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Research Article

Dynamic downscaling of the ERA-40 data using a mesoscale meteorological model

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Abstract

A sophisticated downscaling procedure that was applied to reproduce high resolution historical records of the atmospheric conditions across the Mediterranean region is presented in this paper. This was accomplished by the dynamical downscaling of the European Center for Medium-Range Forecasts ERA-40 reanalyses with the aid of the atmospheric model of the POSEIDON weather forecasting system. The full three dimensional atmospheric fields with 6 hours of temporal resolution and the surface meteorological parameters at hourly intervals were produced for a 10-year period (1995-2004). The meteorological variables are readily available at 10 km resolution and may constitute the atmospheric forcing to drive wave, ocean hydrodynamic and hydrological models, as well as the baseline data for environmental impact assessment studies. A brief overview of the procedure and a quantitative estimation of the benefit of the new dynamical downscaling dataset is presented.

Keywords: Atmospheric forcing; POSEIDON system; Mediterranean region; Dynamical downscaling; Complex terrain.

Introduction

In the marine environment, knowledge of the climatology and the statistics of extreme events is of central interest for a broad range of practical applications. For example, in the design and the planning for most of coastal and offshore applications, detailed knowledge of local marine wind and wave fields is essential. To obtain such information long-term and homogeneous oceanographic and atmospheric databases are needed. However, such time series of direct observations are not always available for sufficiently long periods. Practically, traditional meteorological stations are rather limited with respect to geophysical changes on the scale of interest. Moreover, in mountainous terrain, coastal areas and in places with complex landscapes, significant differences in local environment may occur over neighboring places. For regions that do not have adequate historical observations, or where measurements are not available or lack homogeneity, the application of sophisticated meteorological simulations is often an alternative solution.

The different types of available computational methodologies can be classified into two broad categories: the diagnostic and the prognostic models (PIELKE, 2002). The diagnostic models are limited in their applicability. They can represent satisfactorily the state of atmosphere around the weather stations, but their usefulness is limited due to the insufficient spatial and temporal measurement density. To overcome the shortcomings of the diagnostic models, prognostic atmospheric models have been developed. These models are used to predict the time evolution of the atmospheric state through the integration of time dependent partial differential equations of the conservation of mass, momentum, heat, water, and other gaseous and aerosol materials. The mesoscale models which are integrated over a limited area require proper initial and boundary conditions to provide unique solutions for any set of differential equations. For this purpose, observed data from radiosondes, weather satellites, and surface weather observations are utilized. The irregularly-spaced observations are processed by objective analysis or variational analysis methods (SAKAKI, 1970) which perform quality control and produce fields in evenly-spaced grid structure. These fields represent the analysis which is used in the model as the starting point for the forecast.

Data assimilation is an advanced numerical method to combine background or 'first-guess' gridded field for a short period (typically 6 h) with all available observations for this period in order to produce the analysis at regular temporal intervals (i.e., hourly). Global analyses are produced by large operational centers, like the European Centre for Medium-Range Forecasts (ECMWF) and the US National Centers for Environmental Prediction (NCEP). The operational analyses contain many discontinuous changes due to the improvements in the numerical methods used to produce them (TRENBERTH & OLSON, 1988), introducing artificial changes in the apparent climate record. This problem has been addressed by the 'reanalysis' projects.

Reanalysis products are generated by the assimilation of all available observational data, incorporating data that had not been used in the operational analyses, using the same most recent assimilation method for the entire period of coverage (KALNAY *et al.,* 1996). The most common first generation global reanalysis datasets are: (i) the ERA-15 produced by the ECMWF, which is a 15-year reanalysis starting from 1979, (GIBSON *et al.,* 1997); (ii) a 50-year reanalysis from 1948, produced by the NCEP in collaboration with the National Center for Atmospheric Research (NCAR) (KALNAY *et al.,* 1996; KISTLER *et al.,* 2001); (iii) a 16-year reanalysis from March 1980 produced by the Data Assimilation Office (DAO) of the National Aeronautics and Space Administration (NASA), (SCHUBERT *et al.,* 1995).

The ERA project has produced a new 45-year second-generation reanalysis dataset, the ERA-40 (UPPALA *et al.,* 2005). Currently, ERA-40 is the main reanalysis product and is widely used. However, the spatial resolution of the ERA-40 data is rather coarse (about 125 km grid); consequently, they only describe the large-scale atmospheric features and provide limited representation of the mesoscale atmospheric processes, highly affected by topography and land-sea distribution. Thus, an appropriate downscaling technique is required to resolve the desired fine-scale meteorological fields.

The downscaling methods can be based on statistical schemes or can be conducted within a dynamical framework by nesting a high-resolution limited area model into the coarser resolution reanalysis output. Several studies have discussed a number of issues related to the appropriate choice of the downscaling method for a particular application (e.g., KIDSON & THOMPSON, 1998; FENNESSY & SHUKLA, 2000; DIEZ *et al.,* 2005; SCHMIDLI *et al.,* 2007; XUE *et al.,* 2007). Statistical downscaling is based on fine-scale observed data and has been successfully applied in data-rich regions. However, the dynamical downscaling methods have the potential to outperform statistical methods, particularly when no observed data contribute to the analysis and assumptions have to be adapted in order to interpolate a sparse station network over complex terrain.

This paper presents the dynamical downscaling methodology which was undertaken to produce high-resolution atmospheric conditions over the Mediterranean basin and the surrounding countries. The motivation of this work was the need to provide fine scale atmospheric forcing usable to drive wave, ocean hydrodynamic and hydrological models as well as the baseline data for environmental impact assessment studies. The mesoscale meteorological model of the POSEIDON weather forecasting system (PAPADOPOULOS *et al.,* 2002) has been appropriately configured to run at 10 km grid spacing (as opposed to 125 km grid spacing of the ERA-40). The ECMWF ERA-40 reanalysis data and the ECMWF operational analyses were used to force the mesoscale model at its boundaries and thereafter the mesoscale model downscales the global data by producing fine-scale weather patterns consistent with the coarse-resolution features in the forcing data. Due to the computational cost, the mesoscale model was run only for the period 1995-2004.

Materials and Methods

Global atmospheric reanalysis dataset – ERA-40

ERA-40 is the newest global atmospheric dataset incorporating the most modern assimilation techniques and includes all available observational data (both data from the operational ECMWF archives and data supplied to ECMWF by external organizations). UPPALA *et al.* (2005) demonstrated that the second-generation ERA-40 reanalysis provides products that are better than those from the first generation ERA-15 and NCEP/NCAR reanalyses. Moreover, ERA-40 provides fields with higher horizontal and vertical resolution than is provided by the earlier reanalyses. The ERA-40 data sets include four analyses per day, for 00, 06, 12, and 18 UTC, and for the period from September 1957 to August 2002. The atmospheric model used is a version of the Integrated Forecasting System (IFS CY23r4) with a spectral representation of T159L60. This means that in the horizontal the spectral truncation is at wave–number 159 and the number of the vertical levels is 60 which are extended up to an altitude of about 0.1 hPa ($\sim$70 km). The ERA-40 data are available through public internet access to a comprehensive set of $2.5^\circ \times 2.5^\circ$ resolution and through authorized access to the ECMWF's Meteorological Archive and Retrieval System

(MARS) to a regular $1.125^{\circ} \times 1.125^{\circ}$ latitude/longitude grid spacing products. For the Mediterranean region this grid spacing corresponds to a computational grid length of about 125 km in latitude and 95 km in longitude.

The atmospheric model

The atmospheric model used is based on the latest version of the SKIRON/Eta mesoscale meteorological model (KALLOS *et al.,* 1997; NICKOVIC *et al.,* 2001; PAPADOPOULOS *et al.,* 2002) which is a modified version of the non-hydrostatic workstation Eta model (JANJIC *et al.,* 2001). This version became the core of the second generation POSEIDON weather forecasting system (PAPADOPOULOS & KATSAFADOS, 2009) and is fully parallelized to run efficiently on any parallel computer platform. It uses a two-dimensional scheme for partitioning grid-point space to Message Passing Interface (MPI) tasks. MPI is a protocol for the data exchange and synchronization between the executing tasks of a parallel job.

The Eta model is designed to use either the hydrostatic approximation or the non-hydrostatic correction in order to be able to resolve high resolution atmospheric processes. Consequently, it can be executed with the finest horizontal resolution of less than 10 km. The Eta is formulated as a grid-point model and the partial differential equations are represented by finite-difference schemes. The Eta model 'native' grid is awkward to work with because the variables are on semi-staggered (e.g., the grid for winds is not the same as the grid for mass points) and non rectangular (number of points in x-axis is not constant in respect to y-axis) grids. More specifically, in the horizontal, the model is defined over the semi-staggered E grid, as it is shown in Figure 1a. The choice of the E grid was based on the fact that this shows good performance in simulating smaller-scale processes (such as gravity-inertia disturbances). The method, which provides a proper behavior of the model with variables on the E grid, is developed in cases of strong physical forcing (e.g., orography influence, convection, turbulence). The points denoted by **h** carry surface pressure, temperature, specific humidity, cloud water, vertical velocity, turbulent kinetic energy as well as passive substances. The **v** points carry the u and v components of the horizontal wind. The problem of adequate simulation of mountain effects was a matter for careful consideration from the beginning of the Eta model development. The model uses the Eta coordinate (η) which is a generalization of the σ-coordinates for a better parameterization of step-like terrain. The mountains in the Eta system are represented as grid-box mountain blocks, as schematically shown in Figure 1b.

The Eta model is well-documented and detailed descriptions of its dynamics and physics components can be found in several studies (e.g., MESINGER *et al.,* 1988; JANJIC, 1994; JANJIC *et al.,* 2001, and references therein). However, some of the features of this model are summarized below.

The **dynamics** of the Eta/NCEP model is based on large-scale numerical solutions controlled by conservation of integral properties, energetically consistent time-difference splitting, and the step-like mountain representation. The second-order non-linear advection scheme is designed for the horizontal advection terms in the model equations. This scheme conserves several important parameters such as mass, energy and squared vorticity, thus reproducing the features of the real atmosphere. Conservation properties of the scheme, there-

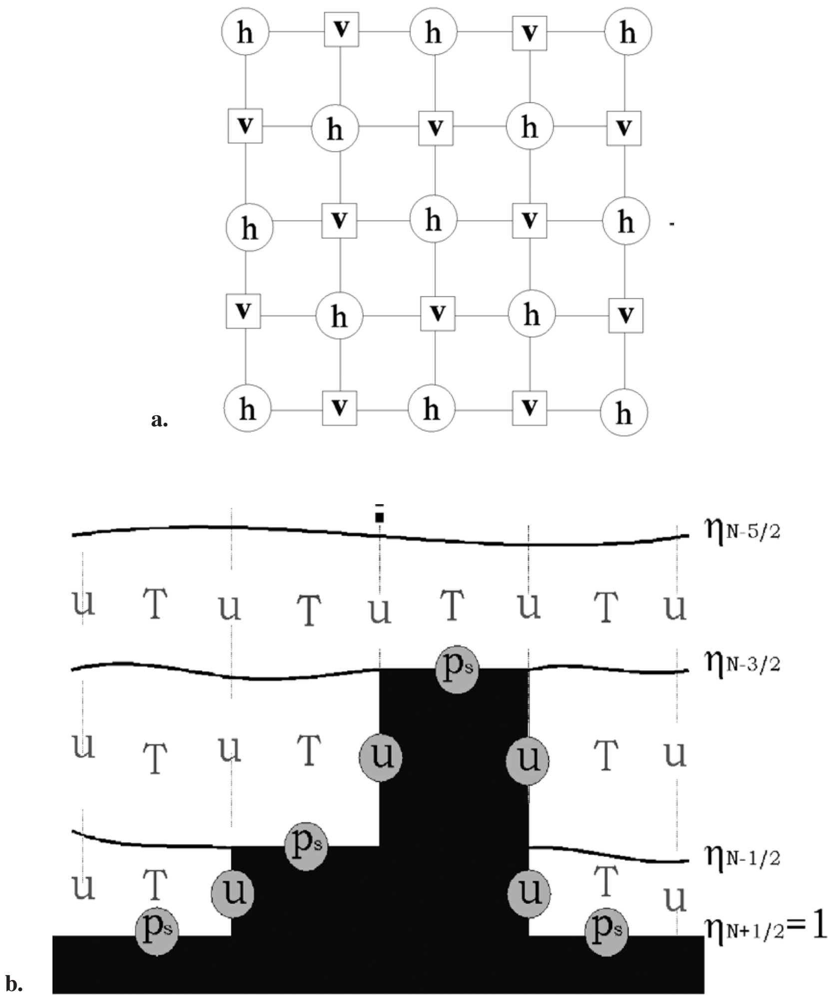


Fig. 1: Eta model horizontal (a) and vertical (b) grid structure.

fore, prevent a false generation of the numerical noise typical for many other atmospheric models. Time differencing in the Eta model is performed with explicit time differencing schemes. Attention is paid to the choice of time discretization techniques in order to provide efficient model executions. For terms related to smaller-scale processes, the forward-backward explicit scheme is used, integrating the continuity equation forward and pressure gradient terms backward in time. The forward-backward scheme is two times faster than any other explicit scheme. By applying a splitting technique, the advection terms (describing slower atmospheric motions) are calculated with several times larger time step than the adjustment step, providing higher model computational efficiency.

The **physical** package of the model represents atmospheric processes, which have smaller scales than the model grid structure; therefore are not resolved explicitly. The physical part of the Eta model is based on several sophisticated parameterization schemes. For the simulation of the radiative atmospheric effects, the Geophysical Fluid Dynamics Laboratory (GFDL) radiation scheme with random interaction of clouds at various levels is used. This scheme is relatively efficient because it uses extensively pre-calculated values of various parameters (look-up tables). The parameterization of the vertical turbulent mixing between levels in the free atmosphere is performed by using mixing coefficients of the Mellor-Yamada 2.5 level turbulence. A non-linear fourth-order lateral diffusion scheme, with the diffusion coefficient depending on the deformation and the turbulent kinetic energy, is introduced to control the level of small-scale noise. The Betts-Miller-Janjic deep and shallow cumulus convection scheme is used in order to represent sub-grid scale convective processes. Alternatively, it can use the Kain-Fritsch convective parameterization. The large-scale condensation scheme (Ferrier) is implemented to simulate moist atmospheric processes of stratiform clouds. The sufficient vertical resolution applied in the Eta model permits the application of a surface layer model based on the well established Monin-Obukhov similarity theory. Then, the Monin-Obukhov based surface layer parameterization scheme provides the lower boundary conditions for the 2.5 level turbulence model. Moreover, the introduction of a viscous sublayer describes a more realistic situation near the surface. Different viscous sublayer approaches are applied over ground and over water surfaces in the model. For the specific application, special care was taken in the calculations of the 10 meter wind. The calculations of the surface parameters within this viscous sublayer have an obvious advantage that decreases the level of uncertainty in the wind, air temperature and humidity fields near the surface. The atmospheric model is coupled with the Oregon State University (OSU) land surface model, which includes surface hydrology, to simulate the surface processes. This advanced model component provides a proper exchange of heat, moisture and momentum between the atmosphere and the earth surface using six soil layers.

For the surface process calculations, a corresponding set of high-resolution surface parameters (topography, vegetation types, soil texture, slopes and the azimuths of the sloping surfaces) are utilized. The topographic dataset used is a dataset from the US Geological Survey (USGS) with 30x30 arc sec resolution (approximately 750-900 m.). The description of the land-cover of the surface follows the classification suggested by the Simple Biosphere scheme (DORMAN & SELLERS, 1989) and is realized using 13 vegetation types plus the type for water body. The finest land cover data set with global cover is available from USGS at a resolution of 30x30 arc seconds. For soil textural class, the UNEP/FAO data set is used after its conversion from soil type to soil textural ZOBLER classes (PAPADOPOULOS *et al.,* 1997). The coverage of this data set is global and the resolution is 2x2 min. In addition to these, the slopes and the azimuths of the sloping surfaces are computed and then used for the calculation of the incoming solar radiation over the sloping terrain. Albedo and surface roughness variations are also computed in the pre-processing stage as being dependent on vegetation.

Model setup – downscaling experiment

In the current dynamical downscaling approach the Eta model was forced by the ERA-40 reanalysis outputs. Because the domain size and the grid spacing are factors crucial for the model's performance, their definition was based on the fully tested model configuration of the finer POSEIDON-1 weather forecasting system (shown as POS-1 10 km in Fig. 2). However, a modified larger model domain has been used in this study. Specifically, the eastern boundary was placed over the Caspian Sea in order to avoid the high Caucasus Mountains in the boundary zone which may produce numerical noise or model instability. The western boundary was moved toward west in order to enclose part of the Northeast Atlantic coastal waters. The northern and southern boundaries were placed close to the original boundary locations of the finer POSEIDON-1 model domain. Therefore, the mesoscale model was integrated over a domain large enough to include all terrain features which might influence the mesoscale flow. Thus, the model domain covers the Mediterranean Sea and part of Europe and North Africa, with latitude roughly between 24.4° N and 51.0° N, and longitude between 21.0° W and 51.0° E (DDD 10 km, as shown in Fig. 2).

The model had a horizontal grid increment of $0.1° \times 0.1°$ (about 10 km) resulting in 247x231 semi-staggered E grid points within the rotated transformed latitude-longitude coordinate system of the Eta model. In the vertical, 38 unevenly spaced levels were used covering the atmospheric layers from the surface to roughly 20 km height, with the maximum resolution within the planetary boundary layer. Although the Eta coordinate system is pressure based and normalized, the height of each vertical level can be defined at height above sea level (ASL)[1]. The fundamental time step of the model was defined to 30 seconds. Moreover, the six soil layers have been defined at the depths of 5, 15, 28, 50, 100, and 255 cm.

As it has been referenced, the ERA-40 reanalysis data are organized in four analyses per day (for 00, 06, 12, and 18 UTC) for the period from September 1957 to August 2002. Therefore, the ERA-40 reanalysis was the source used for the definition of the initial and the boundary conditions for the simulations from January 1995 to August 2002 while the operational ECMWF analysis fields were used for the simulations from January 2002 to December 2004. It is worth noting, that the subsequent archived operational ECMWF analyses were based on the same data assimilation system as the ERA-40, but the resolution of the atmospheric model had increased to a spectral representation of TL511L60, which is about 40 km horizontal grid spacing. The simulations for the common period (January 2002 till August 2002), therefore, have been performed in order to investigate later any influence caused by the different initial and boundary conditions. Both reanalysis and operational analysis fields (geopotential, wind components and humidity) were available for 16 standard pressure levels (1000, 925, 850, 700, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, and 10 hPa) and were interpolated to a regular $0.5° \times 0.5°$ horizontal grid increment using the ECMWF model's

[1] The 38 eta levels were defined at 19.5, 61.7, 112.2, 181.1, 269.8, 378.3, 506.7, 654.8, 822.6, 1010.4, 1218.1, 1446.1, 1694.6, 1964.2, 2255.1, 2568.1, 2903.9, 3263.3, 3647.3, 4057.0, 4493.8, 4959.1, 5455.0, 5983.4, 6547.1, 7148.2, 7786.2, 8452.9, 9129.6, 9799.3, 10469.8, 11185.0, 12006.2, 12983.1, 14151.6, 15566.1, 17232.5, 19321.7 m ASL.

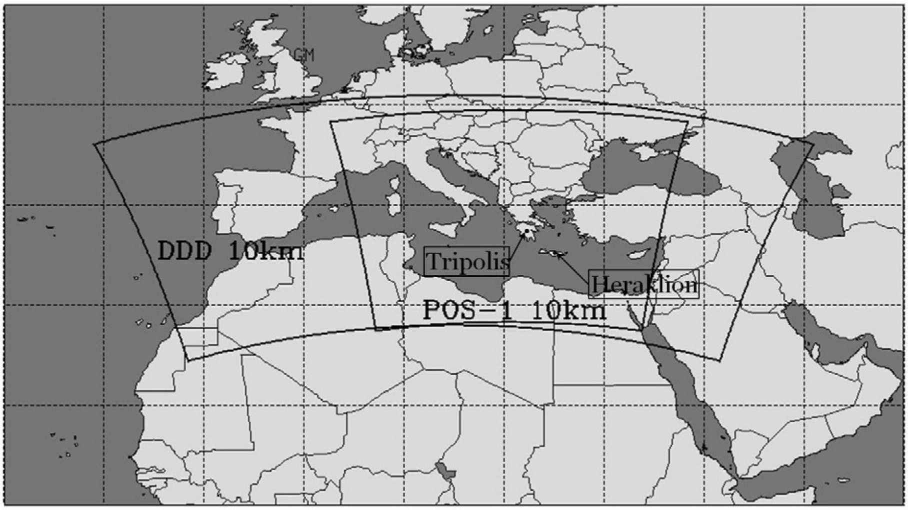


Fig. 2: Model domain in the downscaling method and the POSEIDON operational forecast domains.

own reduced Gaussian grid (PERSSON, 2003). The lateral boundaries of the model domain were updated at each model's time step from the ECMWF data available every 6 hours (at 00, 06, 12, and 18 UTC). For the fields of the sea surface temperature (SST), soil temperature and soil moisture, the ECMWF data at a $0.5^\circ \times 0.5^\circ$ horizontal grid increment were used.

The model was configured to a 30-h forecasting mode and 3,896 simulations (including the common time period) were conducted to cover the 10-year period (1995-2004). For each simulation the initial conditions for the atmosphere and the SST were reinitialized while the soil moisture and temperature were initialized from the previous simulation. The length of each simulation was set to 30 hours in order to avoid a 6-hour spin-up time. Therefore, the model outputs from 6-h to 30-h of each simulation have been used to create the 10-year dataset of atmospheric forcing. The completeness of such demanding simulations would not have been feasible without the high-performance computing capabilities of the Hellenic National Meteorological Service (HNMS) which supported the available computing resources of the Hellenic Centre for Marine Research (HCMR). The two computing systems were combined to optimize computing workloads, data management, data processing and data mining and eventually the overall time for producing the final database was approximately sixteen months.

Results and Discussion

The atmospheric variables produced by the dynamical downscaling of the ERA-40 data are presented in Table 1.

The upper-air parameters were saved at each of the 38 model levels for 00, 06, 12, and 18 UTC of each day for the 10-year period (1995-2004). The soil parameters, thus soil temperature and soil moisture, were also stored at each of the six soil layers with 6 hours of temporal resolution. Meanwhile, the surface and the single level parameters were archived for every hour of the entire time period. The data volume of the com-

Table 1
Upper air, surface, single level and soil parameters of the new dynamical downscaling dataset.

Upper Air parameters	Soil parameters	Surface parameters	Single level parameters
geopotential height	soil temperature	air temperature at 2m	low cloud cover
air temperature	soil moisture	relative humidity at 2m	medium cloud cover
u- wind component		10m u- wind component	high cloud cover
v- wind component		10m v- wind component	top atmosphere short wave radiation
vertical velocity		total precipitation	top atmosphere long wave radiation
cloud water content		convective precipitation	
specific humidity		snowfall	
turbulent kinetic energy		surface pressure	
		mean sea level pressure	
		potential temperature	
		sensible heat flux	
		latent heat flux	
		incoming short wave radiation	
		outgoing short wave radiation	
		incoming long wave radiation	
		outgoing long wave radiation	

plete archive is more than 4 TB. The format of the files is either Fortran binary or GRIB (Gridded Binary) both saved on the model grid. However, experience gained by disseminating the products from the POSEIDON weather forecasting system (e.g., SOUKISSIAN *et al.,* 2008) suggests that the majority of users are mostly interested in the near surface meteorological variables. Thus, a smaller and more practical dataset has been formed consisting of the following surface meteorological variables

- air temperature at 2 m
- wind speed and direction at 10 m
- humidity (relative or specific) at 2 m
- mean sea level pressure
- sensible and latent heat fluxes
- ground fluxes of shortwave and longwave radiation
- amount of precipitation,

As mentioned before, the Eta model is defined over the semi-staggered E grid. To overcome this inconvenience, advanced software has been developed in order to process the model-generated fields and to bilinearly interpolate them in unstaggered grid form. In the unstaggered grids all variables are placed on a common and rectangular grid, also taking into account the wind rotation so that vector data are properly projected. This smaller dataset of surface meteorological variables is approximately 300 GB and is ready for use by other applications across the Mediterranean region.

The advantage of this long-term database is that it can provide more realistic and accurate atmospheric conditions over the Mediterranean basin and the surrounding countries. As it is well known (e.g. PIELKE, 2002), the model-generated conditions represent 'average' conditions over the extent of the model's grid cell, which are correlated to the 'average' characteristics of the surface quantities (i.e., topography, vegetation type, soil type, albedo, roughness, land-water contrast). Furthermore, the model surface is divided into sea and land points, by using a land–sea mask. The land-sea mask is a control array that holds, for every grid point, the proportion of the actual land enclosed in the grid cell. Based on this matrix, a grid point is defined as a land point if more than 50% of the actual surface within the grid-box is land. Logically, the model topography is smoothed to the resolution of the model grid spacing which can differ significantly from the actual topography. However, the finer horizontal resolution allows for a better representation of the landscape and the land-sea distribution. Figure 3 shows the differences in the topographical details of the two databases, focusing over the east-

a.

b.

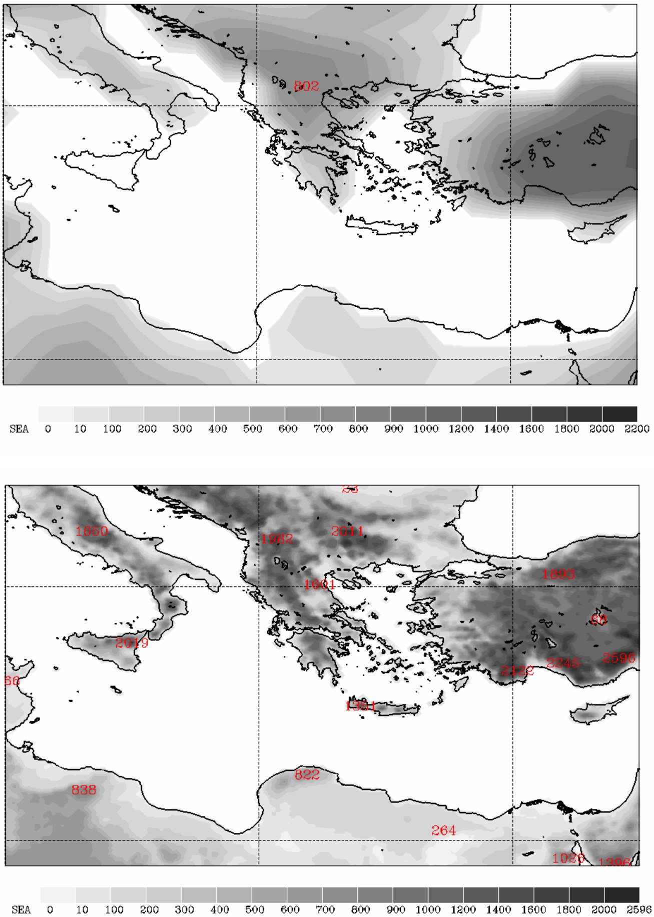


Fig. 3: Topographical details (numbers denote height in meters) for (a) the ERA-40 and (b) the dynamical downscaling datasets.

ern Mediterranean. Noticeably, the ERA-40 topography and land-sea distribution are severely underestimated; even the major islands of Sicily and Crete are not represented and Cyprus is considered as part of the Asia Minor mainland. On the contrary, the mesoscale meteorological model can accurately represent spatial variations of the regional topography, the land-sea contrasts and accordingly the other physiographic characteristics (vegetation types, soil properties, etc). Then, through the dynamical downscaling procedure the mesoscale model maintains the large-scale atmospheric systems from the ERA-40 data and simulates fine scale features that are modulated by interactions with the land surface and mesoscale circulations. These mesoscale circulations yield important differences in the magnitude and distribution of surface variables. For example, Figure 4 shows the air temperature at 2 m height for a typical winter day (as of 0000 UTC on 2 January 2000). Clearly, the application of the downscaling added realistic mesoscale details over the ERA-40 structure of the air temperature.

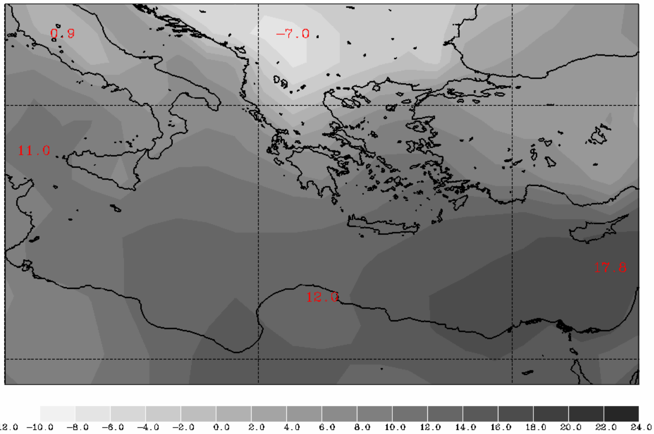
To provide quantitative estimates of the benefit of the new 10-year dynamical downscaling dataset (DDD-10) the air temperature obtained from the two datasets was verified against the observations recorded at Heraklion Airport and Tripolis Airport for the time period 2000-2001. The first one is a coastal station located at 39 m height, while the second is located at the Central Peloponnesus at 652 m elevation. To measure the magnitude of the differences three main statistical scores were estimated: root mean square error (RMSE), BIAS and standard deviation (SD). Tables 2 and 3 show these scores for both stations as well as the standard deviations of the measurements of the shelter air temperature. As expected, the downscaled air temperature yields better statistics, particularly in the mountainous area. Specifically, at Heraklion airport (the coastal station) the RMSE for the ERA-40 is the 31.2% of the standard deviation of the observations and the RMSE for the DDD-10 is slightly lower, namely 30.9%. On the contrary, at the mountainous station the RMSE decreases from 61% (of the standard deviation of the observations) for

Table 2
Statistics of air temperature at 2m height (in ˚C) at Heraklion Airport for 2000-2001.

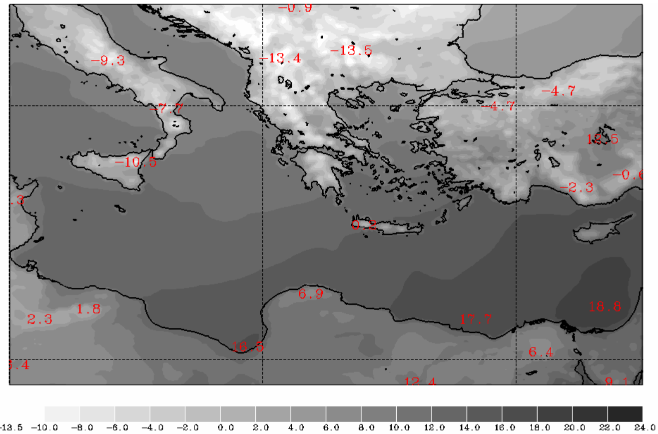
	RMSE	BIAS	SD
ERA-40	1.90	0.83	5.04
DDD-10	1.88	-0.18	6.88
Observations			6.09

Table 3
Statistics of air temperature at 2m height (in ˚C) at Tripolis Airport for 2000-2001.

	RMSE	BIAS	SD
ERA-40	5.80	4.71	7.58
DDD-10	4.61	2.78	8.79
Observations			9.52



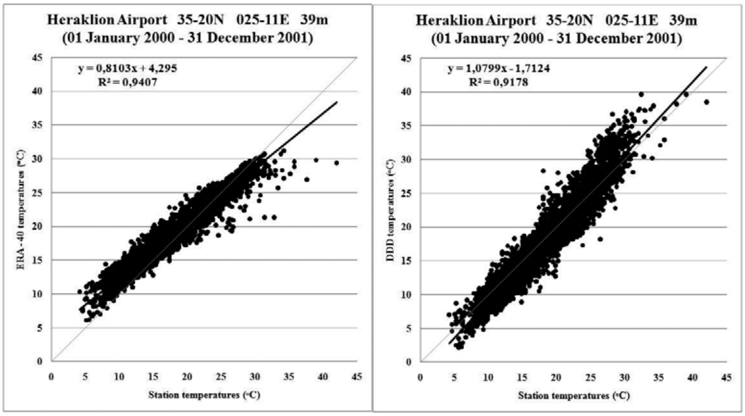
a.



b.

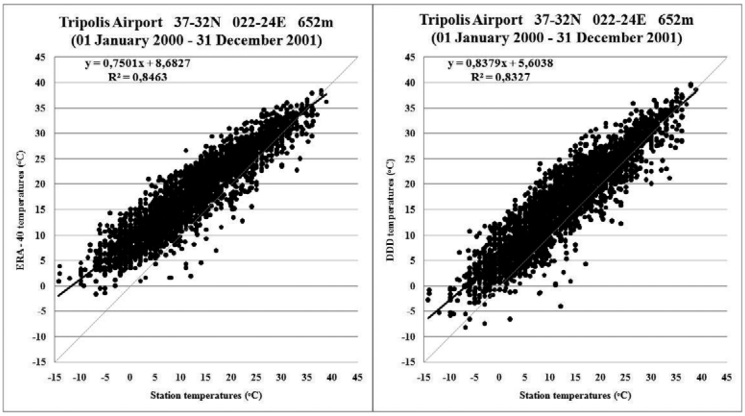
Fig. 4: Air temperature at 2 m (in ˚C) at 0000 UTC on 2 January 2000 obtained from (a) the ERA-40 and (b) the dynamical downscaling datasets.

ERA-40 to 48% for DDD-10. Furthermore, the standard deviation shows higher variability for the DDD temperatures which is closer to the standard deviation calculated from the measurements. This is an indication that the DDD-10 includes a relatively stronger diurnal signal in temperature compared with the ERA-40 dataset. Figures 5 and 6 show the scatter plots of the near surface air temperature of the observations versus the corresponding fields obtained from the two datasets for the two stations, respectively. Arguably, the DDD-10 product exhibits a stronger correspondence with the observations (the slope of the linear regression equation is closer to one and the constant is closer to 0 than those of ERA-40) although the ERA-40 scatter is not much worse, particularly in the intermediate values. Despite the fact of the slightly improved values of the ERA-40 correlation coefficients (quite high for both datasets at 95% confidence level), the DDD-10 data provide a more realistic reproduction of the



a. b.

Fig. 5: Scatter plot of air temperature at 2 m (in ˚C) of observations against (a) the ERA-40 and (b) the dynamical downscaling datasets for Heraklion Airport for 2000-2001. The black bold line illustrates the linear regression line.



a. b.

Fig. 6: Scatter plot of air temperature at 2 m (in ˚C) of observations against (a) the ERA-40 and (b) the dynamical downscaling datasets for Tripolis Airport for 2000-2001. The black bold line illustrates the linear regression line.

high-frequency variations in the diurnal evolution of the air temperature, capturing better the observed maxima and minima temperatures at the locations of both coastal and mountainous stations.

It is important to note that a detailed statistical analysis is needed in order to conclude whether the downscaling dataset offers better forcing data. More specifically, the evaluation period should be larger and the evaluation methodology should be based on the terrain characteristics including more stations, which should be grouped according to the characteristics of the surrounding terrain: flat terrain, mountainous, coastal, complex etc. Anyway, it is worth mentioning that the version of the mesoscale model that was used in the downscaling approach became the core of the second generation POSEIDON weather forecasting system and its performance skill has been rigorously evaluated by Papadopoulos and Katsafados (2009).

Finally, it is noted that the limitations of the ERA-40, particularly over regions with inadequate coverage of observations, have been already recognized by ECMWF. ECMWF is currently producing ERA-Interim, a global reanalysis of the data-rich period since 1989. The ERA-Interim data (SIMMONS *et al.,* 2007) is an 'interim' reanalysis of the period from 1989 until real time in preparation for the next-generation extended reanalysis to replace ERA-40. The ERA-Interim reanalysis caught up with operations in March 2009, and is now being continued in near-real time to support climate monitoring. This forcing data was not available for use in our dynamical downscaling. However, it is in our future plans to perform similar long-term simulations in order to downscale the ERA-Interim fields at 5-km resolution over the Mediterranean region.

Acknowledgements

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References

DIEZ, E., PRIMO, C., GARCIA-MOYA, J.A., GUTIERREZ, J.M. & ORFILA, B., 2005. Statistical and dynamical downscaling of precipitation over Spain from DEMETER seasonal forecasts. *Tellus,* 57A: 409-423.

DORMAN, J.L. & SELLERS, P.J., 1989. A global climatology of albedo, roughness and stomatal resistance for atmospheric general circulation models as represented by the Simple Biosphere Model (SiB). *Journal of Applied Meteorology,* 28: 833-855.

GIBSON, J.K., KALLBERG, P., UPPALA, S., NOMURA, A., HERNANDEZ, A. & SERRANO, E., 1997. ERA Description. In: *ECMWF ERA-15 Project Report Series,* No. 1. European Centre for Medium-Range Weather Forecasts, Shinfield, Reading, UK (available from www.ecmwf.int/ publications).

FENNESSY, M.J. & SHUKLA, J., 2000. Seasonal prediction over North America with a regional model nested in a global model. *Journal of Climate,* 13: 2605-2627.

JANJIC, Z.I., 1994. The step-mountain Eta coordinate model: Further developments of the convection, viscous sublayer and turbulence closure schemes. *Monthly Weather Review,* 122: 927-945.

JANJIC, Z.I., GERRITY, J.P.JR. & NICKOVIC, S., 2001. An Alternative Approach to Nonhydrostatic Modeling. *Monthly Weather Review,* 129:

1164-1178.

KALNAY, E., KANAMITSU, M., KISTLER, R., COLLINS, W., DEAVEN, D., GANDIN, L., IREDELL, M., SAHA, S., WHITE, G., WOOLLEN, J., ZHU, Y., CHELLIAH, M., EBISUZAKI, W., HIGGINS, W., JANOWIAK, J., MO, K.C., ROPELEWSKI, C., WANG, J., LEETMAA, A., REYNOLDS, R., JENNE, R. & JOSEPH, D., 1996. The NCEP/NCAR 40-year reanalysis project. *Bulletin of the American Meteorological Society,* 77 (3): 437-471.

KALLOS, G., NICKOVIC, S., PAPADOPOULOS, A., JOVIC, D., KAKALIAGOU, O., MISIRLIS, N., BOUKAS, L., MIMIKOU, N., SAKELLARIDIS, G., PAPAGEORGIOU, J., ANADRANISTAKIS, E. & MANOUSAKIS, M., 1997. The regional weather forecasting system SKIRON: An overview. p.109-122. In: *Proceedings of the International Symposium on Regional Weather Prediction on Parallel Computer Environments,* 15-17 October 1997, Athens, Greece.

KIDSON, J.W. & THOMPSON, C.S., 1998. A comparison of statistical and model-based downscaling techniques for estimating local climate variations. *Journal of Climate,* 11: 735-753.

KISTLER, R., KALNAY, E., COLLINS, W., SAHA, S., WHITE, G., WOOLLEN, J., CHELLIAH, M., EBISUZAKI, W., KANAMITSU, M., KOUSKY, V., VAN DEN DOOL, H., JENNE, R. AND FIORINO, M., 2001. The NCEP–NCAR 50-year reanalysis: Monthly means CD-Rom and documentation. *Bulletin of the American Meteorological Society,* 82: 247–267.

MESINGER, F., JANJIC, Z.I., NICKOVIC, S., GAVRILOV, D. & DEAVEN, D.G., 1988. The steep-mountain coordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment. *Monthly Weather Review,* 116: 1493-1518.

NICKOVIC, S., KALLOS, G., PAPADOPOULOS, A. & KAKALIAGOU, O., 2001. A model for prediction of desert dust cycle in the atmosphere. *Journal of Geophysical Research,* 106: 18113-18129.

PAPADOPOULOS, A., KALLOS, G., NICKOVIC, S., JOVIC, D., DACIC, M. & KATSAFADOS, P., 1997. Sensitivity studies of the surface and radiation parameterization schemes of the SKIRON system. p.155-164. In: *Proceedings of the International Symposium on Regional Weather Prediction on Parallel Computer Environments,* 15-17 October 1997, Athens, Greece.

PAPADOPOULOS, A., KALLOS, G., KATSAFADOS, P. & NICKOVIC, S., 2002. The Poseidon weather forecasting system: An overview. *The Global Atmosphere & Ocean Systems,* 8 (2-3): 219-237.

PAPADOPOULOS, A. & KATSAFADOS, P., 2009. Verification of operational weather forecasts from the POSEIDON system across the Eastern Mediterranean. *Natural Hazards & Earth System Sciences,* 9: 1299-1306.

PERSSON, A., 2003. User Guide to ECMWF forecast products. *Meteorological Bulletin* M3.2, 123 pp.

PIELKE, R.A., 2002. Mesoscale Meteorological Modeling. Second Edition, Academic Press, 693 pp.

SASAKI, Y., 1970. Some basic formalisms in numerical variational analysis. *Monthly Weather Review,* 98 (12): 875-883.

SCHMIDLI, J., GOODESS, C.M., FREI, C., HAYLOCK, M.R., HUNDECHA, Y., RIBALAYGUA, J. & SCHMITH, T., 2007. Statistical and Dynamical Downscaling of Precipitation: an Evaluation and Comparison of Scenarios for the European Alps. *Journal of Geophysical Research,* 112 (D04105). DOI:10.1029/2005JD007026

SCHUBERT, S., PARK, C.-K., WU, C.-Y., HIGGINS, W., KONDRATYEVA, Y., MOLOD, A., TAKACS, L., SEABLOM, M. & ROOD, R., 1995. A multi-year assimilation with the GEOS-1 system: overview and results. *NASA Technical Reports Series on Global Modeling and Data Assimilation, No. 6.* Data Assimilation Office, Goddard Space Flight Center, Greenbelt, 183 pp.

SIMMONS, A., UPPALA, S., DEE, D. & KOBAYASHI, S., 2007. New ECMWF reanalysis products from 1989 onwards. *ECMWF Newsletter,* 110: 25-35.

SOUKISSIAN, T., PROSPATHOPOULOS, A., KORRES, G., PAPADOPOULOS, A., HATZINAKI, M. & KABOURIDOU, M., 2008. A New Wind and Wave Atlas of The Hellenic Seas. p.1-9. In: *Proceedings of the 27th Annual International Conference on Offshore Mechanics and Arctic Engineering,* OMAE2008-57082.

TRENBERTH, K. & OLSON, J., 1988. An evaluation and intercomparison of global analyses from the National Meteorological Center and the European Centre for Medium Range Weather Forecasts. *Bulletin of the American Mathematical Society,* 69: 1047-1057.

UPPALA, S.M., KALLBERG, P.W., SIMMONS, A.J., ANDRAE, U., DA COSTA BECHTOLD, V., FIORINO, M., GIBSON, J.K., HASELER, J., HERNANDEZ, A., KELLY, G.A., LI, X., ONOGI, K., SAARINEN, S., SOKKA, N., ALLAN, R.P., ANDERSSON, E., ARPE, K., BALMASEDA, M. A., BELJAARS, A. C., VANDE, M., BERG, L., BIDLOT, J., BORMANN, N., CAIRES, S., CHEVALLIER, F., DETHOF, A., DRAGOSAVAC, M., FISHER, M., FUENTES, M., HAGEMANN, S., HOLM, E., HOSKINS, B.J., ISAKSEN, L., JANSSEN, P.A.E.M., JENNE, R., MCNALLY, A.P., MAHFOUF, J.-F., MORCRETTE, J.-J., RAYNER, N.A., SAUNDERS, R.W., SIMON, P., STERL, A., TRENBERTH, K.E., UNTCH, A., VASILJEVIC, D., VITERBO, P. & WOOLLEN, J., 2005. The ERA-40 re-analysis. *Quarterly Journal of the Royal Meteorological Society,* 131: 2961-3012.

XUE, Y., VASIC, R., JANJIC, Z., MESINGER, F. & MITCHELL, K.E., 2007. Assessment of Dynamic Downscaling of the Continental U.S. Regional Climate Using the Eta/SSiB Regional Climate Model. *Journal of Climate,* 20: 4172-4193.