparing WRF and MEMO simulations with observations at each station.

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
Pearson (r)					
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

CONCLUSIONS

The results of the simulations of the two models compared with the measurements of the meteorological stations show that the selected parameterizations perform reliably in all spatial analyses, as the deviations from the observations remain within acceptable limits. In WRF, the 3 km resolution achieves the best balance between spatial detail, numerical accuracy (RMSE, MAE, Bias, r) and reasonable computational cost for the examined variables (relative humidity, temperature and wind speed). In MEMO, when investigating the benefits of higher resolution, the 250 m resolution offers the highest numerical accuracy and successfully highlights local phenomena such as the urban heat island. In conclusion, for the effective protection and management of cultural heritage sites - in urban or non-urban areas - the use of high resolution is necessary to ensure detailed and reliable climatic assessments.

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