

# A High-Resolution Numerical Weather Prediction system for Greece: Model Setup and Performance Analysis

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## Abstract

The Laboratory of Meteorology and Climatology (<http://meteo.geo.auth.gr>) of the Aristotle University of Thessaloniki utilizes the non-hydrostatic Weather Research and Forecasting model with the Advanced Research dynamic solver (WRF-ARW) in order to produce 4-day operational weather forecasts. Three model domains, using 2-way telescoping nesting, cover: i) Europe, the Mediterranean sea and northern Africa, ii) Greece and iii) the wider region of Macedonia - Thermaikos Gulf at horizontal grid-spacings of 15km, 5km and 1.667km, respectively. In the framework of WaveForUs project (<http://wave4us.web.auth.gr>), the WRF-ARW forecasts are employed (offline) by the partners in storm surge, wave and coastal circulation models in order to produce high-resolution operational sea-state forecasts for Thermaikos Gulf. The meteorological and sea-state forecasts are disseminated to end users and the public. The aim of this paper is to describe the meteorological model setup and analyse its performance during the first year of the operational period of the WaveForUs project (June 2013 – May 2014). The statistical scores were computed at different forecast times as a function of the season and the prevailing upper-air synoptic circulation in Greece. This methodology allows the identification of model errors that occur at specific periods and/or synoptic conditions and may otherwise be obscured in aggregate statistics. In general, the maximum errors were associated with cut-off and closed lows while the most predictable conditions occurred in anticyclonic/omega blocking circulations and in summer season.

## Keywords

Numerical weather prediction, nonhydrostatic WRF, model evaluation, Thermaikos Gulf, WaveForUs.

## Introduction

The significant progress in atmospheric numerical models and the increase of available computer power have resulted to a blooming of numerical weather prediction (NWP) during the last years. Moreover, the introduction of non-hydrostatic dynamics and the use of parallel computing have allowed the production of high resolution simulations in research and operational mode at reasonable time frames. A number of operational weather forecasting systems operate in Greece by the Hellenic National Meteorological Service (HNMS), universities and research institutes (Kallos 1997; Lagouvardos et al. 2003; Kallos et al. 2005; Henderson et al. 2005; Gofa et al. 2008; Papadopoulos and Katsafados 2009; Pytharoulis 2009; Bartzokas et al. 2010; Katsafados et al. 2012; and others). The aim of the WaveForUs project is to combine the most recent meteorological, storm surge, wave and coastal circulation models in order to produce high-resolution operational sea-state forecasts for Thermaikos Gulf and disseminate them to end users and the public. The main role of the Laboratory of Meteorology and Climatology of the Aristotle University of Thessaloniki (LMC-AUTH) is to produce and disseminate the meteorological forecasts which are necessary in order to drive the sea models. It is the first time that such fine resolution 4-day NWP forecasts are operationally available to the general public for the entire Macedonia, a large part of Thessaly and mainly Thermaikos Gulf. The outcomes of this project can be directly utilized for fisheries, aquaculture, water sports, recreation, tourism, scientific studies and environmental management and modeling. The aim of this paper is to describe the setup of the NWP system and assess its performance during the first year of the operational period of the WaveForUs project (June 2013 - May 2014).

## Model setup and methodology

The meteorological forecasts are produced by the non-hydrostatic Weather Research and Forecasting (WRF) numerical weather prediction model with the Advanced Research dynamic solver (WRF-ARW Version 3.2.0; Skamarock et al. 2008, Wang et al. 2011). It is a flexible state-of-the-art atmospheric model which can be employed in operational and research mode (data assimilation, parameterization research, case studies, idealized simulations etc) on various scales from the global to the local scale (Wang et al. 2011). Therefore, this model is suitable for the purposes of the WaveForUs project which requires the production of operational forecasts from the Mediterranean basin down to Thermaikos Gulf using high horizontal resolution.

The model is integrated in three telescoping nests which cover Europe, the Mediterranean basin and northern Africa (D01; Figure 1a), Greece (D02; Figure 1b) and the wider region of Macedonia - Thermaikos Gulf (D03; Figure 2). Their horizontal grid-spacings are 15km x 15km, 5km x 5km and 1.667km x 1.667km, respectively. The variables are horizontally distributed on the staggered Arakawa C grid. The inner domain (D03) covers the whole Macedonia, large parts of Thessaly and F.Y.R.O.M. and a region of southwestern Bulgaria. In this way, the wider region of Thermaikos Gulf, which is the area of interest, and the contiguous regions are represented in very high resolution. The two inner grids are two-way nested to their parent domains. In the vertical, 39 sigma levels (up to 50 hPa) with increased resolution in the boundary layer are used by all nests. The initial time of the WRF-ARW forecasts is daily at 1200 UTC. The two inner domains are initialised 6 hours after the coarse domain (D01) in order to reduce the model spin-up. The forecast horizon is four (4) days during the operational phase of WaveForUs project (since June 2013).

High-resolution topography, land/sea mask and land use data (30 x 30 arc sec; Figures 1, 2) provided by USGS (United States Geological Survey) are utilized for the definition of the physiographic characteristics. This is significant for Thermaikos Gulf which is integrated in high resolution and is surrounded by regions with inhomogeneous characteristics: a) high mountains to the west (Olympus and Pieria mountain range), b) combination of highlands and low elevation regions to the east (Thessaloniki, Chalkidiki) and c) the plain of Imathia and Pella as well as the valley of Axios river to the north. Thus, it is influenced by various meteorological phenomena which develop or strengthen in the surrounding regions (e.g. Vardaris wind).

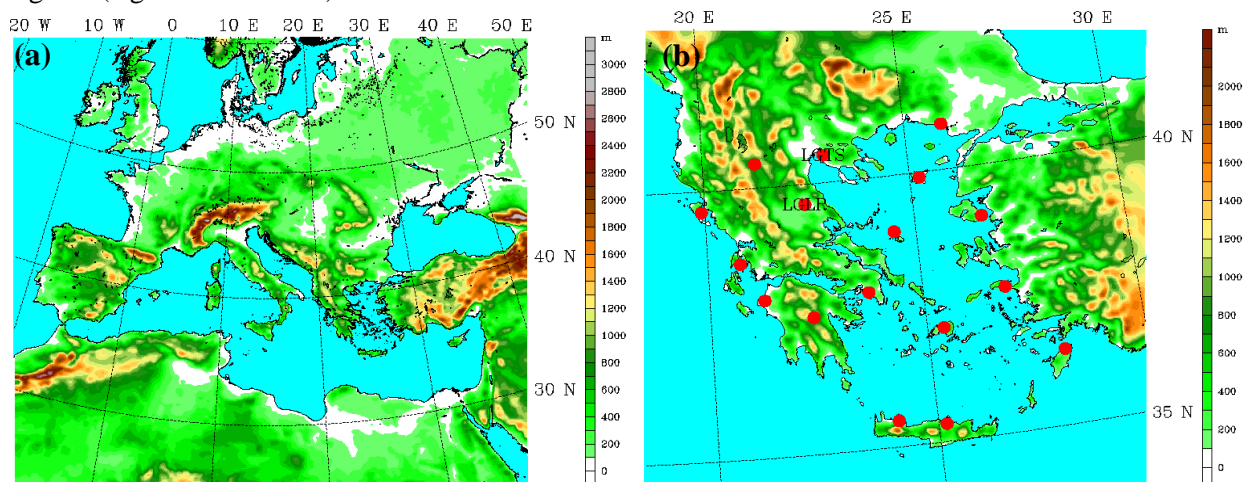


Figure 1. The topography (m) of (a) the first – D01 and (b) the second – D02 domains of WRF-ARW. In panel (b) the bullets depict the HNMS stations utilized in this study. LGTS and LGLR stand for Thessaloniki and Larissa airports, respectively.

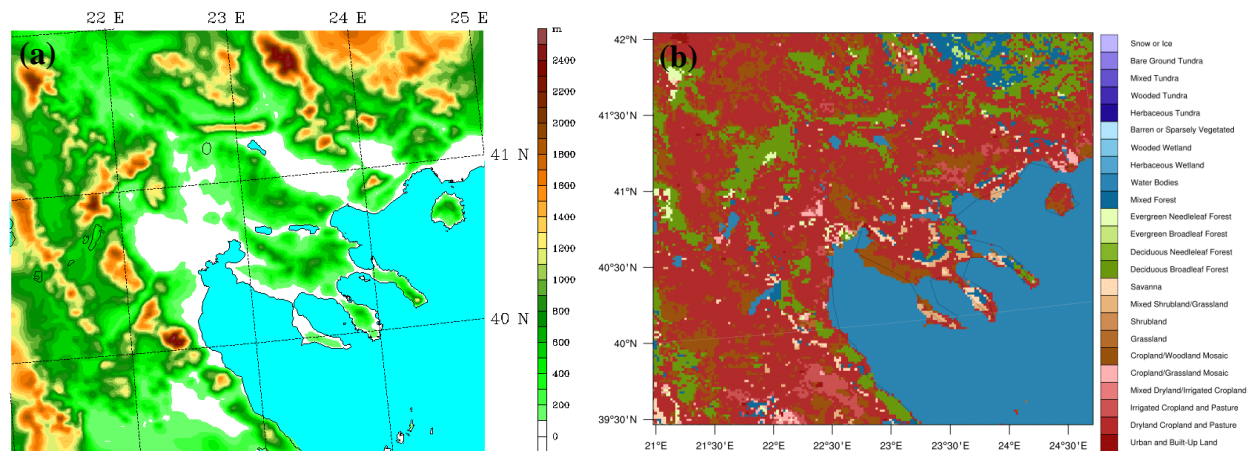


Figure 2. (a) The topography (m) and (b) the land-use categories of the third – D03 domain of WRF-ARW.

The initial and lateral boundary conditions are based on the operational analyses and 3-hourly forecasts, respectively, of the 1200 UTC cycle of NCEP/GFS (National Centers for Environmental Prediction / Global Forecast System; <ftp://ftp.prdd.ncep.noaa.gov>). The necessary input parameters are available on a regular latitude-longitude grid ( $0.5^\circ \times 0.5^\circ$ ), at the surface and on 26 pressure levels up to 10 hPa (with higher resolution at the lowest 100 mb). Moreover, soil temperature and volumetric soil moisture are provided at four soil layers (0-10cm, 10-40cm, 40-100cm and 100-200cm). The sea-surface temperatures (SSTs) are provided daily by NCEP (<http://polar.ncep.noaa.gov/sst/ophi/>) at a horizontal increment of  $1/12^\circ \times 1/12^\circ$  ( $\cong 0.083^\circ \times 0.083^\circ$ ) lat.-long. and remain fixed throughout the forecast horizon. The NCEP SSTs are produced on a daily basis through the assimilation of the most recent 24-hour sea-surface observations and satellite SST measurements.

A large number of physical processes that cannot be explicitly modelled due to the limits on the model's horizontal resolution are represented through parameterization schemes. The microphysical processes are parameterized by the Eta Ferrier scheme (Ferrier et al. 2002), which includes cloud water, rain, cloud ice and precipitation ice, and takes into account the mixed-phase processes. This is a simple efficient scheme employed operationally in NCEP models (Wang et al. 2011). Sub-grid scale convection is represented in D01 and D02 by the moist convective adjustment parameterization of Betts-Miller-Janjic (Janjic 1994, 2000) in which the deep convection profiles and the relaxation time depend on the cloud efficiency. This scheme is also used operationally at NCEP and has been improved over the recent years (Skamarock et al. 2008). The RRTMG scheme is employed in order to calculate longwave/shortwave radiation fluxes and heating rates (Iacono et al. 2008). It includes the MCICA (Monte-Carlo Independent Column Approximation) method to represent sub-grid cloud variability with random cloud overlap (Barker et al. 2003, Wang et al. 2011). The Monin-Obukhov (Eta) (Janjic 1994, 1996) and the Mellor-Yamada-Janjic (Mellor and Yamada 1982, Janjic 2002) schemes are adopted for surface layer and boundary layer processes, respectively. The viscous sub-layer is parameterized explicitly over water surfaces, while its effects are considered through variable roughness length for temperature and humidity over land (Skamarock et al. 2008). The boundary layer scheme, which is also utilized operationally by the well tested Eta model, predicts turbulent kinetic energy solving its production/dissipation differential equation. The soil processes are represented in four layers (0–10, 10–40, 40–100, and 100–200 cm) by the NOAH land surface Unified model (Chen and Dudhia 2001) which includes vegetation processes and a single layer snow scheme. NOAH predicts soil temperature, soil moisture, canopy moisture, snow cover and runoff taking into account the monthly vegetation fraction and the dominant vegetation and soil category at each grid cell.

In the WaveForUs project, WRF provides offline – at hourly timesteps – the atmospheric forcing to ocean models that operate in the Mediterranean sea, the Aegean sea and Thermaikos Gulf. Although the target area of this project is Thermaikos Gulf, it is necessary to provide meteorological forecasts and predict the

sea conditions in larger areas in order to represent the advection of various quantities and the swell from the Mediterranean sea to the Aegean sea and finally to Thermaikos Gulf. Therefore, the dissemination domains of the weather forecasts are: a) Mediterranean sea: 30.22°N - 45.97°N, 7.15°W - 38.00°E, b) Aegean sea: 36.82°N - 41.07°N, 22.53°E - 28.53°E and c) Thermaikos Gulf: 39.97°N - 40.77°N, 22.53°E - 23.57°E. The numerical weather predictions are operationally available to the general public, in the full integration domains (Figures 1 and 2), through the webpage of LMC-AUTH (<http://meteo.geo.auth.gr>) in graphical format. The operational sea-state forecasts are provided to the public through the webpage of the project (<http://wave4us.web.auth.gr>), television broadcasts (DION TV) and a web-GIS application.

The model performance has been statistically evaluated at the locations of the 17 available stations of HNMS (Figure 1b), which comprise the whole country, from June 2013 to May 2014 (during the first full year of the operational phase of the project). Erroneous measurements have been removed through quality control. The parameters of mean sea-level pressure (MSLP), 10m wind speed (WS10m), 2m air temperature (T2m), 2m relative humidity (RH2m) and total 12-hourly accumulated precipitation (06-18 & 18-06 UTC) have been examined up to the forecast horizon of four days.

The statistical scores have been computed at different forecast times for the whole period of June 2013 – May 2014 and as a function of the season and the prevailing upper-air synoptic circulation in Greece. This methodology allows the identification of model errors that occur at specific periods and/or synoptic conditions and may otherwise be obscured in aggregate statistics. The variability of the scores with the synoptic circulation type has been examined using the 10 upper-air categories of Karacostas et al. (1992): 1) zonal flow (ZON), 2) northwest flow (NW), 3) open trough (OPTR), 4) closed low (CLOL), 5) cut-off low (CUTL), 6) southwest flow (SW), 7) open ridge (OPRG), 8) closed high (CLOH), 9) omega blocking (OME) and 10) undefined (high – low) cases (H-L). The frequency of occurrence of all circulation categories in each period has also been calculated in order to understand the significance of the scores.

## Results and Discussion

The numerical weather predictions are initially assessed for the whole period of June 2013 – May 2014. The initialization time is at 12:00 UTC (T+0 hours). Hereafter, in this paper the statistical scores of WRF-D02 correspond to the forecasts at the locations of the 17 available HNMS stations (depicted in Figure 1b). Figure 3 illustrates the Mean Absolute Error (MAE) and the Mean Error or Bias (ME; predicted minus observed values) at 6-hourly intervals up to 96 forecast hours (i.e. 4 days). The MAE of MSLP ranges from about 0.8 to 2.5 hPa, the one of T2m varies between 1.6 and 2.1 K, the error of WS10m lies between 2.0 and 2.5 m/s, while that of RH2m is at about 10-12%. The model systematically underestimates the MSLP and overestimates the WS10m at all forecast times (by -0.8 hPa and 1.5 m/s on average, respectively), in agreement with WRF-NMM (Katsafados et al. 2012). The ME of T2m exhibits a well-defined diurnal cycle with cold (warm) biases in daytime (night & early morning), implying that the average predicted daily temperature range is smaller than the observed one. This behavior may be attributed to errors in the surfaces heat fluxes predicted by the soil and boundary layer parameterization schemes. RH2m shows that moister than observed conditions are predicted at 1200 and 1800 UTC, while almost no bias appears during night and early morning hours. The abovementioned errors lie within the range documented for Greece and the Mediterranean (e.g. Papadopoulos and Katsafados 2009, Pytharoulis 2009). Moreover, as far as T2m, RH2m and WS10m are concerned, WRF seems to keep its predictability over the 4-day forecast horizon.

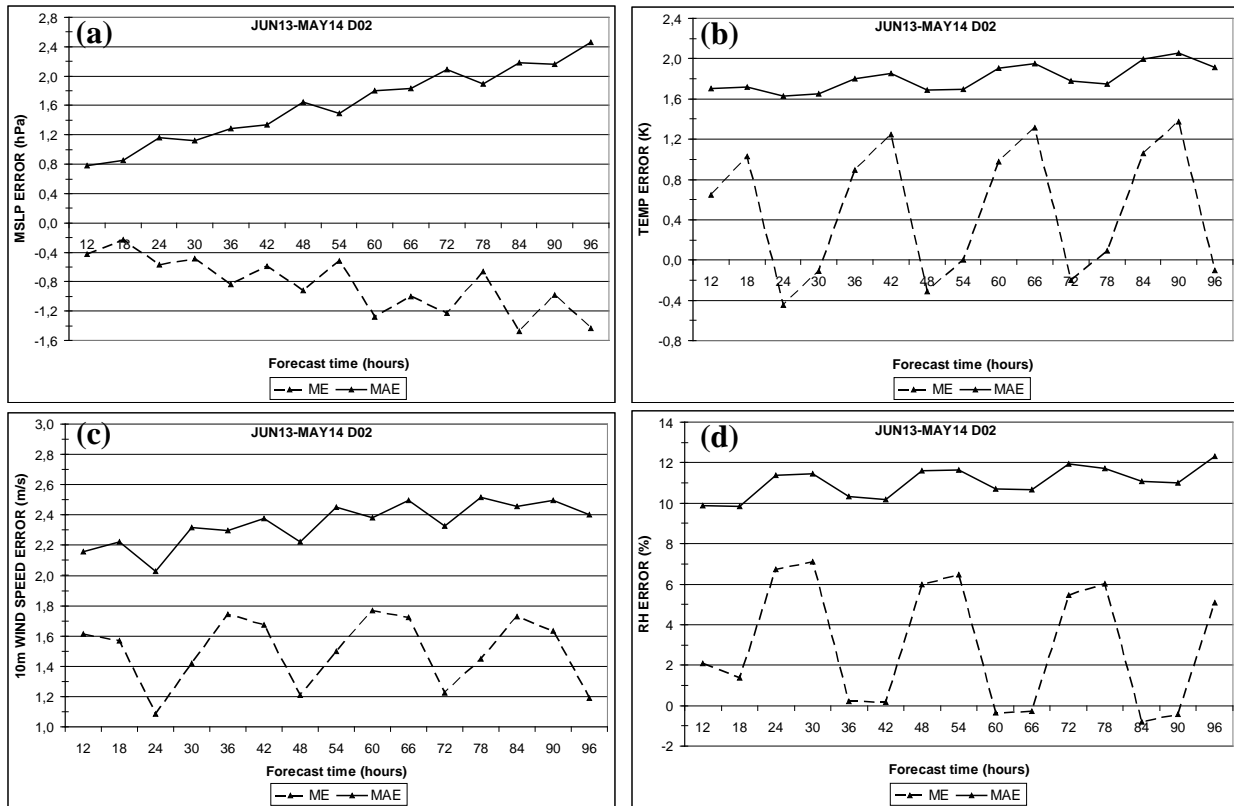


Figure 3. The Mean Error (ME) and Mean Absolute Error (MAE) of a) mean sea-level pressure, b) 2m air temperature, c) 10m wind speed forecasts and d) 2m relative humidity of WRF-D02 in the period June 2013 – May 2014. The initial time is at 1200 UTC.

The performance of WRF-D03 at Thessaloniki airport (in Thermaikos Gulf) and Larissa airport (located about 40 km SW of the gulf) is presented in Figure 4. The MAEs of MSLP, T2m and RH2m are generally similar to the ones over Greece. The maximum error of the former two fields is slightly larger than in D02 by 0.2 hPa and 0.2 K (respectively), while RH2m ranges between about 8-12%. The effect of the very high-resolution of D03 is illustrated through the MAE of WS10m which has been clearly reduced and ranges between 1.3-1.9 m/s. The high resolution improves the representation of the local physiographic features allowing the development of thermal circulations (e.g. land/sea breeze) and channeling flows. The MSLP is systematically underestimated, while the T2m and the WS10m are both overestimated. The ME of RH2m exhibits a diurnal cycle with negative values (denoting predicted conditions drier than the observed ones) at the vast majority of forecast times. The comparison of Figures 4b and 4d illustrates an anti-correlation between T2m and RH2m biases, suggesting that the warmer mean temperature errors are associated with drier predicted conditions near the surface. This is sensible from the Clausius-Clapeyron equation as an isolated warmer air mass can hold more water vapour (at saturation) and hence for the same water vapour mass the relative humidity is reduced. Of course warmer air temperatures may increase the evaporation from the surface or reduce the soil moisture thus increasing or decreasing the water vapour mass. It is not clear whether there is a direct physical link between the T2m and RH2m biases and/or they are both due to an erroneous reduction of soil moisture in the model, which in turn would affect the surface heat and moisture fluxes.

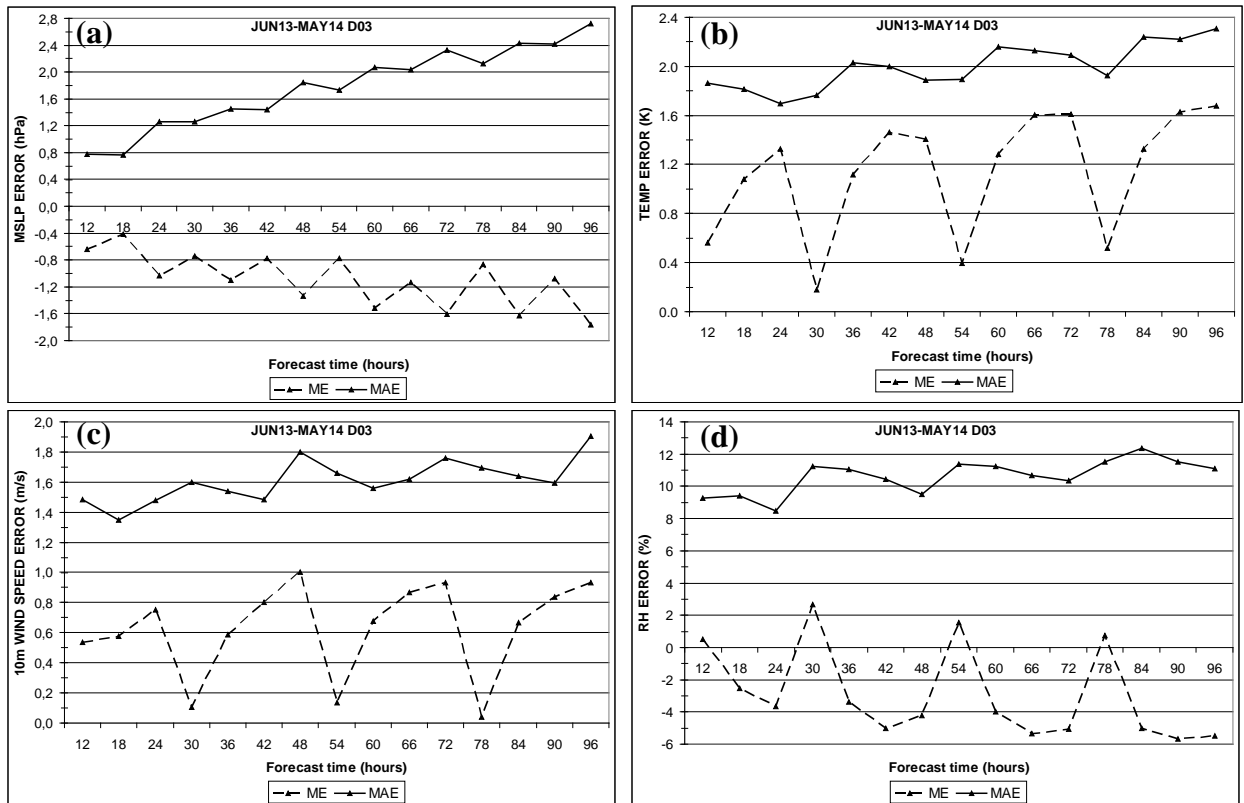


Figure 4. Similar to Figure 3 for WRF-D03 at the airports of Thessaloniki and Larissa in the period June 2013 – May 2014. The initial time is at 1200 UTC.

The frequency Bias (BIAS) and Heidke Skill Score (HSS) of 12-hourly WRF-D02 and WRF-D03 precipitation forecasts at the locations of the 17 HNMS stations (WRF-D02) and at Thessaloniki and Larissa airports (WRF-D03) in June 2013 – May 2014 are shown in Figure 5. The thresholds of 0.1 and 10.0 mm are employed for WRF-D02 while only the former threshold is used in WRF-D03. The 10.0 mm (per 12 hours) threshold is not used in D03, because only a limited number (17) of such strong precipitation events were recorded at Thessaloniki and Larissa airports in the whole year.

The BIAS of all events (at 0.1mm threshold) exhibits values between 1.30 – 1.83 in D02 and 1.05 – 1.88 in D03 (Figure 5). It is interesting to note the occurrence of higher overestimation of precipitation events at the early forecast times (since their values are further away from the optimum value of unit), which is likely to be due to errors in the initial conditions. Regarding stronger events in D02 ( $\geq 10.0$  mm), the model underestimates their number (bias=0.59-0.95). These results are in agreement with Katsafados et al. (2012) who showed that WRF-NMM model overestimates the total number of precipitation events at all forecast times and underestimates the strong ones. HSS which shows the accuracy of the forecasts relative to that of random chance, ranges between 0.47-0.58 in D02 and 0.40-0.59 in D03 when all the precipitation events are considered, while it drops to 0.21-0.39 in D02 at the threshold of 10.0mm (Figure 5).

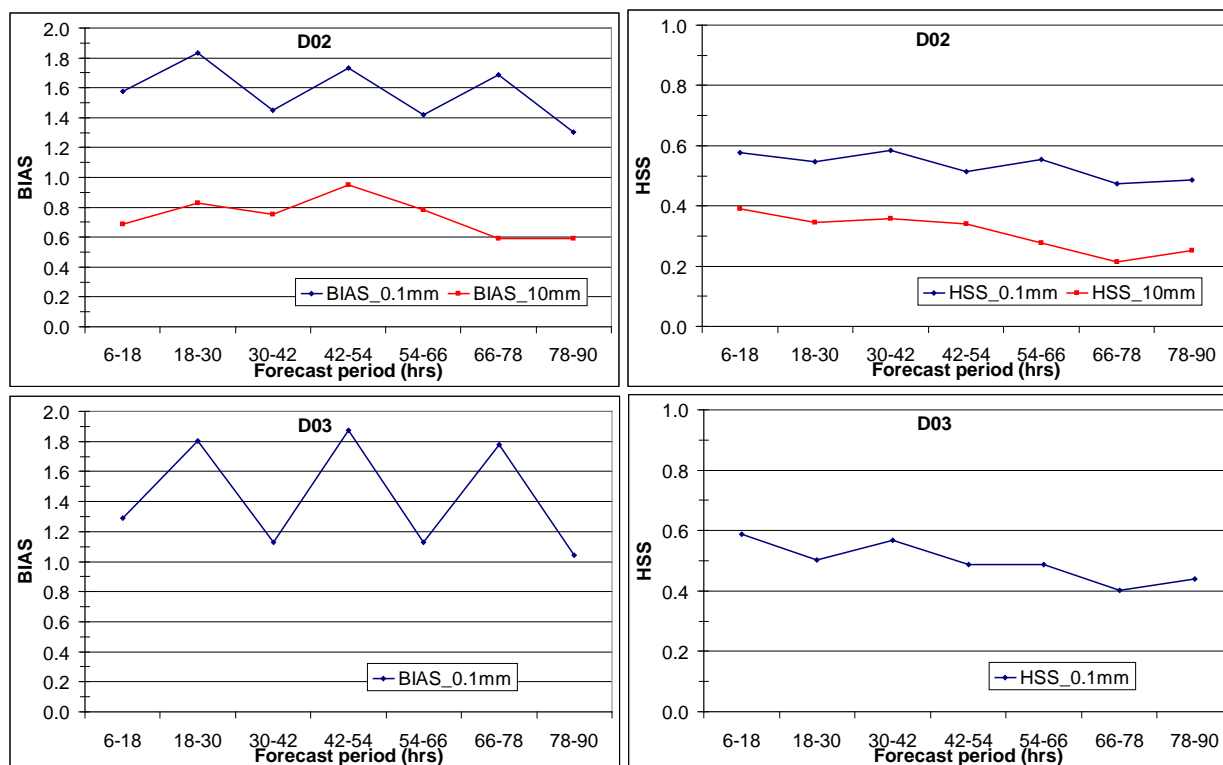


Figure 5. The frequency Bias (BIAS) and Heidke Skill Score (HSS) of WRF-D02 and WRF-D03 precipitation forecasts at 12-hourly intervals in the period June 2013 – May 2014. Blue line: 0.1mm/12hrs threshold, red line: 10mm/12hrs threshold. The initial time is at 1200 UTC.

The seasonal variability in the MAEs of WRF-D02 forecasts of MSLP and WS10m, which are two crucial parameters for ocean modelers, is depicted in Figure 6. It is characteristic that the WS10m error does not increase significantly with forecast time at all seasons (e.g. increase of 0.39 m/s, that is less than one knot, from T+24 to T+96 hrs in winter and spring). The largest errors of WS10m appeared in winter (2.3-2.9m/s), followed by autumn (2.0-2.7m/s), spring (2.0-2.4m/s) and summer (1.8-2.3m/s). The occurrence of this seasonal variation is probably due to the stronger prevailing synoptic activity and larger variability, associated with more and stronger transient low pressure systems, in the cold season of the year. This is verified by the standard deviation of daily geopotential heights at 1000 hPa (from NCEP reanalysis; not shown) which exhibited values of about 45-60 gpm in Greece in winter 2013-14 against values less than or equal to 20 gpm in summer 2013. As far as MSLP is concerned, the seasonal variability is not similarly clear, because the largest MAEs appeared in spring 2014 during the first three forecast days (Figure 6). Certainly, the MSLP errors depend only on the pressure values, while the WS10m errors are affected by the pressure gradient, the local topographic features and mesoscale phenomena (e.g. thunderstorms). Further analysis is needed, in order to understand the occurrence of larger MSLP MAEs in spring 2014. The seasonal predictability of MSLP and WS10m forecasts of WRF-D02 at the 17 HNMS stations is also analysed in Figures 7 and 8 (respectively), as a function of the upper-air synoptic conditions that prevailed in Greece at each season of June 2013 – May 2014. The minimum, maximum and average MAE during the four forecast days (using the fifteen 6-hourly values from T+12 to T+96 hours) and the observed frequency of each synoptic circulation type are included. The synoptic classification was performed subjectively using 6-hourly analyses.

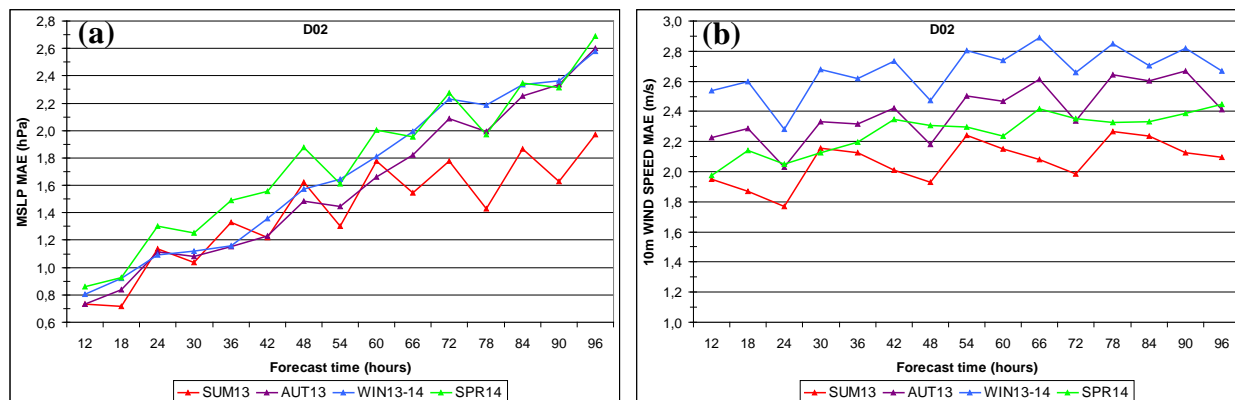


Figure 6. Seasonal values of Mean Absolute Error (MAE) of a) mean sea-level pressure (hPa) and b) 10m wind speed (m/s) forecasts of WRF-D02 in the period June 2013 – May 2014. The initial time is at 1200 UTC.

In summer, autumn and spring the largest (average and maximum) MAEs of MSLP were associated with cut-off lows, reaching an average value of 3.0 hPa and a maximum of 4.7 hPa at 96 forecast hours in autumn (Figure 7). This is important because this upper-air synoptic category is among the most frequently observed ones. These systems begin as an upper air trough which evolves to a closed circulation and becomes completely displaced from the basic westerly current, and are frequently associated with bad weather and convective activity. Therefore, high quality observations with dense spatiotemporal resolution are required in order to simulate/predict them successfully. On the other hand, large MAEs (up to 2.6 hPa on average) appeared during omega circulations over Greece in winter 2013-14. However, this category occurred only in 10 cases (2.7%) in that season. The closed lows (with a frequency of 5.1%) were the next less predictable systems in that season attaining an average MAE of 2.2 hPa. The most frequently observed category of winter was the SW flow (23.2%) which exhibited an average (and a maximum) error of 1.9 hPa (3.1 hPa), respectively. The lowest MAEs in summer, autumn and spring (Figure 7) occurred during either closed high or omega synoptic types (although one must bear in mind that they were the less frequently observed ones). In winter, as far as MSLP is concerned, the most predictable conditions were associated with the frequently occurring (16.2%) open ridge category with an average error of 1.4 hPa.

The most prominent feature of Figure 8 is the small change of the MAEs of WS10m with forecast time at all seasons of June 2013 – May 2014. This is a clear indication that the model maintains the predictability of this important parameter in the 4-day forecast horizon. The largest average errors of WS10m were associated with cut-off lows in autumn (3.3 m/s), cut-off lows and closed lows in winter (2.9 m/s) and spring (2.4 m/s), and closed lows in summer (2.4 m/s). Similarly to MSLP, in winter 2013-14 the largest errors occurred during the rarely observed omega circulation (Figure 8) and ranged from 2.6 to 4.5 m/s. The reasons of this behavior are suggested to be investigated through a case study approach in the future, in order to understand whether they are due to initialization and/or internal model errors. The lowest average MAEs of WS10m occurred during either the open ridge, closed high or omega upper air circulation category. In general, the results of 10m wind speed agree with the outcomes of the corresponding MSLP analysis. A dense network of high quality surface and upper air observations is necessary not only in Thermaikos Gulf and Greece, but also in the upstream areas, especially over the data sparse sea regions west and southwest of Greece.

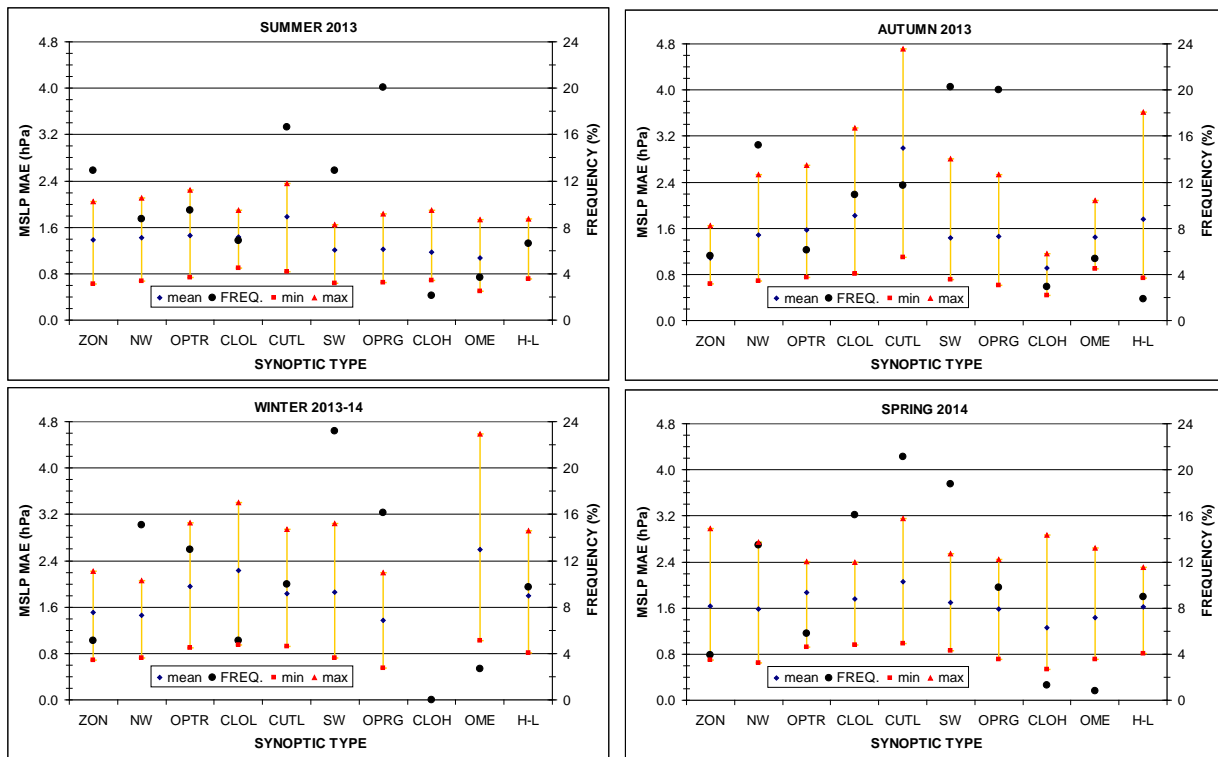


Figure 7. MAE of mean sea-level pressure (hPa) forecasts of WRF-D02 versus the synoptic type in different seasons of June 2013 – May 2014. The frequency of occurrence (%) of each synoptic type is indicated. The MAEs correspond to the forecasts from T+12 hrs to T+96 hrs.

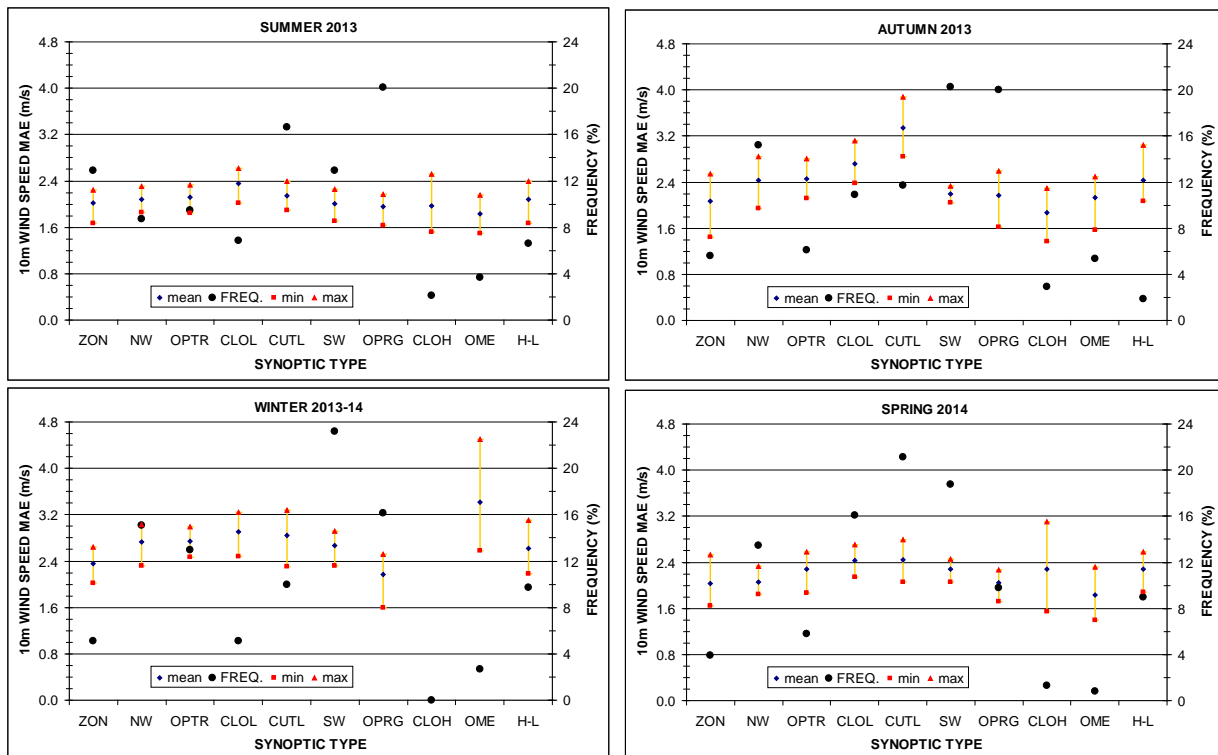


Figure 8. Similar to Figure 7 for 10m wind speed (m/s) forecasts of WRF-D02.

## Summary - Conclusions

This study described the setup and assessed the performance of the non-hydrostatic numerical weather prediction model WRF-ARW which is used operationally in the project WaveForUs. The model produces meteorological forecasts for Europe, Greece and mainly Thermaikos Gulf which is the target region and is represented with a grid spacing of 1.667 km. It is the first time that such fine resolution 4-day NWP forecasts are operationally available to the general public for the entire Macedonia, northern Thessaly and mainly Thermaikos Gulf. The model performance was assessed in the domains of Greece and Thermaikos Gulf during the first year of the operational phase of the project (June 2013 – May 2014) using the conventional surface observations of the available HNMS stations. In Greece, the MAE of MSLP ranges from about 0.8 to 2.5 hPa, the one of T2m varies between 1.6 and 2.1 K, the error of WS10m lies between 2.0 and 2.5 m/s, while that of RH2m is at about 10-12%. At the stations of Thessaloniki and Larissa airports (using the WRF-D03 forecasts) the MAEs exhibit similar values except from that of WS10m which has been clearly reduced and ranges between 1.3-1.9 m/s. The predictability of WS10m is clearly maintained during the 4-day forecast period at almost all synoptic conditions and seasons. The model seems to overestimate the total number of precipitation events at all forecast times and underestimate the strong ones. The error analysis relative to the prevailing synoptic conditions and the season suggests that the maximum errors are associated with cut-off and closed lows while the most predictable conditions occur in anticyclonic/omega blocking circulations and in summer season. Finally, the analysis identified upper-air synoptic circulations (e.g. omega) which do not prevail frequently, but may be related to large forecast errors. This kind of analysis allows the identification of model errors that occur at specific periods and/or synoptic conditions and may otherwise be obscured in aggregate statistics.

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