Assessment of Wind Forecasts in Yerevan by Weather Research and Forecasting Model

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ABSTRACT

Simulation of thermally induced valley winds in Yerevan has been performed using the Advanced Research Weather Research and Forecasting model (WRF-ARW) and verified with in situ observations in sensitivity experiments for July-August, 2014. The Mellor-Yamada-Janjic (MYJ) and the Yonsei University (YSU) planetary boundary-layer (PBL) schemes have been applied for implementation of the sensitivity study. It has been demonstrated that summertime mountain-valley winds developing around 1500 UTC have significant local impact on boundary-layer processes in Yerevan mainly during the evening and night hours strongly affecting near-surface wind conditions. Sensitivity analysis indicates that the PBL scheme variations significantly affect the model's performance. Overall, the results of this study demonstrate that the non-local YSU scheme performs better in simulating thermally induced valley winds in Yerevan than the turbulent kinetic energy (TKE) closure MYJ scheme.

Keywords

Mountain-valley winds; WRF model; Yerevan; planetary boundary-layer

1. INTRODUCTION

Simulation of thermally induced valley winds is examined in this study using Weather Research and Forecasting (WRF) model. Wind modelling is challenging as it requires an adequate representation of large-scale atmospheric circulations, simulation of spatial structure and evolution of both daytime and nighttime planetary boundary-layer (PBL), finer scale effects such as hydraulic jump, terrain channeling, etc. In earlier studies, WRF model and other high resolution models have been applied to examine local valley winds and boundary-layer processes over various regions with complex terrain [1], [6]-[7], [9]-[10], [12]. These studies considered sensitivity experiments with various spatial and vertical model resolution, boundary-layer parameterizations, physical configurations, surface-layer schemes, land-use schemes, etc. Some of those studies showed high sensitivity to the choice of PBL schemes [7], [9], particularly, for near-surface wind and temperature estimates. It has been found that non-local PBL schemes perform better under daytime convective boundary-layer (CBL) conditions, while turbulent kinetic energy (TKE) closure PBL schemes are preferable for nighttime stable boundary-layer (SBL).

The study region is located in the mid-latitudes and characterized by complex and highly variable large-scale and regional-scale atmospheric circulation regimes (Fig. 1) [4].

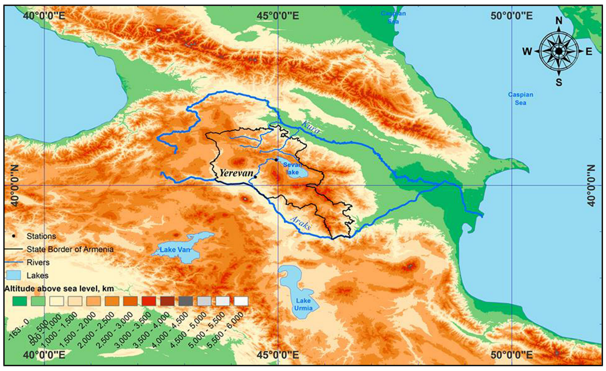

Fig. 1. Topography map of the Armenian Highland

Accuracy of modelling of strong winds which frequently occur in Yerevan in summer season has been examined. Summertime winds in Yerevan are associated with large-scale factors, thermally induced mountain-valley circulation and terrain channelling effects. Previous studies of this phenomenon demonstrated that strong valley winds during the evening hours develop mainly within PBL [3]. An extended mountain massifs and plateaus of the Armenian Highland (the western part in Fig. 1) are strongly heated during daytime in summer (July-August). As a result, strong daytime temperature and pressure gradients in the lower troposphere develop between the heated Armenian Highland and the colder (low-elevated) Kura-Araks plain and the Caspian Sea [8], [13]. Furthermore, Gevorgyan and Melkonyan (2014) noted that significant enhancement of westerly subtropical jets passing over the study region is observed at 300 hPa level during the days with strong valley winds in Yerevan.

It is important to compare the advantages and deficiencies of different WRF PBL schemes for understanding systematic errors, uncertainties and suitability of PBL schemes for simulation of PBL evolution over a mountain terrain characterized by thermally and mechanically driven local valley flows. Valley winds bring relatively cooler and humid air in the evening hours after hot daytime temperatures reaching up to 35.0 ^{0}C on average, hereby enhancing ventilation and moderating heat-stress related health issues in the highly-populated city [2]. However, one of the negative impacts of these strong winds with wind gusts often exceeding 20 m s^{-1} is that the strong winds make serious obstructions for operational work of Zvartnots international airport during landing and takeoff of airplanes.

2. DATA AND METHODS

Sensitivity experiments using WRF-ARW model version 3.6 have been performed in this study. In this experimental set up WRF-ARW model domain was concentrated on Armenia and it covered the region of interest where the thermally induced meso-scale mountain-valley winds develop (Fig. 2). The model domain size consists of 201x201 spatial grid points with a grid size of 3 km. There are 31 vertical terrain-following (eta) levels extending from the ground surface to the 50 hPa level. WRF-ARW model was run using initial and boundary conditions from Global Forecast System (GFS) analysis at 0.5 deg spatial resolution. The period of sensitivity experiments covers July-August 2014. July-August time period is selected because during these two months impact of thermally induced winds is the most pronounced [2]. For each day of the study period (62 days), the WRF-ARW model simulations started at 0000 UTC and integrations were conducted for 24 hours.
The following schemes were used in the physical configuration of WRF-ARW model: Dudhia shortwave radiation scheme, Rapid Radiative Transfer Model (RRTM) longwave radiation scheme, the WRF Single-Moment 6-Class Microphysics scheme (WSM6), the Noah land-surface scheme, the Kain-Fritsch scheme with deep and shallow convection sub-grid parameterization.

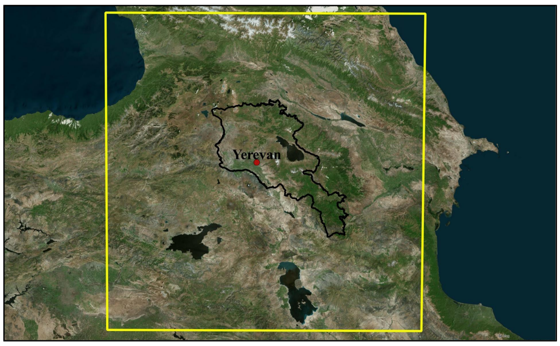

Fig. 2 WRF-ARW model domain (yellow square). State border of Armenia is indicated in black (Bing areal map is used)

Simulation of thermally induced valley winds is highly sensitive to boundary-layer processess. In this study, only the variation of PBL schemes in WRF-ARW model was tested, keeping all other parameterization parameters described above fixed. To this end the Mellor-Yamada-Janjic, MYJ [5] and the Yonsei University, YSU [6] PBL schemes were applied for implementation of sensitivity study. Both MYJ and YSU schemes are well researched by other scientific groups around the world [9]-[10] and regarded as top performers, hence this is our rational to explore their performance for the Armenian region. Furthermore, these PBL schemes apply different approaches to reproduce the boundary-layer processes. The YSU is a non-local first order scheme which estimates the PBL vertical mixing from the basic atmospheric field conditions. The PBL depth is diagnosed using the critical bulk Richardson number approach. The YSU scheme allows for explicit treatment of interaction processes at the PBL top. By contrast, the MYJ is considered as a TKE closure scheme. The MYJ scheme applies only local mixing with the local diffusivity throughout the both SBL and CBL. The *PBLH* is defined as the height where the prognostic TKE is close to a critical value. MYJ and YSU schemes use surface-layer parameterization based on the Monin–Obukhov similarity theory, with slightly different treatments of stability functions and empirical parameter values. The MM5 and Eta schemes of surface-layer similarities were used with the YSU and MYJ PBL schemes, respectively.
Observational data from Yerevan-Zvartnots station located at Zvartnots International Airport, at 854 m above sea-level were used. Three-hourly observations of 10-min average wind speed and direction have been used in this study. To evaluate the impact of valley winds on near-surface wind regime in Yerevan, days with strong and weak wind gusts were defined [8]. During the period of sensitivity experiments with WRF-ARW model, i.e. during July-August 2014, 25 and 8 days with strong and weak wind gust events, respectively, were observed at Yerevan-Zvartnots station. Seven days on which precipitations were recorded were excluded from the sensitivity experiment because summertime precipitations and thunderstorms of either convective or frontal origin may lead to local strong wind gusts and rapid changes in wind direction and wind speed not associated with the thermally induced circulation and valley wind regime in Yerevan.

3. THE IMPACT OF VALLEY WINDS IN YEREVAN: COMPARISON OF WRF-ARW MODEL OUTPUTS WITH *IN SITU* OBSERVATIONS

In this section, results of sensitivity experiments with WRF-ARW model are presented. An initial forecast step in WRF-ARW model is at 0300 UTC of a given day (3-hour forecast), while the last forecast is at 0000 UTC of the following day (24-hour forecast). Therefore, diurnal variations of the observed and WRF-ARW simulated near-surface wind (and the other near-surface meteorological variables) in Yerevan are considered starting from 0300 UTC (0700 LCT) of the given day and ending at 0000 UTC (0400 LCT) of the following day with 3-hour intervals (Figs. 3a-b). Figures 3a-b show that wind forecasts based on the YSU PBL scheme reproduce diurnal variation of the observed wind speed in Yerevan more successfully than the MYJ PBL forecasts both during the days with strong and weak wind gusts. During the initial 9 hours of WRF-ARW model spin-up period wind speed forecasts do not show significant sensitivity to PBL parameterizations, generally underestimating observed wind speed in the morning and afternoon hours. It can be seen from Fig. 3a that the observed winds and both PBL schemes show sharp increase in wind speed at 1500 UTC. This rapid increase in wind speed at 1500 UTC is due to arrival of valley winds. However, 1500 UTC wind speed forecasts are largely overestimated by the MYJ and YSU simulations with mean bias of 5.0 and 2.1 m s^{-1}, respectively. It should be noted that the YSU scheme is able to capture correct timing of daily maximum wind speed around 1800 UTC, while the MYJ scheme shows the daily maximum 3 hour earlier than the observations (around 1500 UTC, Figs. 3a and 3b). During the days with weak wind gusts the impact of valley winds on diurnal cycle of wind speed is significantly reduced (Fig. 3b, red line). The evening wind speed increase is much weaker and shifted 3 hour later (at 1800 UTC). Both the MYJ and YSU schemes also simulate relatively weaker winds. However, the MYJ scheme simulates too strong valley winds developing around 1500 UTC which leads to wind speed overestimation by 3.9 m s^{-1}, whereas the YSU scheme simulates much calmer winds which are quite close to 1500 UTC observations (with forecast bias of 0.7 m s^{-1}). Nevertheless, overestimation of wind speed in the evening hours (at 1800 UTC) is present in both PBL schemes showing very similar wind bias (2.8–2.9 m s^{-1}). Also, both

PBL schemes underestimate nocturnal (0000 UTC) wind speed during the days with strong valley winds (by about 1.5 m s^{-1}, Fig. 3a), while during the days with weak valley winds nocturnal wind speed is overestimated by the YSU and MYJ schemes (Fig. 3b).

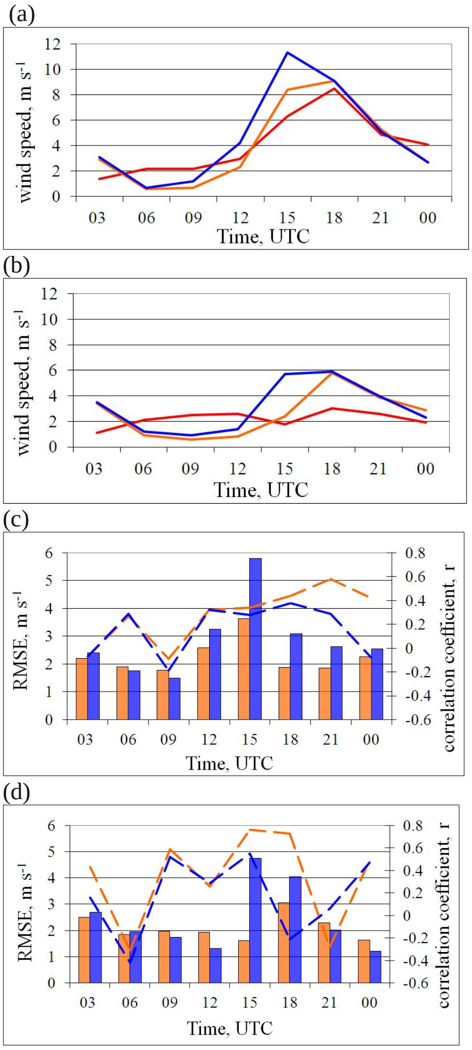

Fig. 3 Diurnal variation of mean observed (red lines) and WRF-ARW simulated (orange – YSU; blue – MYJ) 10-m wind speeds (a-b) and verification statistics (c-d) estimated for Yerevan-Zvartnots station for July-August, 2014 during the days with strong (a,b) and weak (c,d) wind gusts. RMSE and r estimates are presented by bars (left-side axis) and dashed lines (right-side axis), respectively.

WRF-ARW model's performance for wind speed forecasts in Yerevan using two PBL schemes presented in Figs. 3 c-d shows that in general the YSU scheme outperforms the MYJ scheme considering the RMSE and r statistics. In particular, wind speed forecasts show the strongest sensitivity to the PBL parametrizations during the period of impact of evening valley wind systems (from 1500 UTC to 1800 UTC) with the YSU producing substantially higher forecast skill. Thus, 1500 UTC RMSE values for the YSU were 1.6 and 3.6 m s^{-1} for days with weak and strong wind gusts, respectively, while those for the MYJ were 4.8 and 5.8 m s^{-1}, respectively. Furthermore, the correlation coefficients between the observed and simulated evening wind speeds (r) generally did not exceed 0.6. The foregoing suggests that both the YSU and the MYJ schemes have some deficiencies to adequately reproduce timing and strenght of evening winds in Yerevan.

Valley winds lead to a sharp shift not only in wind speed but also in wind direction in Yerevan. The mean July-August diurnal cycles of the observed and WRF-ARW simulated near-surface wind direction in Yerevan during the days with strong and weak wind gusts are presented in Figs. 4a-b. It can be seen from Fig. 4a that during the days with strong valley winds in Yerevan wind direction sharply turns from southerly (in the morning and afternoon, 170–180 deg.) to northeasterly (56–58 deg.) in the evening hours when valley winds are present (from 1500 to 1800 UTC). The YSU successfully reproduces diurnal variation of wind direction in Yerevan from 0600 UTC to 2100 UTC. By contrast, the MYJ performs poorly with significantlty larger biases than those in the YSU scheme for all days. However, examining performance of the PBL schemes presented in Figs. 4c-d, there is no systematic effect of parameterization choice on RMSE and r estimates. Figure 5c shows that both PBL schemes produce the lowest RMSE values around 1500 and 1800 UTC (68-72 deg.) when the strong valley winds are observed in Yerevan, while under calm wind conditions the YSU and MYJ show large uncertainties and perform much worse for those hours, with RMSE varying from 100 to 200 deg.

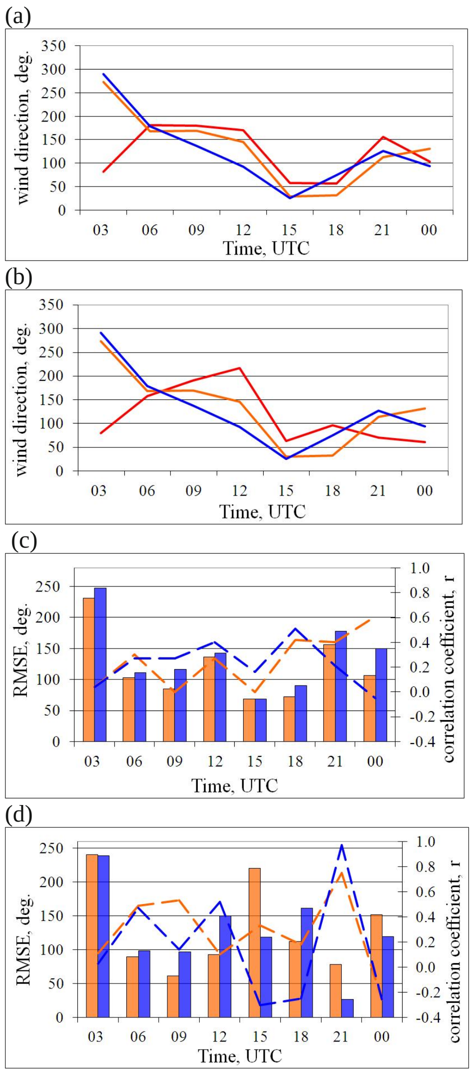

Fig. 4 Diurnal variation of mean observed (red lines) and WRF-ARW simulated (orange – YSU; blue – MYJ) 10-m wind directions (a-c) and verification statistics (d-f) estimated for Yerevan-Zvartnots station for July-August, 2014 during the days with strong (a,d) and weak (b,e) gusts.

RMSE and r estimates are presented by bars (left-side axis) and dashed lines (right-side axis), respectively.

4. DISCUSSIONS AND CONCLUSIONS

Simulation of thermally induced valley winds in Yerevan is examined in this study using observational data and WRF-ARW sensitivity experiments for the time period of July-August, 2014. Overall, verification results showed that non-local YSU scheme performs better in simulating near-surface winds in Yerevan than TKE-based MYJ scheme. In particular, the strongest sensitivity to PBL scheme was found during the evening hours (1500 UTC to 1800 UTC), when the valley winds are observed. In particular, the YSU scheme more successfully reproduces rapid shifts in wind speed and direction in Yerevan associated with the valley winds. Therefore, the main conclusion derived from this study is that the YSU scheme simulates thermally induced valley winds in Yerevan better than the MYJ. However, relatively high RMSE values and low correlation coefficients suggest that accuracy of both the MYJ and the YSU forecasts is not adequate, and further work is required to improve parametrization. Wind overestimation in the evening hours is likely due to inappropriate representation of surface friction or drag effects, roughness length, land-use and land-cover types, soil conditions utilized in the WRF-ARW model.

Strong influence of initial conditions on outcomes of WRF-ARW model simulations at very short spin-up time (3 to 6 hours) has also been found. Substantial errors and a low forecast skill have been found in simulation of the near-surface wind in Yerevan at the initial (3-hour) forecast step. In addition, verfication results show almost no sensitivity to PBL scheme choice. Therefore, it is essential to improve initial conditions used in WRF-ARW model. In particular, it is important to test whether the WRF-ARW simulations could be improved when the data from a global analysis (GFS data in this study) are assimilated with as much as possible stations data from Armenia through application of OBSGRID software.

In summary, this study demonstrated that summertime valley winds have significant influence on boundary-layer processes impacting local wind conditions in Yerevan. Accurate representation of these local impacts caused by valley wind systems is challenging for the WRF-ARW model. The sensitivity analysis showed that the PBL parametrization is important for skillful performance of the WRF-ARW model. Therefore, we believe it would be beneficial for future sensitivity studies on PBL schemes to further examine application of different parameters for representation of boundary-layer processes. Furthermore, both the evening time and nocturnal valley winds have well-defined vertical structures leading to formation of low-level jets (LLJs), [7], [11]. Thus, performing sensitivity experiments with different vertical resolutions within PBL as well as assessing the role of height of the lowest model level in WRF-ARW could improve the modeling of these LLJs [4], [12]. Increase of spatial resolution could significantly improve the simulation results.

5. ACKNOWLEDGEMENTS

WRF-ARW simulations were performed at the Institute for Informatics and Automation Problems (IIAP) of the National Academy of Sciences of the Republic of Armenia within the framework of the state target programme titled “Applying of a National Research e-Infrastructure for Solving the Natural Sciences' Problems” in collaboration with the specialists from Service of the Hydrometeorology and Active Influence on Atmospheric Phenomena. The authors express gratitude to Dr. Hamlet Melkonyan and Dr. Vladimir Sahakayan for their assistance in this study.

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