# WRF-ARW Model for Prediction of High Temperatures in South and South East Regions of Armenia

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***Abstract*—The ultimate goal of the study is to develop an early warning system for the south and southeast regions of Armenia (11 in total) by defining specific thresholds for issuing alerts for adverse and severe weather phenomena. In the article the high temperature, wind and precipitation weather elements are discussed based on the experiments performed during the summer periods of 2011 and 2014. The system has been implemented based on the mesoscale Weather Research and Forecasting (WRF) model [1], which is adapted to the territory of Armenia and used for operational weather forecasting. The verification methodology is to analyze the model results against observations received from four ground hydrometeorological stations located in the south and southeast regions of Armenia. The correlation coefficients, standard deviations of the differences and biases are calculated for the air temperature and wind speed and for precipitation amount and yes/no contingency tables are constructed.**

***Index Terms*—WRF-ARW, Armenia, severe weather phenomena, correlation coefficients;**

## I. Introduction

Due to its complex relief and diversity of natural conditions Armenia is exposed to various types of hydrometeorological hazardous events, amongst it is worth noting heavy rainfall, strong winds, heat waves, hailstorms, snowfall, frosts, etc. These hazards often lead to disasters, causing considerable economic and human losses. In order to be prepared for the above mentioned hazards and prevent exposure of populations to disasters it is crucial to produce accurate forecasts and issue warning with sufficient time lead. This is difficult, as there are six climatic zones in Armenia from dry subtropical to rigorous high mountainous and from the everlasting snowcaps to warm humid subtropical forests and humid semi-desert steppes. Generally the climate of Armenia is described as continental with hot and dry summers and severe snowy winters.

In recent years there have been increasing tendencies of dangerous meteorological phenomena, for instance due to the climate change, the deviation of the mean temperature in Armenia during 1935-2013 increased by about 1.03 $^0$C, relative to the stable mean temperature during 1961-1990 [2]. The analyses of the hydrometerological centre show that the mean temperature in Armenia is predicted to increase by about 1.5 $^0$C between 2011-2040, and by about 2 $^0$C between 2041-2070.

Moreover, increased air temperatures and decreased precipitation during the summer period would enhance desertification process in Armenia. It is crucial to deal with the desertification phenomenon in Armenia, as being located in the central part of the subtropical dry climate zone the territory of Armenia has all the characteristics of an arid region.

One of the natural desertification factors in Armenia are frequently recurring natural phenomena - drought and hot winds, which are common in the Ararat valley, Vayots Dzor and Syunik regions (up to altitudes of 1200-1400m). For example, the probability of formation of hot winds with a duration of 4-7 days lies between 30-35% in recent years. These and other circumstances were fundamental for the study of temperature, wind and precipitation regimes in Armenia using the advanced implementation of the WRF model.

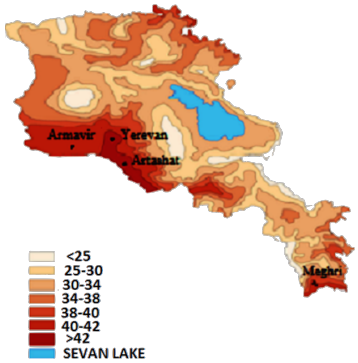


Fig. 1: Distribution of the maximum air temperatures in the territory of Armenia.

Extreme weather phenomena such as high temperatures and droughts are mostly associated with the South cyclone formed in the Arabian Peninsula (thermal depression). In case of the penetration of the hot waves a dramatic rise of temperature is seen, mostly in the Ararat valley, Vayots Dzor and Syunik regions. Fig. 1 shows the distribution of maximum air temperatures for the warm period during 1948 to 2012 at the height of 2 m.

The temperature was particularly high in 2006, 2010, 2011, and 2014. The number and the characteristics of annual hot days have been analyzed in 2011 and 2014 in order to determine the frequency of recurrent tendency of hot days. The results show that for the mountainous areas hot days are characterized by maximum temperatures exceeding +30 $^0$C, with temperatures exceeding +33 $^0$C and and +37 $^0$C in the foothills and lowlands respectively. These temperatures were isolated as thresholds in the early warning system. As for the levels for issued warnings, it was decided to adopt the three-level warning system (yellow, orange, red), since local authorities are already familiar with this subdivision.

The main focus of the article is the study of temperature, wind, and precipitation background in the selected time series and on data issued by the model built a warning system off-scale threshold. The system is important for minimizing the possible impact on vulnerable, at-risk agriculture, water resources, public health, energy, transport, environment, etc., which are crucial for Armenia as a small country. Previous work has shown that major mountain ranges acting as natural barriers play an important role in regional and synoptic scale circulations of the study region redirecting the movement of cold fronts from the northwest and northeast and blocking northerly flows in the lower troposphere. These externally and internally produced weather patterns may interact with each other. All these processes make the atmospheric circulation and the spatial distribution of precipitation, temperature and wind quite complicated in this region [3].

Many researchers have studied severe weather events in Armenia in the past, but the attention has been mainly focused on the climatology of these events and not on the analysis and evaluation of high-resolution weather forecasts [4]. By taking into account the aforementioned meteorological, geographical and morphological characteristics of Armenia, the use of a meteorological model at high-resolution is crucial, in order to simulate and forecast the significant local circulations and processes that take place over this region.

The synoptic situation prevailing in the summer period (June, July, August) causes weather conditions including high temperature. The Iranian thermal forms over the Arabian Peninsula and expands to the Caucasus. Hot and dry tropical air masses move into the territory of Armenia from the Arabian Peninsula. In case of continuous advection, the average daily air temperature may increase by 7-9 $^0$C (even more in Syunik), which leads to the establishment of extremely high temperatures. The time series of summer 2011 are of great interest and have been used in our experiments, especially the high temperature period from the 30$^{th}$ of July to the 3$^{rd}$ of August. For example on July 31, 2011 the maximum air temperature in Meghri was 43.7 $^0$C due to the fact that the territory of Armenia was under the influence of the thermal depression. But these high temperatures are often directly followed by heavy rains, hail and strong winds, which seems to be a new phenomenon in the region. On August 27th, a cold front passed through the territory of Armenia with wavy perturbations that caused downpours of torrential rains accompanied by thunderstorms and hail in separate regions. Therefore it is very important to establish an early warning system for the creation of such phenomena.

The Ararat valley, the south and south east regions of Armenia, are of significant interest from a meteorological point of view as they often experience severe weather events. Because of the computational limitations, high-resolution mesoscale models were rarely used for real-time numerical weather prediction, and with a limited number of case studies, it is hard to know the performance and systematic behaviour of these high-resolution models in day-to-day weather prediction.

Several studies have been carried out to develop and implement early warning systems for extreme weather phenomenon based on the analyses and experiments of the WRF model. For example different systems have been implemented to forecast extreme temperatures, such as that of Bartzokas et al. [5] for northwest Greece. The model verification was carried out by comparing the model results with observations received from the meteorological station the model verification was carried out. In recent years, a mixed-physics ensemble approach has been investigated as a method to better predict mesoscale convective system (MCS) rainfall. For both mixed-physics ensemble design and interpretation, knowledge of the general impact of various physical schemes and their interactions on warm season MCS rainfall forecasts is useful. For instance the impact of different WRF model physical parameterizations have been studied by Jankov I., et al [6] using three different treatments of convection, three different microphysical schemes, and two different planetary boundary layer schemes. Based on the sensitivity analyzes of the WRF model for the severe thunderstorm events over Southeast India [7], the

Thompson scheme simulated surface rainfall distribution close to observations. For the hot-dry season, the WRF results perform relatively poorly for all configurations [8], making comparative evaluation difficult in case of the evaluation of precipitation simulations over Thailand using a WRF regional climate model.

## II. Study Area

The south and south east regions of Armenia are the most densely populated regions, particularly only Yerevan houses one-third of the country's population. Being the the most mountainous country in the Caucasus, it is distinguished by its complex relief and varied natural conditions. The highest point, the top of mount Aragats, is 4,095 m while the lowest point is at 380 m in the north-east.

The study area covers non only Ararat Plain, which is the one of the more important of the distinctive regions of Armenia surrounding with foothills and mountains, but also Vayotz Dzor, essentially the basin of the Arpa River and Syunik in the extreme southeast, which is a maze of gorges and river valleys cutting through high ranges. There are five altitudinal vegetation zones in the study area: semidesert, steppe, forest, alpine meadow, and high-altitude tundra. The semidesert landscape, climbing to a rise of 1300-1400m, consists of a slightly rolling plain covered with sparse vegetation, for the most part sagebrush. Steppes predominate in Armenia at altitudes of 1,300-1400m. The forest zone lies in the southeast of Armenia, at heights of 1,900-2000m, where the humidity is considerable.

The parent domain D1 covers the major part of Europe and all the Caucasus and some parts of the Central Asia and the Middle East (40.0_ N, 44.7_ E) with 202x202 grid points at a 18-km resolution, the nest domain D2 (6-km horizontal grid increment) covers the whole territory of Armenia with 97x70 grid points and the fine nested domain D3 with 145x91 grids at a 2-km resolution (see Fig. 2) covering the southern regions, namely the territory of Ararat valley, Vayots Dzor, Syunik regions, Yerevan and partly Gegharkunik (see Fig. 3).

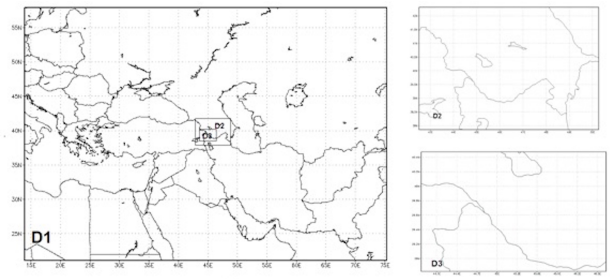


Fig. 2: Representation of the three D1, D2, D3 domains.

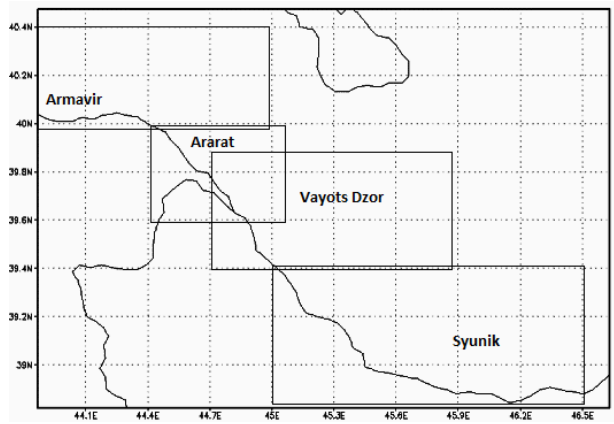


Fig. 3: D3 domain in detail.

## III. Methodology

The Lambert conformal projection is used, as it is well suited for the mid-latitude domains. The weather forecasts are performed on a daily basis, using the following 1-way nesting strategy.

The model uses vertical 31 eta_levels and geographic data resolution is 30 seconds. The model was initialized with the initial and boundary conditions of Global Forecast System (GFS) at 00:00 UTC (local time on 04:00) since the beginning of the summer 2011. Due to the limited computing resources, we have considered the innermost domain with 2 km resolution, which covers only the southern regions and run for 24h. For comparison the data were taken from all weather stations that passed through GTS every 3 hours (transmission time for 00,03,06,09,12,15,18.21 UTC). Since its maximum temperature usually reaches 12h UTC, then were taken to verify the actual data for 12h UTC.

WRF model is initialized using NCEP GFS analysis and forecasts at 0.5 deg horizontal resolution. Data produced during pre-processing and simulations of WRF are in the Lambert conformal projection, which is well suited for mid-latitude domains. Based on a series of experiments [9], in the present study, the Single-Moment 6-class Microphysics scheme [10] and the convective parameterization scheme of Kain and Fritsch for the parent domain [11] were selected. For the verification procedure, meteorological data received from four weather stations located in the nested domain is used.

The WRF model consists of real.exe and wrf.exe programs, to prepare to and to actually run the model respectively. These programs are both run in parallel using the MPICH (Message Passing Interface CHameleon) package. The WRF and all the other external libraries needed by WRF, for instance NetCDF, were built using gfortran compiler and MPI stacks. High performance computing resources (up to 512 cores) of Armenian national grid infrastructure [12] have been used for conducting the series of experiments, particularly the resources of the Armcluster (number of nodes: 64, number of cores: 128, network: Myrinet) [13]. Myrinet network of the Armcluster is used, as the WRF model is communication-intensive, with

several halo exchanges and collective communications required throughout the simulation. As WRF is computationally intensive due to the large amounts of calculations involved in weather simulations, the all CPUs of the Armcluster (128 cores) is used. The simulation runtime is about 120 minutes for the 72 hours forecast.

## IV. Model Verification

Figure 4 shows the distribution of observed high temperatures in the territory of Armenia for the study period.

The WRF outputs at the six neighbouring grid points that are closest to meteorological stations have been used for the following verifications of the model:

- Air temperature. The verification has been carried out for the t+12h forecast outputs of the model of the nested domain (Grid 3). These outputs have been compared with the observations at 12:00 UTC (Armenia local time is UTC+4 during winter and summer), which have been selected, by taking into account that the air temperature approaches the daily maximum values at these times of the day;
- Wind. Since winds mostly intensify in the afternoon, the values of the model at t+12h is used to verify the wind speed;
- Precipitation. The verification refers to the forecast of the total daily amount (24-h accumulated precipitation, starting at 00:00 UTC).

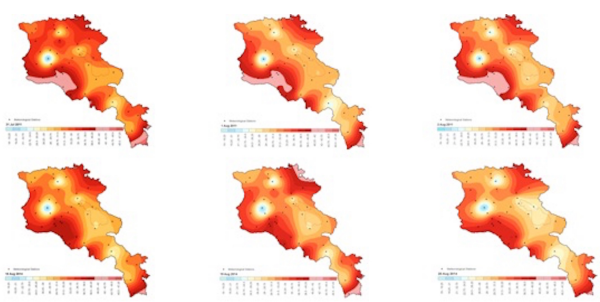

Fig. 4: The influence of heat waves over the Armenian territory for the summers of 2011 and 2014 respectively.

The following verification scores were carried out in order to describe particular aspects of high temperature and wind speed forecast performance:

- correlation coefficients;
- standard deviations of the differences;
- BIAS measures the ratio of the frequency of forecast events to the frequency of observed events and it indicates whether the forecast system has a tendency to under predict (BIAS<1) or over predict (BIAS>1) events.

For the precipitation amounts, a 2X2 (yes/no) contingency table [14] is then constructed (see table 1) for each station. Categorical statistics are computed in order to describe particular aspects of precipitation forecast performance.

We usually verify the forecast occurrence of an event greater than a certain threshold (daily rainfall of at least 1 mm/day).

TABLE I: Contingency table illustrating the counts used in verification statistics for dichotomous (e.g., Yes/No) forecasts and observations. The values in parentheses illustrate the combination of forecast value (first digit) and observed value. For example, YN signifies a Yes forecast and and a No observation.

| Forecast | Ovserved | | |
|---|---|---|---|
| | Yes | No | Total |
| Yes | Hits (YY) | False Alarms (YN) | YY+YN |
| No | Misses (NY) | Correct Nulls (NN) | NY+NN |
| Total | YY+NY | YN+NN | YY+YN+NY+NN |

The contingency table is a useful way to see what types of errors are being made. The contingency table for the summer period of 2011 for four stations is given in the table 2.

TABLE II: The contingency table for the 01 June 2011 to 31 August 2011 period.

| Station | Hits | False Alarms | Misses | Correct Nulls |
|---|---|---|---|---|
| Armavir | 15 | 10 | 2 | 65 |
| Artashat | 10 | 3 | 2 | 77 |
| Meghri | 7 | 4 | 2 | 79 |
| Yerevan | 15 | 6 | 2 | 75 |

For the precipitation verification and analyses, the bias score (BIAS), probability of detection (POD), false alarm ratio (FAR) and threat score (CSI) have been used.

As stated above, the temperature, wind and precipitation outputs of the model are used as an input for a severe weather event warning system. The entire study area was divided into sub-regions taking into account morphological and population characteristics. The warning system has been implemented for each area separately (see Fig. 5). When the value of a meteorological parameter, at one or more grid points of a region during a 6-h period, is forecasted to be above specific thresholds, a yellow, orange or red warning is set for this particular region, depending on the severity of the event.

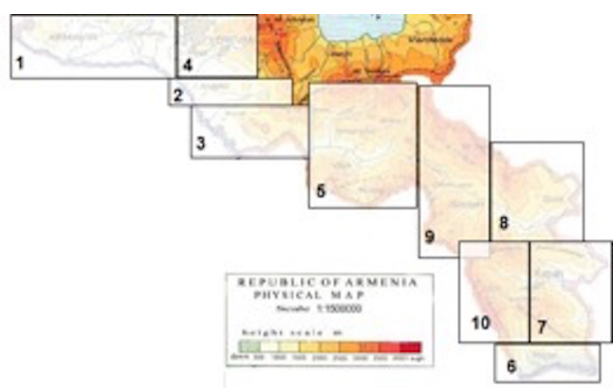


Fig. 5: The sub-regions of south and south east of Armenia.

The warnings have been set for extremely high temperatures, high wind speeds and heavy precipitations using the thresholds for the various meteorological parameters given in the table 3.

TABLE III: Thresholds for the severe weather event alerts.

| Parameter | Yellow level | Orange level | Red level |
|---|---|---|---|
| High Air Temperature (_C) | 33-35 | 36-38 | >=39 |
| Precipitation (mm/12h) | 10-15 | 16-24 | >=25 |
| Wind (Beaufort) | 7-8 | 8-9 | >9 |

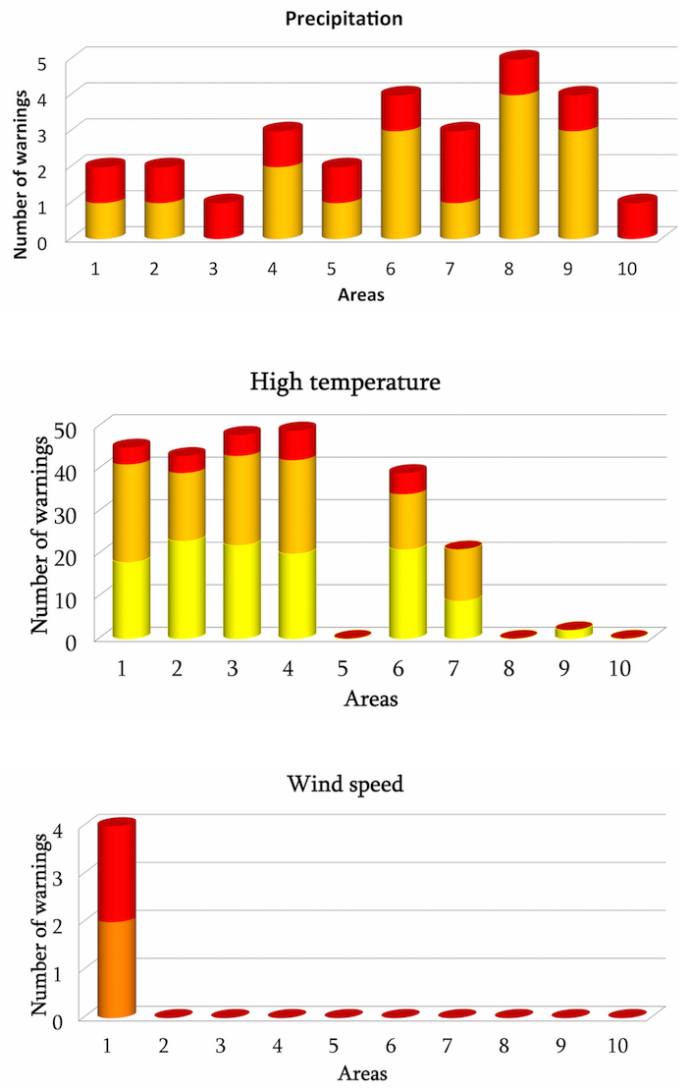


Fig. 6: Yellow, orange and red warnings for each event per meteorological station for the summer, 2011.

## V. Results and Discussions

At first, a brief overview of the number of warnings issued by the system during the study period is presented. Fig. 6 presents the histograms of the number of yellow, orange and red alerts for the study areas of Armenia. It can be seen from Fig. 6 that the maximum temperature does not exceed during the warm season in the mountains and foothill areas do not exceed the predefined threshold, while in the valleys, a risk of off-scale temperature exists.

In Fig. 6, as expected, most of the high temperature warnings are issued for the lower altitude regions mainly in Ararat valley and the Vayots Dzor valley of Syunik. For precipitation, most of the warnings are issued for the high altitude regions (the mountainous Vayots Dzor and foothills of Syunik region). Usually most of the warnings correspond to the high altitude areas, but according to the observation data follow the normal distribution.

For verification purposes the data has been taken into account to evaluate the model results from the following four meteorological stations indicated in Fig. 1

- Armvair (Arm. lat=40.14, long=43.90, height=861 m);
- Artashat (Art., lat=39.93, long=44.52, height=829 m);
- Meghri (M, lat=38.90, long=46.24, height=627 m);
- Yerevan (Y, lat=40.15, long=44.40, height= 853 m).

The verification method is to compare the observed meteorological data of the selected stations with the output data of the model Grid 3 at the grid nodes that are closest to each station. It should be noted that the differences of standard deviations of 2-m temperatures at altitude between the meteorological stations and the corresponding model grid points is small, and thus it is not affecting the results. The comparison is performed at 12:00 UTC. More specifically, 12:00 UTC air temperature values are compared with the corresponding t+12 model forecasts, respectively (see Fig. 7).

Correlation coefficients, biases and standard deviations of the differences of Armavir and Artashat Station are presented in Table 3. The 12:00 UTC temperature is underestimated, but the bias does not exceed 1.4 $^0$C for the t+12h. The maximum Std temperature is 4.8 at the station Megri, the wind speed is 2.6 at the Armavir, and the precipitation is 3.4 for at the Yerevan station.

## VI. Conclusion

The WRF-ARW meteorological model is applied operationally in the valley areas of Armenia for the summer period of 2011 and 2014 and the results are used in order to develop an early warning system for severe weather events. July and August are the most common periods of high temperature warnings in the Ararat, Syunik and Vayots Dzor flatlands regions. Heavy rainfalls dependent on processes seen in all the study region. Verification of the model was carried out based on a comparison of the model outputs with the data sets received from the meteorological stations.

The verification and analyses of CSI indicated in the table 4 shows that the model provides enough accurate results of the amount of precipitation. The verification and analyses of Bias shows that the model forecast is close to the observed values in the stations Artashat (1.08), Meghri (1.22) and Yerevan (1.23), but for Armavir we receive an overestimated result, which is 1.47. In case of the verification of POD it is close to the stations located in Yerevan and Armavir.

According to the verification results and the frequency of the warnings, the conclusion is that the daily maximum temperature is slightly overestimated by the model. Underestimation

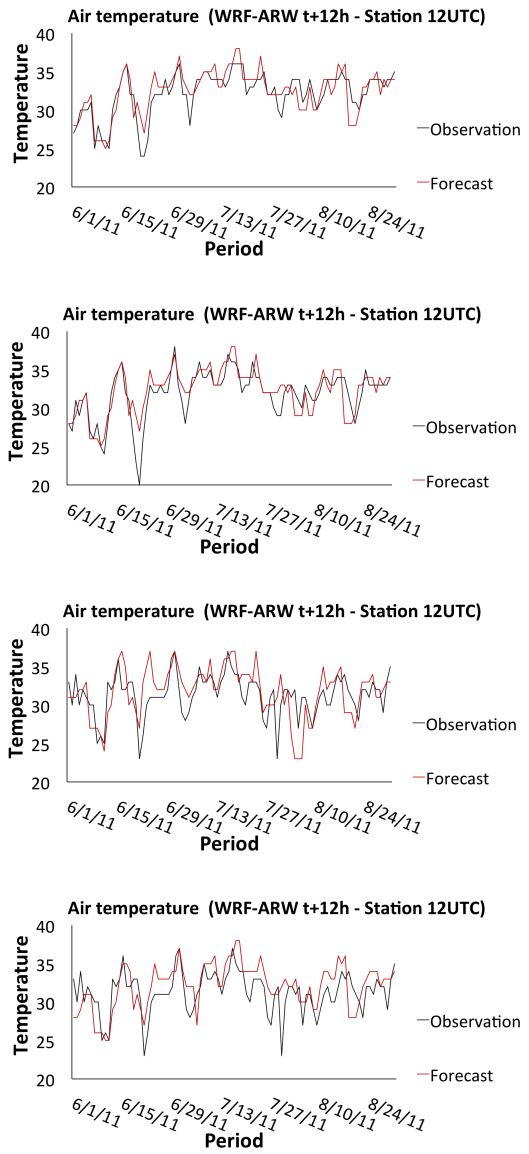


Fig. 7: Verification of air temperature forecast for Armavir, Artashat, Meghri, and Yerevan.

TABLE IV: Categorical statistics for the 24-hour interval (00:00-24:00 UTC) accumulated precipitation.

| Station | Categorical statistics | | | |
|---|---|---|---|---|
| | CSI | Bias | FAR | POD |
| Armavir | 0.55 | 1.47 | 0.13 | 0.88 |
| Artashat | 0.66 | 1.08 | 0.04 | 0.83 |
| Meghri | 0.53 | 1.22 | 0.01 | 0.78 |
| Yerevan | 0.68 | 1.23 | 0.07 | 0.88 |

is strongest in the inland area of Meghri, where the bias for the maximum temperature is equal to 1.4 $^0$C in case of t+12h forecast and Stdev is equal to 4.8. The correlation coefficient for all stations is acceptable, which means strong correlation with the forecasted values.

Taking into account the above mentioned, we plan to continue our investigations for other seasons and severe weather events and by physical parameterization aspects in order to develop an integrated early warning system in Armenia and beyond in a regional level. We intend to carry out some predictive modelling under different climate change scenarios too.

## Acknowledgment

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