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On the Dependence of WRF Model Air Temperature and Precipitation Forecast Skill on the Weather Type for Northwestern Greece †

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Abstract: The WRF model temperature and precipitation forecast skill for the area of northwestern Greece is examined separately for each of the 10 objectively defined Weather Types (WTs). The WTs are defined for the 10-year period: 1 January 2009–31 December 2018. Their definition is achieved with the application of k-means Cluster Analysis on ERA5 meteorological data. The WRF model is applied in three domains (Europe—Greece—NW Greece) using the one-way nesting technique in a spatial resolution of 18, 6 and 2 km. Specifically, the model runs for 64 days (10% of the number of days attributed to the WT with the highest number of days) with the lowest distances from each WT's cluster center. The WRF forecast data of 2 m air temperature and precipitation are compared with the available meteorological observations operated by the METEO unit at the National Observatory of Athens. The validation of 2 m air temperature is performed for 04UTC and 12UTC for the first and second days of forecast using the Cressman method, separately for each meteorological station and WT. The validation of precipitation is performed for daily accumulated values for the first and second days of forecast, using forecast data from the $3 \times 3 = 9$ surrounding grid points of each meteorological station and calculating categorical statistics based on contingency tables for each WT and for different thresholds. According to the results, there is a remarkable overestimation of 04UTC air temperature for the anticyclonic WTs, especially for the inland stations, while the precipitation forecast skill generally depends on the threshold and the WT characteristics.

Keywords: WRF validation; air temperature; precipitation; weather types

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1. Introduction

The area of northwestern (NW) Greece presents significant interest from a meteorological point of view, not only because of its orientation but also because of its complex terrain. Many studies [1–3] have been carried out for the validation of a mesoscale numerical weather prediction (NWP) model. The ultimate goals of these studies are to provide us with useful information of the prediction skill of each model, which is based on specific physical parameterizations. A study on weather type classification for NW Greece [4] shows that 10 objectively defined Weather Types (WTs) have been defined for a 10-year period; these types explain the meteorological conditions over that area. WT definition is achieved with the application of k-means Cluster Analysis on ERA5 grid point meteorological data. The defined WTs of this study [4] are used as a basis for a validation of air temperature and precipitation derived from a mesoscale forecast model.

In this study, the Weather Research and Forecasting (WRF) model is used running in three domains (Europe—Greece—NW Greece), with a one-way nesting technique in a spatial resolution of 18, 6 and 2 km. Specifically, the model runs for 64 days (represents the

10% of the number of days of the most common WT) with the lowest distances from each WT cluster center in order to validate the forecasts of air temperature and precipitation for each WT separately.

2. Data and Methodology

The database consists of air temperature and precipitation recordings at the available meteorological stations (Figure 1) from the surface network operated by the METEO unit at the National Observatory of Athens [5]. Data availability within the period of study, starting from 1 January 2009 until 31 December 2018, is set at least to 95% for each selected meteorological station. Meteorological stations installed only on the ground are selected for the validation of 2 m air temperature leading to 11 stations, while 17 stations are selected for the validation of precipitation, including those whose sensors are installed at different heights above ground level.

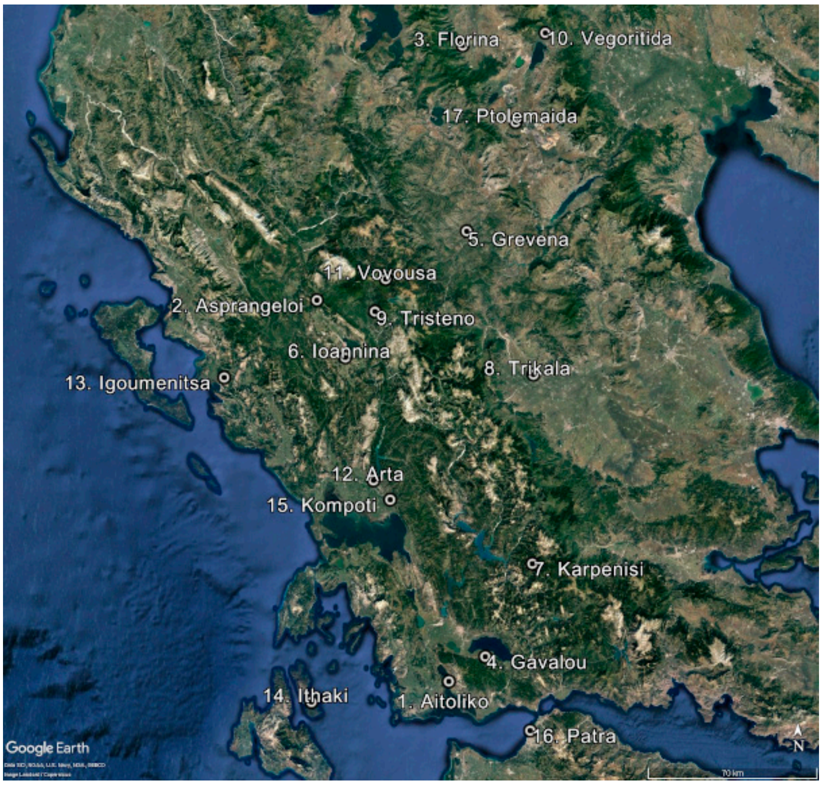


Figure 1. Representation of meteorological stations used for validation of air temperature (numbers 1 to 11) and precipitation (numbers 1 to 17).

For the initialization of the WRF model, the GFS forecast data are used at a $0.5° \times 0.5°$ resolution. The WRF model starts running at 12UTC for 36 and 60 h forecasts in order to receive data for the first and second days of forecast, considering the first 12 h of forecast as a spin-up of the model, shifting the starting day accordingly each time. The results of the model that are compared to observations are those derived from the fine domain of NW Greece with a spatial resolution of 2 km.

The validation of 2 m air temperature is performed for 04UTC, in which usually the lowest temperature is observed, and for 12UTC for the first and second days of forecast using the Cressman method separately for each meteorological station and WT. According to the Cressman method, the air temperatures of the four nearest grid points are projected to the meteorological station using Equations (1) and (2), where T is the temperature at a meteorological station, T_n are the temperatures of the four nearest grid points, R is the horizontal dimension of the grid and D_n are the distances between the meteorological station and each grid point. Also, the model outputs of temperature resulting from the

Cressman method to the observation point are linearly interpolated from the weighed altitudes of the four nearest grid points of model to the altitude of the meteorological station with an empirical lapse rate of 6.5 K/km in order to properly compare observations with modelled data.

$$T = (\sum_{n=1,4} W_n\ T_n)/(\sum_{n=1,4} W_n), \tag{1}$$

$$W_n = (R^2 - D^2{}_n)/(R^2 + D^2{}_n),\ D < R. \tag{2}$$

The validation of precipitation is performed for daily accumulated values for the first (from t + 12 h to t + 36 h) and second (from t + 36 h to t + 60 h) days of forecast using forecast data from the 3 × 3 = 9 surrounding grid points of each meteorological station. The closest forecasted value to observation from the 9 surrounding grid points is considered for comparison each time. It is a method suggested in cases when a model with fine spatial resolution is used for an area with irregular topography.

3. Results

For the comparison of the observed and modelled 2 m air temperature, the mean error ($t_{modelled} - t_{observed}$) and standard deviation are calculated for each WT and meteorological station separately, for 04UTC and 12UTC for the first and second days of forecast. Some of the results of air temperature validation for the first day of forecast are presented for WT9, which is one of the most frequent WT in the study area, and WT3, which is characterized by cyclonic conditions in Figure 2. The 500 and 1000 hPa geopotential height patterns of WT9 and WT3 are presented in Figure 3.

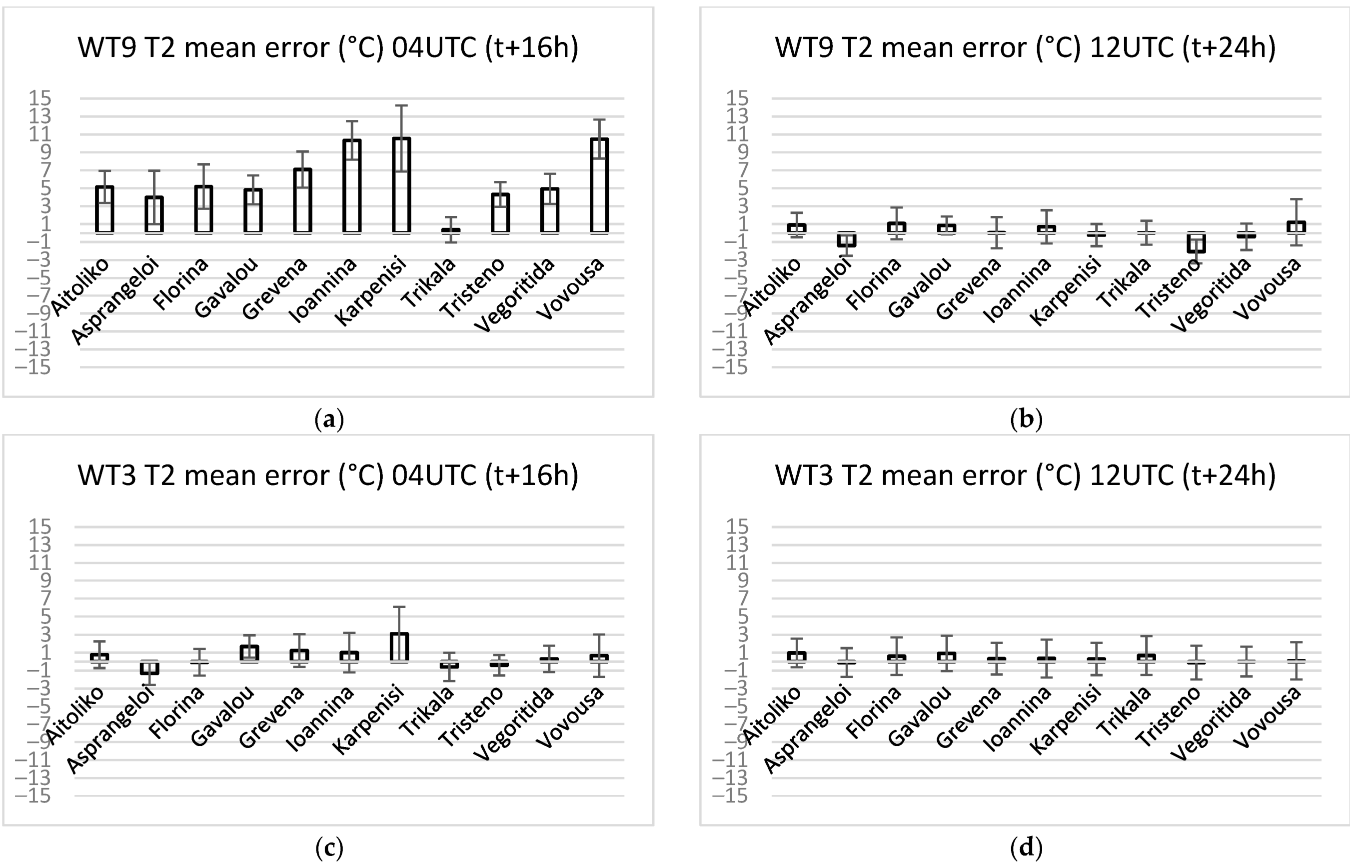


Figure 2. Graphical representation of mean errors (in °C) and standard deviations of the differences between forecasted and observed values of 2 m air temperature (T2) for all meteorological stations (**a**) for WT9 at 04UTC (forecast value t + 16 h) (**b**) for WT9 at 12UTC (forecast value t + 24 h) (**c**) for WT3 at 04UTC (forecast value t + 16 h) (**d**) for WT3 at 12UTC (forecast value t + 24 h).

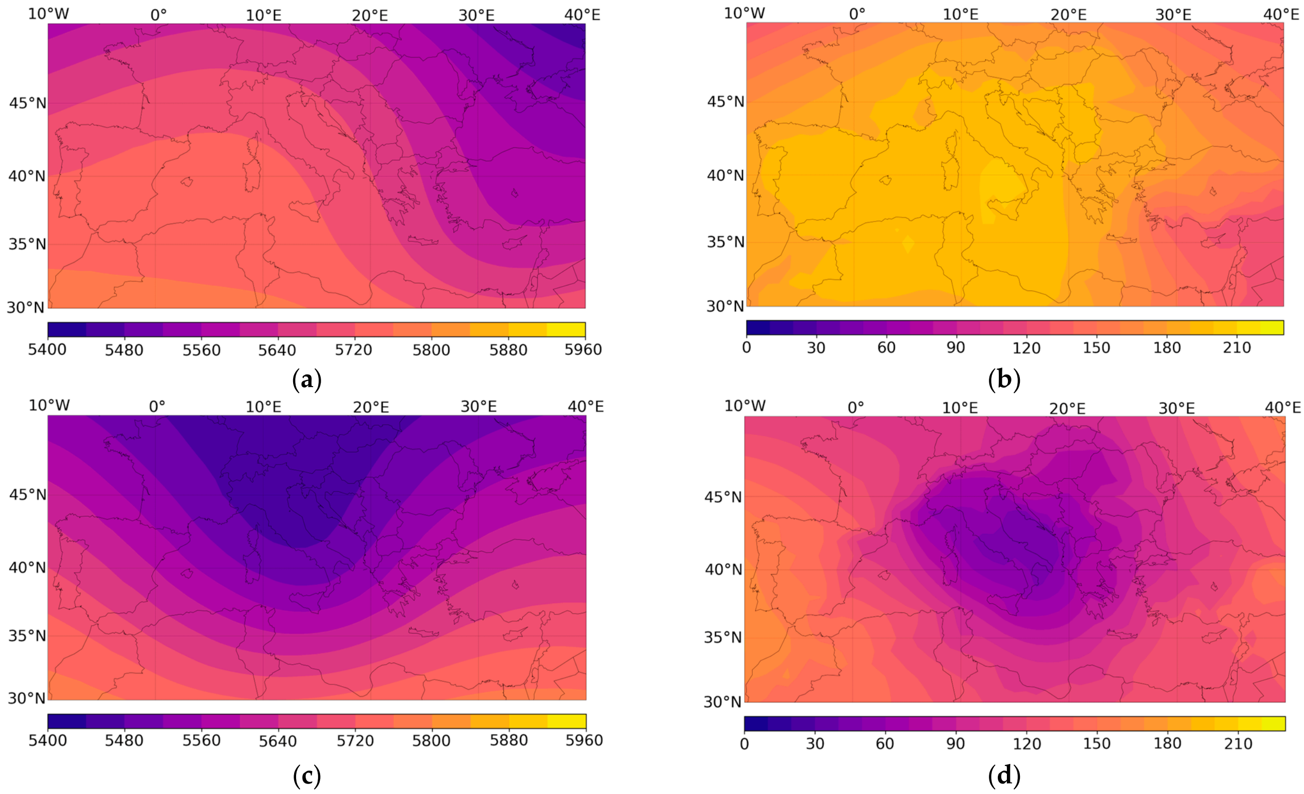


Figure 3. Graphical representation of mean 12UTC: (**a**) 500 hPa for WT9, (**b**) 1000 hPa for WT9, (**c**) 500 hPa for WT3 and (**d**) 1000 hPa for WT3 geopotential height patterns (gpm).

As it can be seen in Figure 2, there are significant differences between the observed and forecasted air temperatures at 04UTC at almost all the meteorological stations for WT9, while for 12UTC, the air temperature corresponding differences are quite small. WT9 is an anticyclonic WT with clear skies and low wind speed over the study area. It is noted that similar results were found for the other anticyclonic weather types, too, while for the cyclonic types, like WT3 characterized by cloudy conditions and significant vertical mixing, the forecast skill is satisfactory for both 04 and 12UTC air temperatures. The latter supports the fact that the low forecast skill of the model for 04UTC temperature is probably connected to the model parametrizations related to the simulation of the early-morning surface temperature inversion favored by anticyclonic conditions.

In order to compare the observed and modelled daily precipitation, statistics of mean error (ME) and root mean square error (RMSE) are calculated for each WT separately considering all the data from 17 meteorological stations. These statistics are calculated for five classes in order to estimate the forecast skill of the model based on small, medium and large amounts of precipitation. The five classes that are set are (a) 0.5–2.5 mm, (b) 2.5–5.0 mm, (c) 5.0–10.0 mm, (d) 10.0–20.0 mm and (e) >20.0 mm. The results are presented at Figures 4 and 5 for 7 out of 10 WTs which include a considerable number of precipitation days. Also, statistics are calculated for each WT that have enough days (at least 1% of total cases of study) of precipitation that reach each threshold.

In order to further examine the predictability of the model for precipitation, it is necessary to also apply categorical statistics on contingency tables which are calculated for each WT separately considering all the data from 17 meteorological stations for five precipitation thresholds. The five thresholds that are set for categorical statistics are (a) >0.5 mm, (b) ≥2.5 mm, (c) ≥5.0 mm, (d) ≥10.0 mm, and (e) ≥20.0 mm. Because of the lack of data for the largest thresholds, only cases that reach at least 1% of total data are taken into account for the calculation of categorical statistics. In Figure 6, the Frequency Bias and the Gilbert Skill Score (GSS) [6] are presented for the first (t + 12 h to t + 36 h) day of forecast. Frequency Bias is the ratio of the number of forecasts of occurrence to the number of actual occurrences. Values of Frequency Bias greater than one show that the forecast precipitation is overestimated, while values less than one show that the forecast precipitation is underestimated for the specific threshold. Perfect forecasts provide GSS = 1, while the zero-skill forecast of a model based on GSS is when GSS = 0.

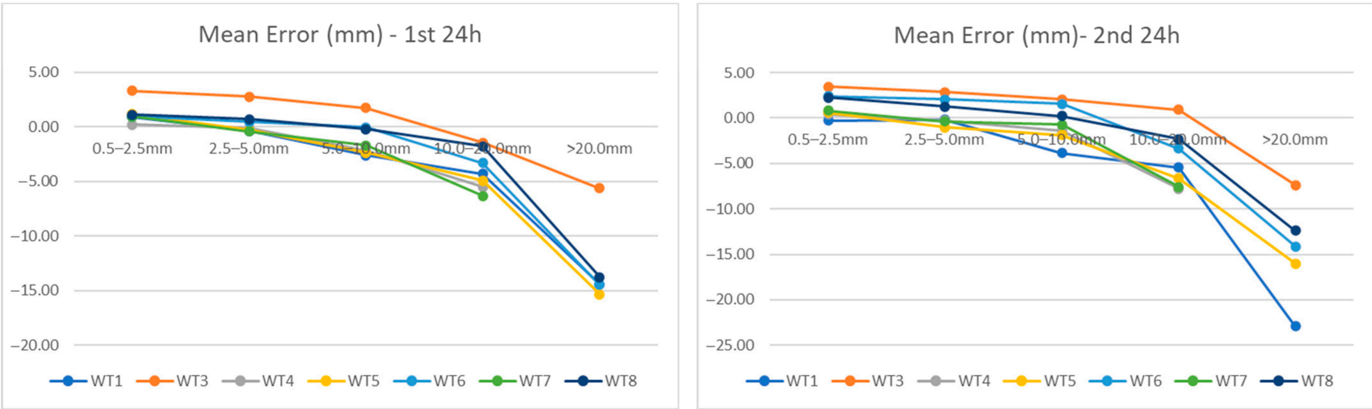


Figure 4. Mean Error (ME) for (**a**) 1st (t + 12 h to t + 36 h) and (**b**) 2nd (t + 36 h to t + 60 h) days of forecast for each WT and for five precipitation classes.

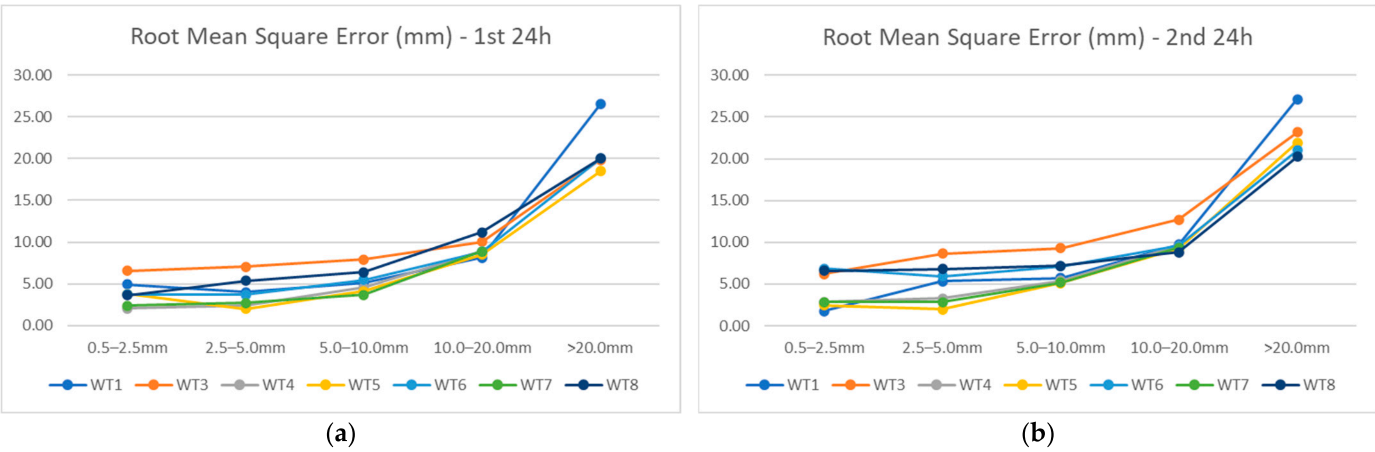
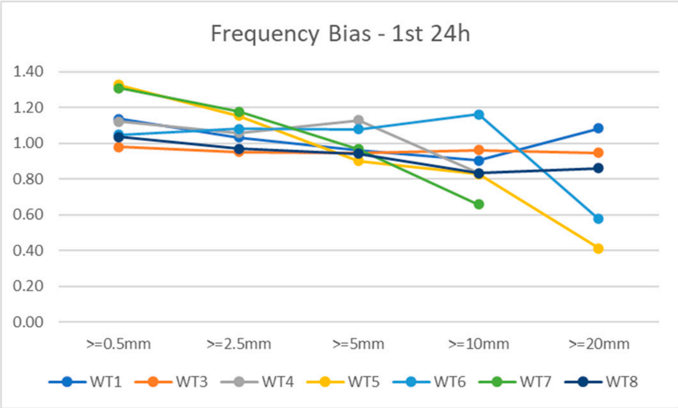
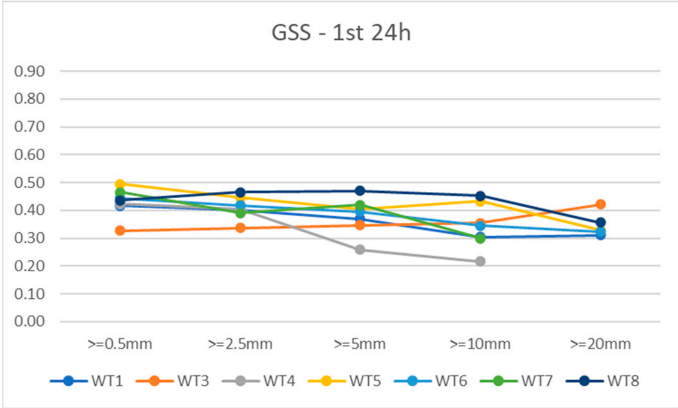


Figure 5. RMSE for (**a**) 1st (t + 12 h to t + 36 h) and (**b**) 2nd (t + 36 h to t + 60 h) days of forecast for each WT and for five precipitation classes.

In Figures 5 and 6b, it appears that precipitation forecast skill is slightly better for low precipitation thresholds, which means that it is easier for a model forecast to exceed a lower precipitation threshold if a precipitation event occurs. It can be seen for WT3 that the GSS is increased for high precipitation values. This is due to the largest amounts of daily precipitation which are observed for WT3 within all WTs. Also, WT8 and WT6 are generally characterized by higher forecast skill in relation to WT4, which has the lowest cases of daily precipitation that exceeds the threshold of 2.5 mm. It is noted that the WTs with higher precipitation forecast skill are mainly the cyclonic WTs of the cold period.



(a)



(b)

Figure 6. (**a**) Frequency Bias and (**b**) GSS for the 1st (t + 12 h to t + 36 h) day of forecast for each WTs and for five precipitation thresholds.

4. Conclusions

In this study, the WRF model temperature and precipitation forecast skill for the area of northwestern Greece is examined based on WTs that are objectively defined for the study area. A significant overestimation of 04UTC surface air temperature is found by the WRF model, mainly for some inland meteorological stations and for the WTs characterized by anticyclonic conditions. On the contrary, the 2 m air temperature at 12UTC is well forecasted by the model for all WTs. There are no remarkable differences between first and second days of air temperature forecast for all WTs. As it concerns the precipitation forecast skill, the largest errors occur in the highest amounts of precipitation. Also, according to the results of frequency bias, there is a general overestimation by the model in lowest precipitation thresholds, while there is a general underestimation in the highest thresholds. In addition, it seems that the WRF model forecast of precipitation is better for cyclonic WTs of the cold period.

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