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Discussions

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Evaluating the extreme precipitation events using a mesoscale atmosphere model and satellite based precipitation product

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Abstract

Quantitative precipitation estimates are obtained with more uncertainty under the influence of changing climate variability and complex topography from numerical weather prediction (NWP) models. On the other hand, hydrologic model simulations depend heavily on the availability of reliable precipitation estimates. Difficulties in estimating precipitation impose an important limitation on the possibility and reliability of hydrologic forecasting and early warning systems. This study examines the performance of the Weather Research and Forecasting (WRF) model and the Multi Precipitation Estimates (MPE) algorithm in producing the temporal and spatial characteristics of the number of extreme precipitation events observed in the West Black Sea Region of Turkey. Precipitations derived from WRF model with and without three-dimensional variational (3-DVAR) data assimilation scheme and MPE algorithm at high spatial resolution (4 km) are compared with gauge precipitation. WRF-derived precipitation showed capabilities in capturing the timing of precipitation extremes and in some extent the spatial distribution and magnitude of the heavy rainfall events wheras MPE showed relatively weak skills in these aspects. WRF skills in estimating such precipitation characteristics are enhanced with the application of 3-DVAR scheme. Direct impact of data assimilation on WRF precipitation reached to 12 % and at some points there exists quantitative match for heavy rainfall events, which are critical for hydrological forecast.

1 Introduction

Influences of global warming and climate change become more dominant with more catastrophic events observed around the world. With global warming, major changes in rain and water cycles are being observed, frequency of meteorological disasters such as heavy rainfalls is increasing continuously, and consequently resulting in high drought and flood risks. For example, the study of precipitation amounts using last 50 yr on

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land shows that the percentage of extreme precipitation against total precipitation has increased (Trenberth et al., 2007). As occurring and evidencing on several geographical regions on the earth, these types of extreme events are also being observed throughout regions more prone to flooding in semiarid environments. Also, on regions having complex topography, extreme events show significant temporal and spatial variations and generate extensive amounts of precipitation in short durations.

Flood forecasting systems are becoming more widespread for emergency cases where life and property are concerned. Such systems help to predict hazardous events and allow sufficient time for action. Ideally, they should not only produce accurate and reliable forecasts, but also provide long enough lead-times for appropriate action to be taken. To achieve a reasonably long lead-time, which enables timely issuance of flood warnings, quantitative precipitation forecasts with a spatial resolution compatible with that of the flow forecasting model are frequently required. Prediction of severe convective rainfalls is one of the many challenging problems in meteorology; at the same time, it is very important for many agencies engaged in disaster preparedness and mitigation to timely issue early flood warning. Weather forecasting has been a highly challenging task for more than half a century. Traditionally, weather forecasting has been based mainly on numerical weather prediction (NWP) models and they are most reliable source for atmospheric forecasts with a large spatial coverage and high temporal resolution (Liu et al., 1997). Mesoscale NWP models have played an important role in operational as well as severe weather forecasting. High-resolution mesoscale models can contribute to localized weather forecasting, particularly in areas where the topography and land-use heterogeneity modulate synoptic-scale weather. The verification studies of these mesoscale models, which is essential in terms of model predictability, has been gaining interest in the recent years. A number of studies such as those by Colle et al. (2003a, b), Kim and Lee (2006), Lin and Colle (2009), Shi et al. (2010), have verified the predictability of mesoscale models and generally focused on quantitative precipitation forecasts/estimates (QPF/QPE) and evaluated various statistical techniques for improved QPF/QPE.

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However, accurate precipitation calculations from NWP models are still a challenge. With appropriate initial and lateral-boundary conditions, high resolution mesoscale models offer great potential for improved QPF/QPE because models with this resolution can have skill in predicting the initiation and organizational mode of convective systems (Done et al., 2004). A study from Weisman et al. (1997) showed the 4 km grid spacing appears to be sufficient to resolve the dominant circulations in organized convective systems. NWP models provide an accessible tool for better understanding and improving the predictability of complex weather phenomena such as heavy rainfall events while they are performed to add to the insufficient observational data for identifying extreme precipitation events. Because of the insufficient enforcement of initial and boundary data to identify storms, the initiation of mesoscale systems in real cases was difficult to simulate well (Choi et al., 2011). Therefore, many studies have suggested that data assimilation is a useful tool in order to improve the initial conditions for simulations (Liu et al., 2005; Yu, 2007; Choi et al., 2011) and the three-dimensional variational assimilation (3-DVAR) has become a predominant method for providing initial model data in these studies and others (e.g. Lee et al., 2010). However, 3-DVAR assimilation technique is yet to be successfully applied for severe weather estimation, especially the amount of heavy rainfall, in Turkey. Therefore, it is imperative to conduct mesoscale model tests and verify the results to provide a direction for the improvement of model forecasts.

Heavy precipitation events are serious weather hazards in the eastern Mediterranean and Black Sea region. Although the number of previous studies (e.g. Borga et al., 2007; Nikolopoulos et al., 2013) focused on the prediction efforts of these rainfall events in the eastern Mediterranean, the studies are significantly limited in Black Sea region. The General Directorate of Meteorology (MGM) in Turkey uses its operational NWP models over this region but the verification studies of NWP results for heavy rainfall events observed in the western Black Sea region of Turkey have been lacking so far. Therefore, this study marks an effort to evaluate the Weather Research and Forecasting (WRF) model that is also being used as an

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operational model in MGM, with the inclusion of 3-DVAR assimilation scheme for its performance and error statistics, notably in the west Black Sea region that experiences multiple flood threats especially during spring and summer seasons. As a result, this study aims to improve the ability of WRF model to estimate heavy-rain-producing systems and the associated QPE and evaluate the forecast impacts of 3-DVAR data assimilation system and the performance of mesoscale WRF model at 4 km resolution. Nonconventional observation such as meteorological satellites provide additional and sufficient information for heavy rainfall events at high spatial (4 km) and temporal resolution (15 min) and therefore, precipitation derived from Multi-sensor Precipitation Estimates (MPE) algorithm (Heinemann et al., 2002) are also used in comparison when WRF model with and without assimilation is evaluated against observations.

2 Methodology

2.1 Study area and data

The study area together with nested configuration of WRF domains at 12 and 4 km resolutions in Fig. 1a and the detailed view of fine domain together with rain gauge locations and city provinces in western Black Sea Region of Turkey in Fig. 1b are shown. The study area is impacted by polar air masses with continental origin (Iceland Low and cold Siberian High) in the winter and by subtropical air-masses (Azores High and part of Pakistan Low) in the summer. When Siberian High crosses the Black Sea approaching the northern coasts of Turkey, cold and dry air turns into maritime continental air-mass due to the acquired moisture content. The diversity of the geographic structure, extension of the mountains and effects of the seas in the vicinity of the land determine the climate types of the region. Mountains, which lie parallel to the shore line and elevate up to 2065 m restrict transfer of precipitation to the inland zones, where temperature and precipitation decrease and the effects of continental climate are observed. Therefore, mean annual precipitations in the

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coastal zones vary between 700 and 1050 mm, higher than the mean annual value of Turkey, i.e. approximately 650 mm, whereas this value becomes as low as about 400 mm in the south of mountains. Number of rainy days in a year is about 130 in coastal zones, whereas it decreases to 70 days in the inland regions while most of the precipitations are observed in fall and winter (Sensoy et al., 2008). West Black Sea Region of Turkey is prone to have multiple extreme rainfall events and associated flood threats especially during spring and summer seasons. MGM develops the record of extraordinary meteorological events occurred throughout Turkey for each year. As main criteria, MGM considers any damage occurrence due to these events when selecting and recording these events. Number of heavy rain and associated flood events has been observed and marked in these records within this study region. According to these records developed by MGM, the 25 specific "heavy rain and flooding" tagged hydro meteorological events between years 2000 and 2011 are selected for this study and they are shown in Table 1 with their event number, rainfall maxima locations and event durations. For each precipitation event shown in Table 1, the hourly rainfall data obtained from 34 rain gauges of MGM at the automated weather stations are used for statistical evaluation with the WRF- and MPE-derived precipitation. Table 2 shows the name, altitude, latitude and longitude of these stations together with their associated numbers which are also displayed within the study area in Fig. 1b. Information such as, sensor specifications, observation period, etc. about the raingauges used in this study can be found in the reference of Sönmez (2013). Quality control tests applied to these rain gauge data are also described in this reference. In comparing the data between the WRF- and MPE-derived rainfall against rain gauges the point comparison method is used, in which 4 km WRF and satellite pixels encompass each gauge measurement.

2.2 WRF modeling system

In this study, the Weather Research and Forecasting (WRF) model (Skamarock et al., 2005) of mesoscale NWP system that incorporates advanced numeric and data-assimilation techniques (3-DVAR), a multiple nesting capability, and numerous state-

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of-the-art physics options is suitable for extreme weather applications in this study. Development and verification of WRF have been carried out in many applications, including Lee et al. (2010) and Flesch and Reuter (2012), which are most recent studies focused on heavy rainfall predictions at high spatial resolution. The WRF was employed in a nested configuration with grid points at 12 and 4 km resolutions, with its fine-sized domain covering the West Black Sea region in the north-west of Turkey (see Fig. 1). The model was initiated, and time-varying lateral boundaries for the coarse domain then nudged every 3 h, using 25 km analysis fields from the European Centre for Medium Range Weather Forecasts (ECMWF). A high-resolution (30 s) dataset was used to characterize modelled land surface across the fine-grid domain, while the modelled atmosphere was described at 23 levels (up to level slightly higher than stratapouse), these being stretched in the lower levels to ensure that resolution in the boundary layer is adequate for use of the planetary boundary layer scheme. As the lowest boundary of WRF model, Noah land surface model calculates the soil–vegetation–atmosphere interactions between surface and atmosphere. Microphysical and cumulus schemes were kept active to calculate convective and non-convective precipitation processes on both domains. Convective tendencies are usually resolved within 1–4 km grid scale and therefore the 4 km grid of model inner domain is found to be appropriate in simulating heavy rainfall events in this study. Only precipitation from fine resolution domain at hourly time step is used in analyses.

2.2.1 3-DVAR setting

Errors in deriving initial and boundary conditions can cause large variations in model estimates. Liang et al. (2004) found large uncertainties in boundary conditions, mostly over oceans and other areas lacking complete data, contributed greatly to model error. Model initiation is important because of the inability of most NWP models to accurately forecast beyond several days. WRF model is, therefore implemented with 3-DVAR assimilation scheme that introduces conventional meteorological observations including the surface and upper-air measurements of pressure, temperature, humidity

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and wind speed into initial stage of model and adjust boundary conditions to improve the performance of short-term simulations of heavy rainfall events. With 3-DVAR, WRF is started by new initial analysis, which is being obtained by a generalized inverse operator applied on observation. In assimilation process, in addition to the two primary sources of input data (observations and a previous ECMWF background forecast), estimates of observation and background error are required to compute the new analysis. In 3-DVAR, the background error covariance matrix, which is aimed to have weights to adjust errors in features of the ECMWF background field is approximated via the NMC-method of Parrish and Derber (1992) that averages forecast differences of WRF simulations in 12 hourly period for 3 days. Since background errors vary between each application, a recalculation of background error is considered for each event shown in Table 1 where the background field changes. Finally, new initial data sets to be used in WRF are defined and with respect to new analyses, model boundary conditions are updated. As an example, Fig. 2 shows the distribution of initial surface temperature, contours of sea level pressure and wind vectors for coarse domain on 25 October 2008 at 00:00 UTC in (a) for WRF without assimilation (control) and in (b) for WRF with assimilation. The difference in these fields is significantly traceable hence the effect of assimilation becomes clear. With assimilation initial condition over land is colder while over sea it is warmer and associated changes in wind and pressure are observable for this particular case.

WRF model simulations with and without assimilation are performed for the duration of each event shown in Table 1. Hereafter, the control WRF simulation and the WRF simulation with 3-DVAR scheme will be referred to as WRF NOAS and WRF AS, respectively.

2.2.2 Parameterization testing

Several options for physics parameterizations that are actual model representations of sub-grid scale processes are available in WRF system. Note that only radiation, land surface and boundary layer physics in Table 3 were chosen as standards from available

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literature. The implementation of various physics schemes as well as their interactions cause a large variation in the forecast output (Zhang et al., 2006), especially the choice of cumulus scheme and microphysics. The particular skill of a cumulus and microphysics scheme in simulating rainfall is dependent upon the region and storm being modeled (Giorgi and Mearns, 1999). Therefore, key parameterization of cumulus convection and microphysics in WRF model was tested to yield an optimal configuration that would give reasonably good precipitation simulation for heavy rainfall events. All these tests with WRF AS and WRF NOAS were performed on a particular heavy rainfall event that was recorded on 12–17 July 2009 and identified by event number 14 in Table 1. Table 3 lists the four combinations of cumulus and microphysics parameterizations; namely *"mp14cp1", "mp2cp1", "mp2cp5", "mp14cp5"* as well as other standard physics options (radiation, land surface layer, and boundary layer) used in WRF model.

Bias, root mean square error (rmse) and false alarm rate (far) statistics for 3 hourly rainfall are calculated for each combination after running the WRF AS and WRF NOAS with the specified combination for event number 14 and their results are shown in Fig. 3a for bias, (b) for rmse, and (c) for far. The best statistics is obtained with the combination of *mp14cp1* for WRF-AS and WRF-NOAS simulations. This combination set consistently yields lowest bias, rmse and far values for both AS and NOAS simulations. The worse combination is obtained by *mp2cp5* because of the choice of Grell cumulus (cp = 5) scheme in this study region. It should also be noted that highest sensitivity is to the choice of convective treatment rather than microphysics. On the other hand, WRF skill is improved with AS according to statistics between AS and NOAS. After testing the combinations of these schemes, the resulting optimal physics configuration is: Lim and Hong (2010) (microphysics scheme); and Kain and Fritsch (1992) (cumulus convection).

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2.3 Satellite rainfall algorithm

The MPE is an instantaneous rain rate product, which is derived from 10.7 µm brightness temperatures of Infrared (IR)-data of Geo-stationary EUMETSAT satellites by continuous re-calibration of the algorithm with rain-rate data from polar orbiting microwave sensors (Heinemann et al., 2002). The MPE provides precipitation data with high spatial resolution at 4 km and temporal resolution every 15 min. The algorithm is only suitable in convective weather situations. Frontal precipitation, especially at warm fronts is very often wrongly located and overestimated. MPE product gives indications where the product should be used and where it may be problematic. MPE data in this study are obtained from MGM for whole satellite cycle (3712 × 3712 at 4 km grids) in 15 min period for heavy rainfall events observed after 2005 in Table 1. Since comparison analyses are performed in hourly time interval the 15 min MPE estimates are also converted to hourly values by aggregating the four 15 min instantaneous rain rates within an interested hour.

3 Results

3.1 General analyses

Area-averaged time series of WRF AS, WRF NOAS, and MPE against observations are shown for event 13 and 23 in Fig. 4a and b, respectively. These two events are selected among 25 because they are the most representative of showing data assimilation impact on a temporal dimension during an event. For both events, assimilated WRF model better follows observed temporal fluctuations than non-assimilated WRF and MPE except during the second peak of rainfall event 13 where MPE shows a great match with observation. Assimilation provided perfect match with observation for event 23 by reducing the rainfall amount produced by WRF NOAS on late afternoon of 9 October 2010 in Fig. 4b. However, MPE completely misses the peak of this event.

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The scatter analyses of WRF AS/NOAS and MPE against observations using data from all 25 rainfall events are performed in order to inspect their degree of association. The levels of scattering between data pairs as well as overestimation and underestimation tendencies against observations are determined from these analyses. Figure 5 shows the scatter plots in (a) between WRF AS and observation, (b) between WRF NOAS and observation, and (c) between MPE and observation for 3 hourly rainfalls. The linear trend lines of data pairs are also shown in this figure. WRF AS shows less scatter than WRF NOAS, hence it produces better degree of association with observation. Comparing to WRF AS, somewhat higher level of scattering inspected in WRF NOAS that is mainly attributed to extreme overestimation and underestimation data points is tended to be modified by WRF AS through data assimilation. MPE gives slightly higher correlation values than WRF with and without assimilation as it releases less extreme rainfall amounts and tendency to underestimate heavy rainfall events.

Rmse, bias and correlation coefficient (R) of WRF AS, WRF NOAS and MPE are calculated for 1, 3, 6, and 24 hourly rainfalls and the results with regular and conditional precipitation (only non-zero observed precipitation cases) are given in Table 4. According to results, the assimilation shows a consistent improvement on WRF precipitation at all time intervals. With WRF AS the lower rmse, bias values and higher correlation coefficients comparing to WRF NOAS are obtained. Correlation coefficients increase with increasing time interval from 1 to 24 h. Negative biases at all time intervals with MPE indicate persistent underestimation feature in regular and conditional rains and this feature becomes more significant with latter. However, WRF with and without data assimilation shows the underestimation only with conditional rain. When comparing to WRF model MPE shows better statistics in 1, 3, and 6 hourly rains but it shows lower correlation than WRF at daily rains because of more pronounced effect of high negative biases at this interval. It should be pointed out that the lower rmse values with MPE are largely due to lower average rainfall intensity and not necessarily indicative of greater accuracy. With conditional rains, statistical performances of WRF and MPE decreases further with higher rmse and biases, and

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lower correlation when only observed rainy periods are considered. Higher negative biases with conditional rains of WRF model indicate a fact that assimilation generally tends to reduce the precipitation amount in WRF. Across the study area the error is reduced by 2.53 % in 1 h, 3.59 % in 3 h, 3.13 % in 6 h, and 2.66 % in 24 h intervals with regular rain analysis and by 0.94 % in 1 h, 2.45 % in 3 h, 3.96 % in 6 h, and 2.63 % in 24 h intervals with conditional rain analysis with the addition of the 3-DVAR scheme in the WRF model. Precipitation with 3 h interval in regular analysis and 6 h interval in conditional analysis showed highest improvement.

The skills of the WRF and MPE algorithm are evaluated further by calculating the equitable threat score (ETS) and its bias (ETS Bias) for daily rainfall as functions of different daily precipitation threshold values.

These scores are defined (Lee et al., 2004) as follows:

$$\text{ETS} = (A - H)/(A + B + C - H), \quad H = (A + B)(A + C)/(A + B + C + D),$$

$$\text{ETS Bias} = (A + B)/(A + C),$$

where A is the number of matching precipitation while both observation and model (WRF and MPE) shows precipitation; B is the number of occurrence where observation shows precipitation and model shows zero precipitation; C is the number of occurrence where model shows precipitation and observation shows zero precipitation; and D is the number of occurrence where both observation and model shows zero precipitation. For a perfect algorithm, ETS = 1 and ETS Bias = 1. For ETS bias, scores greater than 1 show overestimation while scores less than 1 indicate underestimation for the model being evaluated. ETS and ETS Bias scores of WRF AS, WRF NOAS, and MPE are shown, respectively in Fig. 6a and b for different daily precipitation threshold values. In Fig. 6a, there is more gradual decrease in ETS scores of WRF AS and NOAS than decrease in those of MPE along with increasing precipitation thresholds. MPE does not produce any score after approximately threshold value of 48 mm day^{-1}. Significant discrepancy between WRF AS/NOAS and MPE scores after about 3 mm day^{-1} threshold value explains that MPE shows roughly 10 % lower

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performance than WRF model on capturing daily precipitation thresholds. WRF AS and NOAS show a steady increase in ETS Bias after threshold value of 15 mm day^{-1}, while MPE shows a gradual but continuous decrease in ETS Bias along with threshold range in Fig. 6b. In addition, ETS Bias values with the WRF always stay above 1 while those with MPE always stay far below 1. It is notable that the overestimation feature of WRF increases gradually up to 40 % while the underestimation feature of MPE increases up to 90 % towards higher precipitation thresholds. These behaviors in WRF and MPE consequently cause decreasing trend in ETS with increased precipitation thresholds. On the other hand, for both of these skill measures, WRF AS consistently produced better skills than WRF NOAS almost at all threshold values while both WRF (AS and NOAS) scores (ETS and ETS Bias) yielded much better performance than MPE. The substantial underestimation feature of MPE already given in Table 4 is consistent with these score analyses of different precipitation thresholds.

3.2 Event- and station-based analyses

The performance of WRF and MPE is investigated by the analysis of precipitation with spatial variation using 34 stations for each event and temporal variation using 25 events for each station. A cross validation of the models with a spatial and temporal overview is performed in this way. Bias, rmse, and correlation coefficient (R) of WRF AS, WRF NOAS, and MPE are calculated and shown for 3 hourly rainfall for each event in Fig. 7a and for each station in Fig. 7b. Overall in all events and stations a general decrease in bias, rmse and increase in R are observed on WRF AS with respect to WRF NOAS while majority of events (87 %; 13 out of 15 events) and stations (71 %; 24 out of 34 stations) shows significant negative biases with MPE as this was the case in previous analyses. The dry bias character of MPE results in falsely lower rmse comparing to the WRF in many cases but correlation coefficient or general pattern of MPE yields better skill than the WRF with and without assimilation in 44 % of the events and 41 % of the stations. On the other hand, WRF AS yields better performance than WRF NOAS in 60 % of the events (15 out of 25 events) and 70 % of the stations (24 out of 34 stations)

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based on root mean squared errors, and in 72 % of the events (18 out of 25 events) and 79 % of the stations (27 out of 34 stations) based on correlation coefficient values. Improvement with data assimilation is more evident in station-based analyses than that in event-based analyses and, thereby the temporal effects are better interpreted than spatial effects with assimilation within the WRF. This can be attributed to greater uncertainty of spatial effects than temporal effects as the study covers mostly the summer-time convective precipitation events. Furthermore, in both event- and station-based analyses, the correlation coefficient inspection releases higher number and more traceable improvement with assimilation than root mean squared error. This is an indication of high impact of assimilation on the track of precipitation pattern rather than its magnitude.

Mean rmse values of 1, 3, 6, and 24 hourly precipitation obtained from WRF AS, WRF NOAS, and MPE are calculated for event- and station-based data and their summary is given in Table 5. The WRF model with assimilation produced lower mean errros comparing to no assimilation at all time intervals. Temporal effects described by station-based analysis is better resolved by the WRF model as this analysis releases the lower errors comparing to those in the event-based analysis. NWP models in general have high uncertainty in parameterizing convective activities, hence they yield poor skill for precipitation resulting from convective type of systems. However, this situation is reversed with the MPE as its rainfall character shows great variability inter events per station. To point out the impact of assimilation on the WRF-derived precipitation amount, the mean error reduction rate or improvement rate in precipitation is computed for both event- and station-based analyses at each rainfall interval and their results are shown in Table 6. In both event- and station-based analyses, 3 hourly rain interval showed the highest improvement rates with 5.13 % in event-based and 4.29 % in station-based when data assimilation is used in WRF model. In some cases shown in Fig. 7a and b, the assimilation degrades precipitation against observations because of the chaotic status of the atmosphere. By excluding such cases from error analyses, the direct impact of assimilation on precipitation is more isolated and

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it enhances the error reduction rates further as seen in Table 6. In this case, for example, the mean improvement rate is increased up to 11.39 % for 3 h interval. Liu et al. (2013) showed the impact of 3-DVAR with 16 % improvement on a 10 km single grid of 24 h accumulative rainfall when they used WRF with 3-DVAR using traditional meteorological observations at the initial state to simulate a rainfall storm.

While the improvements provided by assimilation were given per event and per station basis in previous analyses, Probability of Detection (POD), FAR, and Critical Success Index (CSI) values (Kidd et al., 2011) are evaluated together to trace the change in precipitation performance of WRF with and without assimilation and MPE. For example, Fig. 8 shows these score values in (a) for 1 h interval, (b) for 3 h interval, (c) for 6 h interval, and (d) for 24 h interval for each of the 25 events while Fig. 9a–d shows the equivalent diagrams for each of the 34 stations. As both event and station charts along with 1–24 hourly intervals are examined in these figures, the MPE shows substantially higher FAR, slightly higher POD and lower CSI than those of the WRF model at all time intervals. Also, as time interval aggregates from 1–24 h, the desired pattern of significant increase in POD and decrease in FAR is witnessed. Thus, CSI value, which is a function of both POD and FAR, converge towards 1, shown within contours. FAR is the least improved parameter of MPE along with time intervals and this finding confirms an existing of systematic problem in MPE that makes the algorithm persistently underestimates precipitation. In Fig. 8, a few stations show consistently low FAR values at all intervals in contrast to the rest of the stations with MPE as the algorithm shows some ability to capture the track of storms from different events at these stations. Inter-event variability (see Fig. 8) on these statistical parameters is much more evident than the variability (see Fig. 9) appears among stations.

4 Summary and conclusions

In this study, QPE from the MPE rainfall algorithm and WRF model with and without data assimilation were evaluated against the network of 34 rain gauges installed in

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the partially mountainous terrain region of the West Black Sea in Turkey during 25 different spring/summer/fall heavy rainfall event periods selected from 2000 to 2011. The study provides a comprehensive validation of the characteristics of WRF- and satellite-estimated precipitation to examine their abilities to accurately reproduce heavy rainfall events. In an effort to further improve the developed QPF by WRF model, the WRF model was also applied with 3-DVAR data assimilation scheme and its potential in producing QPF for heavy rainfall events and for flood forecasting purposes was shown. Comparisons indicate a promising potential of the WRF model in producing heavy rainfall events and with the use of data assimilation in WRF the results are further improved with a better model performance. However, with MPE algorithm some systematic bias structures exist that need to be addressed. The primary conclusions of the present research are as summarized as follows:

- The Kain–Fritsch cumulus and The Lim and Hong microphysics schemes produced more accurate rainfall across the study area for a single heavy rainfall event for both assimilation and no-assimilation. Also, precipitation is found to be most sensitive to the cumulus scheme rather than the microphysics scheme according to experimental design of determining the optimum parameterization in WRF as this agrees with the results of Lowrey and Yang (2008).

- Overall, WRF model with and without assimilation generates an overestimation trend against observations, while MPE substantially underestimates the precipitation. However, when only conditional rains are considered WRF model also shows some underestimation feature.

- On mean areal time series, especially assimilated WRF model is managed to match temporal observation trends and rain amounts up to some extent. While temporal consistence shows variance for each event, in some events this consistency is observed much significantly. The MPE manages weakly to match dense local rain gradients observed on WRF because of its underestimation behaviour.

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– WRF with assimilation greatly improved precipitation with respect to no assimilation at all time intervals and the improvement was the highest with 3 hourly precipitation. Error statistics shows that across the network, the assimilation improved the rainfall by 4 % in various time intervals, but mostly over the 3 h interval for regular and conditional rainfall. Assimilation tends to trim the precipitation amount in WRF according to the area-averaged conditional rain analyses across the events. WRF with and without assimilation showed substantially better performance than MPE with threshold analysis while AS yielded better skill than NOAS almost at all threshold values.

– Improvement with data assimilation was more evident in station-based analyses than event-based analyses whereas MPE acted reversely by releasing smaller mean error in event-based analysis. For both analyses, the 3 hourly mean error is reduced roughly by about 5 % with data assimilation and when the chaotic cases are not included in analyses the mean error reduction rate is improved to 10 % for event-based and 12 % for station based analyses. Assimilation shows a tendency of higher impact on precipitation trend than its magnitude.

– Time aggregation from 1 to 24 h make the POD, FAR and CSI converge towards their high success values. In both event and station based charts, MPE values show overwhelmingly higher FAR and somewhat lower CSI trends while showing POD values close to WRF's and this feature persists at all time intervals. Mean variability among stations is clearly less than among events according to POD, FAR, CSI combination.

The study showed that WRF was often able to detect heavy rainfall signals based on 25 events. Though it may not simulate both the occurrence time and the rainfall magnitudes accurately, it manages to simulate them satisfactorily. Data assimilation has a significant role in this satisfactory performance of WRF system. In addition, as a beneficiary point of data assimilation used in this study, Liu et al. (2013) found that obvious improvement can be observed regarding both the rainfall cumulative curve

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and the 24 h rainfall total after assimilating the traditional observations via 3-DVAR in WRF. They also stated the improvement with radar data assimilation through 3-DVAR is negligibly small when it is compared with the assimilation of the traditional meteorological observations. The local scale improvement of convective storms, which is apparently provided by data assimilation in this study benefits flood warning issues performed at fine scale locations. The capability of modeling system is quite crucial, particularly as an Advisory tool, for taking flood early warning measures. The heavy rainfall signals could be well in advance detected by WRF, which is very useful for flood advisory particularly for locations showing very short hydrologic response time for the heavy rain events. On the other hand, although the MPE provides realistic precipitation in a few cases as to a good supplement for WRF, it requires modifications for its substantial underestimation behavior that was the evident mostly observed in this study. Contrary to this, for example, the operational Hydro Estimator (HE) rainfall algorithm of the National Oceanic and Atmospheric Administration (NOAA) that is Infrared based algorithm similar to MPE shows a tendency to overestimate precipitation with heavy rainfall events occurring during larger, more organized convective storms (Yucel et al., 2011). Perhaps, the bias structure suggests that the MPE may have a decreased sensitivity to deep convection, which weakly generates heavy precipitation in many events in this study. Also, it is suggested that the calibration equation that is used to modify IR based rainfall estimates with microwave data requires tuning in MPE algorithm.

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Table 1. Events studied and their occurrence periods with the rainfall peak locations are given.

Event No.	Start date	End date	Peak observation locations
1	2 Jun 2000	7 Jun 2000	Bartın
2	4 Aug 2002	12 Aug 2002	Kastamonu (Devrekani)
3	16 Aug 2002	23 Aug 2002	Kastamonu (Devrekani)
4	11 Aug 2004	16 Aug 2004	Zonguldak (Ereğli)
5	14 Aug 2004	19 Aug 2004	Bartın, Kastamonu
6	23 Aug 2004	28 Aug 2004	Bartın
7	28 Apr 2005	5 May 2005	Bartın, Bolu, Düzce
8	2 Jul 2005	9 Jul 2005	Bartın
9	13 Jul 2005	18 Jul 2005	Bartın, Zonguldak
10	5 Jun 2007	15 Jun 2007	Kastamonu (Cide), Zonguldak (Devrek)
11	30 Jul 2007	4 Aug 2007	Zonguldak
12	20 Sep 2007	25 Sep 2007	Zonguldak, Duzce (Akçakoca)
13	27 Sep 2008	2 Oct 2008	Kastamonu (İnebolu, Bozkurt)
14	12 Jul 2009	17 Jul 2009	Bartın, Kastamonu (Devrekani)
15	26 Jul 2009	29 Jul 2009	Kastamonu (Cide, Inebolu)
16	6 Sep 2009	12 Sep 2009	Sakarya, Bolu
17	19 Sep 2009	25 Sep 2009	Bartın
18	25 Jun 2010	2 Jul 2010	Bartın, Bolu, Kastamonu (Devrekani)
19	6 Jul 2010	11 Jul 2010	Çankırı (Ilgaz), Bolu
20	31 Aug 2010	4 Sep 2010	Bartın
21	13 Sep 2010	16 Sep 2010	Bartın
22	1 Oct 2010	4 Oct 2010	Kastamonu (Bozkurt)
23	7 Oct 2010	12 Oct 2010	Bartın, Kastamonu (Bozkurt)
24	25 May 2011	5 Jun 2011	Kastamonu (Devrekani), Karabuk (Yenice)
25	9 Jun 2011	14 Jun 2011	Bartın, Zonguldak (Ereğli, Devrek)

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Table 2. The name, elevation, latitude, and longitude of automated rain gauge stations of MGM used in this study are given.

Station No.	Station type	Elevation (m)	Latitude (°)	Longitude (°)
1	Akcakoca	10.0	41.083	31.167
2	Bartin	33.0	41.633	32.333
3	Zonguldak	136.0	41.450	31.800
4	Inebolu	64.0	41.983	33.783
5	sinop	32.0	42.033	35.167
6	Kocaeli	76.0	40.767	29.933
7	Sakarya	31.0	40.683	30.417
8	Bolu	743.0	40.733	31.600
9	Duzce	146.0	40.833	31.167
10	Kastamonu	800.0	41.367	33.783
11	Cankiri	751.0	40.617	33.617
12	Amasra	73.0	41.750	32.383
13	Cide	36.0	41.883	33.000
14	Bozkurt	167.0	41.950	34.017
15	Devrekani	1050.0	41.583	33.833
16	Cerkes	1126.0	40.817	32.900
17	Ilgaz	885.0	40.917	33.633
18	Tosya	870.0	41.017	34.033
19	Devrek	100.0	40.517	30.300
20	Acisu-radar	1112.0	41.181	31.799
21	Eregli	191.0	41.283	31.417
22	Geyve	100.0	41.217	31.950
23	Ulus	162.0	41.582	32.637
24	Yenice	140.0	41.200	32.333
25	Boyabat	350.0	41.467	34.767
26	Caycuma	50.0	41.400	32.083
27	Arac	650.0	41.250	33.333
28	Gerede	1270.0	40.800	32.200
29	Seben	757.0	40.417	31.583
30	Kıbriscik	1025.0	40.417	31.850
31	Catalzeytin	75.0	41.950	34.217
32	Boludagi	948.0	40.717	31.417
33	Eskipazar	757.0	40.967	32.533
34	Goynuk	780.0	40.400	30.783

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Table 3. Combinations of microphysics and cumulus parameterizations for optimal configuration as well as other physics used in the WRF model. mp and cp stand for microphysics and cumulus schemes, respectively, which are used with options 2 and 14 for mp and 1 and 5 for cp available in WRF model.

Combination	mp14cp1	mp2cp1	mp2cp5	mp14cp5
Microphysics (mp)	Lim and Hong (2010)	Lin et al. (1983)	Lin et al. (1983)	Lim and Hong (2010)
Cumulus (cp)	Kain and Fritsch (1992)	Kain and Fritsch (1992)	Grell et al. (1995)	Grell et al. (1995)
Radiation	Dudhia (1989)	Dudhia (1989)	Dudhia (1989)	Dudhia (1989)
Land surface layer	Chen and Dudhia (2001)	Chen and Dudhia (2001)	Chen and Dudhia (2001)	Chen and Dudhia (2001)
Boundary layer	Hong and Pan (1996)	Hong and Pan (1996)	Hong and Pan (1996)	Hong and Pan (1996)

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Table 4. Bias and rmse in [mm] and correlation coefficient (R) in [%] of WRF AS, WRF NOAS, and MPE for regular and conditional rain amounts at 1, 3, 6 and 24 h intervals are given.

Obs.		WRF AS		WRF NOAS		MPE	
Interval		Regular	Conditional	Regular	Conditional	Regular	Conditional
1 h	BIAS	0.0389	−1.0240	0.0493	−1.0048	−0.0885	−1.2968
	RMSE	1.6171	3.8412	1.6590	3.8774	1.3200	3.4998
	R	0.1088	0.0664	0.1030	0.0615	0.1613	0.1562
3 h	BIAS	0.1300	−1.1792	0.1604	−1.1097	−0.2733	−2.1068
	RMSE	3.6279	6.6968	3.7630	6.8647	2.9886	6.0921
	R	0.1696	0.1296	0.1541	0.1092	0.2016	0.2078
6 h	BIAS	0.2581	−1.0870	0.3174	−0.9508	−0.5249	−2.8489
	RMSE	5.8472	9.4730	6.0361	9.8639	4.7591	8.4245
	R	0.2270	0.1819	0.2114	0.1559	0.2397	0.2450
24 h	BIAS	0.8478	−0.2519	1.0530	0.0237	−1.8022	−5.3121
	RMSE	13.3393	18.5403	13.7038	19.0404	10.8916	16.3499
	R	0.3645	0.2939	0.3605	0.2910	0.2822	0.2038

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Table 5. Mean Rmse in [mm] values of WRF AS, WRF NOAS and MPE at 1, 3, 6, and 24 h intervals are given for event- and station-based analyses.

	Event based			Station based		
	WRF AS	WRF NOAS	MPE	WRF AS	WRF NOAS	MPE
1 hourly	1.641	1.693	1.235	1.453	1.497	1.291
3 hourly	3.559	3.701	2.794	3.256	3.385	2.871
6 hourly	5.765	5.897	4.405	5.21	5.368	4.527
24 hourly	11.973	12.302	9.997	11.783	12.175	10.082

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Table 6. Error improvements in [%] with the use of 3-DVAR in WRF are given at 1 h, 3 h, 6 h, and 24 h intervals for event- and station-based analyses. These improvements are provided for all data and part of data after excluding chaotic values with data assimilation.

Analysis type	Data type	Hourly time period			
		1 hourly	3 hourly	6 hourly	24 hourly
Event Based Analysis	All	4.31 %	5.13 %	3.72 %	4.21 %
	Excluding chaotic values	7.80 %	9.19 %	9.29 %	10.12 %
Station Based Analysis	All	2.79 %	4.29 %	3.81 %	4.08 %
	Excluding chaotic values	8.99 %	11.39 %	11.46 %	11.20 %

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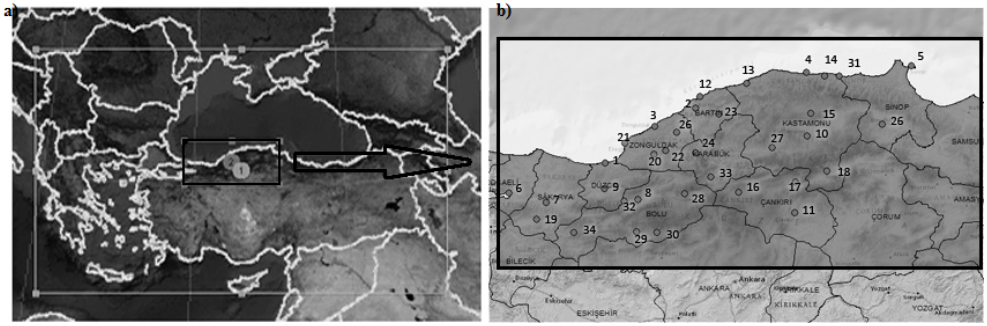

Fig. 1. The study area with WRF model configuration of two nested domains at 12 and 4 km resolutions is shown in **(a)** and the detailed view of 4 km domain with the locations of raingauge stations used in comparison and border of city provinces in the region is shown in **(b)**. Number 1 and 2 located at the center point of coarse and fine resolution domains identify 12 and 4 km domains, respectively.

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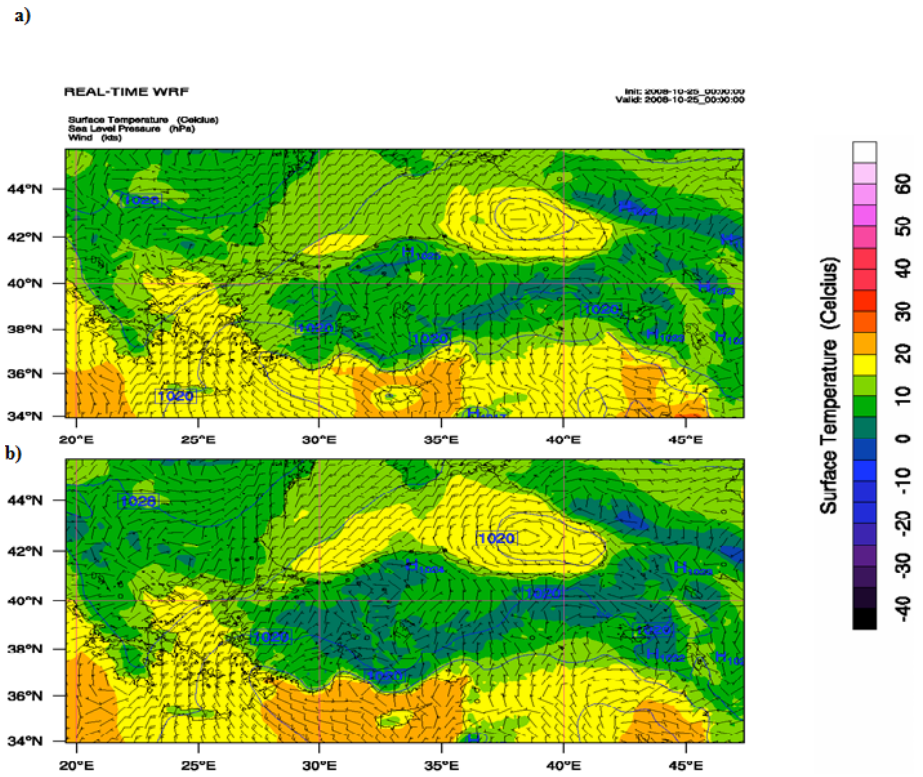

Fig. 2. The distribution of initial surface temperature, contours of sea level pressure and wind vectors for coarse domain on 25 October 2008 at 00:00 UTC in **(a)** for WRF without assimilation (control) and in **(b)** for WRF with assimilation is shown.

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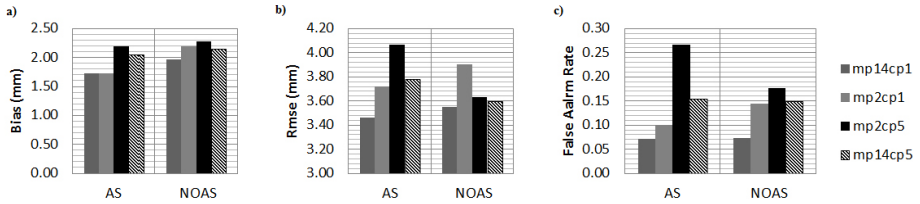

Fig. 3. Bias, rmse, and false alarm rate (far) are shown in **(a)**, **(b)**, and **(c)**, respectively for different microphysics and cumulus options when WRF model is simulated with assimilation (AS) and without assimilation (NOAS) on 12–17 July 2009.

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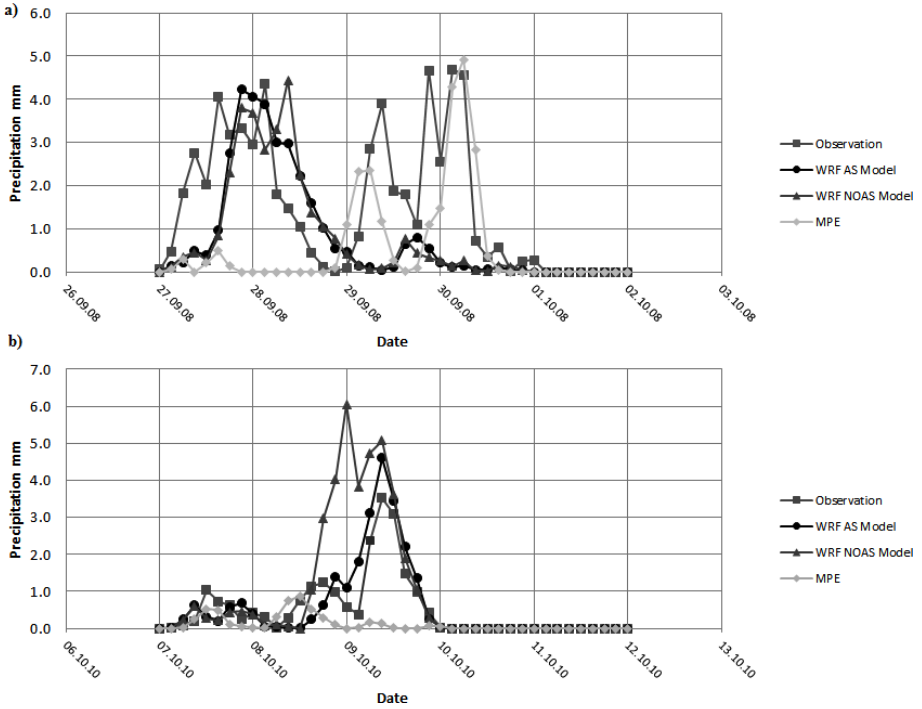

Fig. 4. Area-averaged time series of WRF AS, WRF NOAS, and MPE against Observations are shown in **(a)** for event number 13 and **(b)** for event number 23.

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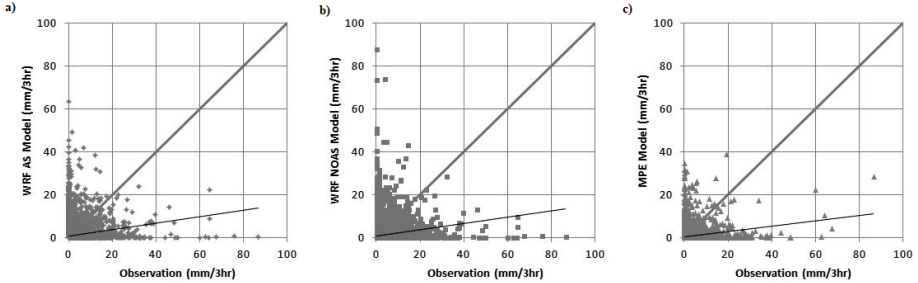

Fig. 5. Scatter diagrams of all data at 3 h interval are shown in **(a)** between WRF with assimilation and observation, **(b)** between WRF without assimilation and observation, and **(c)** between MPE and observation.

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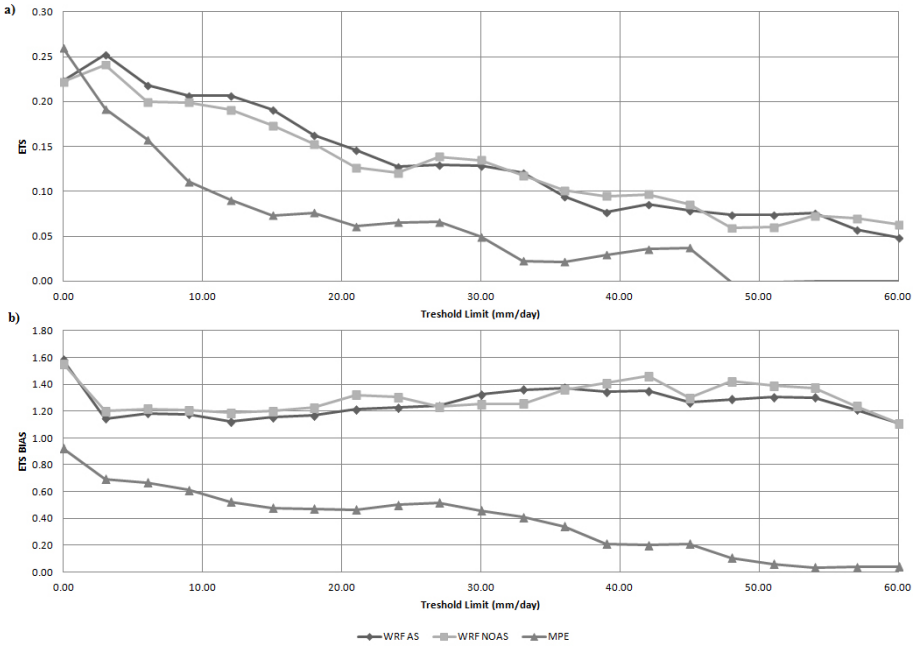

Fig. 6. ETS and ETS Bias scores of WRF AS, WRF NOAS, and MPE are shown, respectively in **(a)** and **(b)** for different daily precipitation threshold values.

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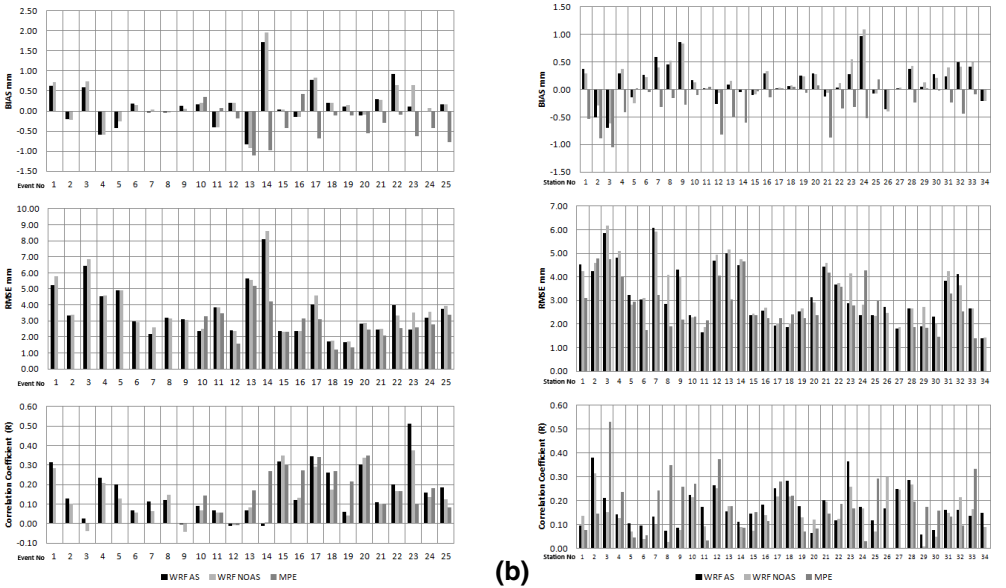

Fig. 7. Bias, rmse, and correlation coefficient (R) of WRF AS, WRF NOAS, and MPE at 3 h interval are shown in **(a)** for each event and **(b)** for each station.

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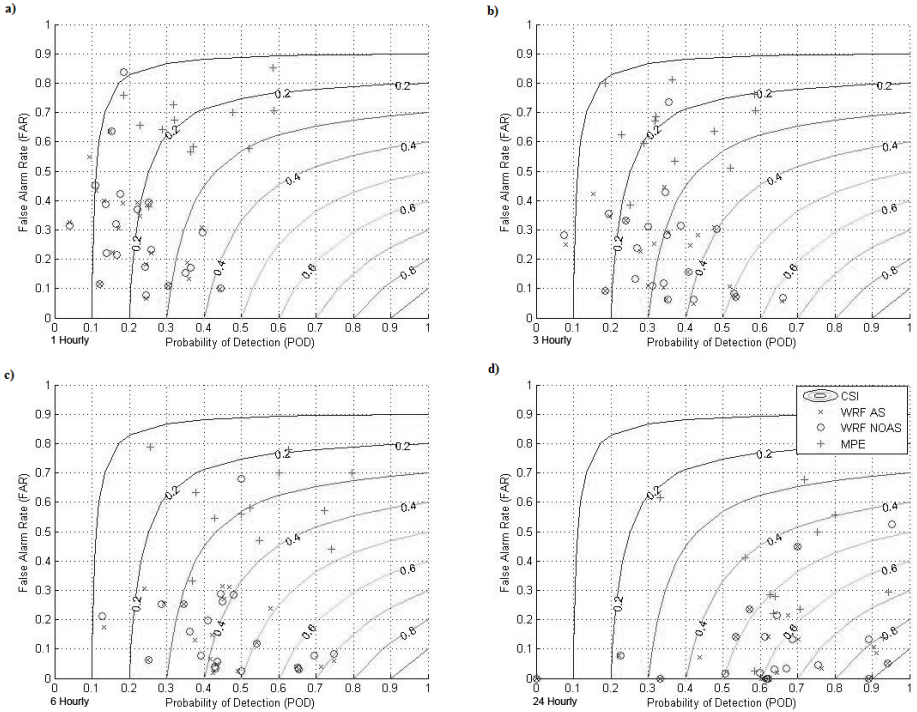

Fig. 8. POD, FAR and CSI statistics of WRF AS, WRF NOAS and MPE are shown together for each of the 25 events at 1, 3, 6, and 24 h intervals in **(a–d)**, respectively. Contours represent CSI values.

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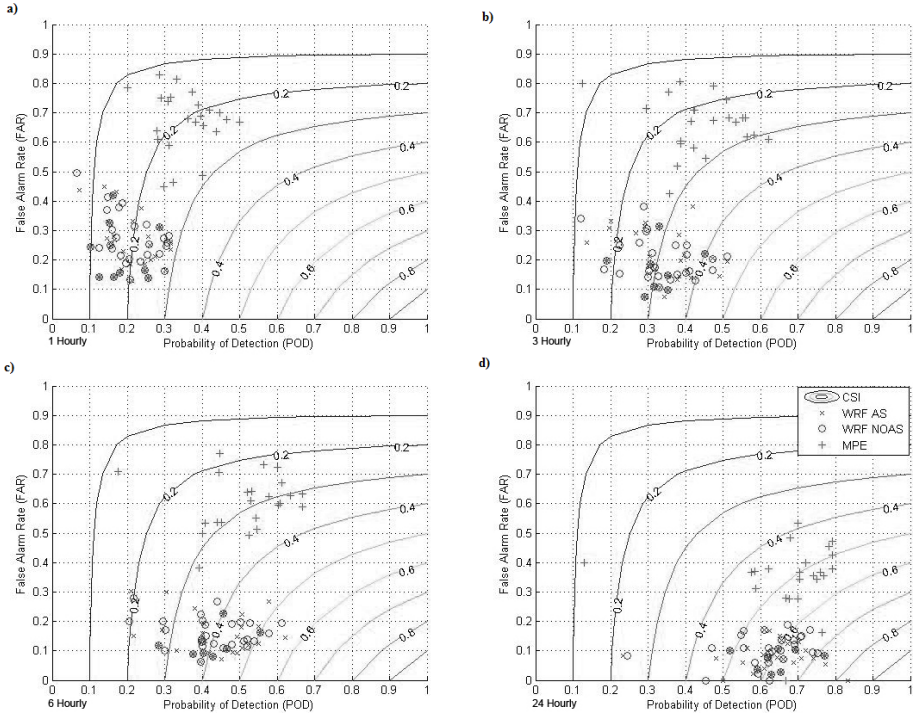

Fig. 9. POD, FAR and CSI statistics of WRF AS, WRF NOAS and MPE are shown together for each of the 34 stations at 1, 3, 6, and 24 h intervals in **(a–d)**, respectively.

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