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Research Article

Simulating Heavy Precipitation with HARMONIE, HIRLAM and WRF-ARW: A Flash Flood Case Study in Istanbul, Turkey

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Abstract

The paper discusses the ability of three different numerical weather prediction models (HARMONIE, High Resolution Limited Area Model (HIRLAM) and WRF) to forecast a heavy precipitation event that occurred on 8–9 September 2009. The precipitation forecast for each model is compared against rainfall observations from 28 meteorological stations in the region. All models are performed on domains centred on the Thracian region (north-western Turkey). All three models forecast heavy precipitation in the area; however, the locations of the most intense rainfall are off by several tens of kilometres. The models forecast good signals of heavy precipitation, but locations of the forecasted maxima are shifted with respect to the observed locations.

Key words: Rainfall, natural hazards, forecasting, modelling, NWP

İstanbul'da 8-9 Eylül 2009'da Meydana Gelen Aşırı Yağışın HARMONIE, HIRLAM ve WRF-ARW ile Simülasyonu

Öz

Bu çalışmada, 8–9 Eylül 2009 tarihlerinde meydana gelen aşırı yağışın üç farklı sayısal hava tahmin modeli (HARMONIE, Yüksek Çözünürlük Sınırlı Alan Modeli (HIRLAM) ve WRF) kullanarak tahmin yeteneklerini değerllendirmektedir. Her bir model yağış tahminleri bölgedeki 28 yağış gözlemleriyle karşılaştırılmıştır. Tüm modeller İstanbul batısı baz alınarak çalıştırılmıştır. Her üç modelde bölgede yoğun yağış tahmin etmektedir, ancak, en yoğun yağış alanlarının yerleri onlarca kilometer uzaklıktadır. Modeller, aşırı yağışların sinyallerini iyi tahmin etmektedir, ancak maksimumların konumları, gözlenen yerlere göre farklıdır.

Anahtar kelimeler: Yağış, doğal felaketler, tahmin, modelleme, sayısal hava tahmini

1. Introduction

Flash flood is an important hydrometeorological phenomenon that causes widespread disruption, damage and loss of lives. The number of the natural disasters has been increasing in frequency and becoming more hazardous worldwide over the last few decades: The International Database reports indicate that the number of reported natural disasters was about 30 per year in the 1950s and more than 400 per year since 2000 (EM-DAT 2012). Furthermore, the number of people affected by such disasters has risen from about 25 million per year in the 1960s to some 300 million per year since 2000 (EM-DAT 2012). The main cause of this trend is the increasing number of climate-related disasters (EM-DAT 2012). Floods are responsible for 40% of all natural disasters and half of the loss of lives around the world (Bich et al. 2011).

In the last decade, some significant flood events with a major economic and social impact have occurred in various countries, with different climatic conditions, and from river basins that differ in both size and topography (Knight and Samuels 2007). During flood events, property and the risks to life are usually more severely affected in urban areas, depending on their topography, where changes to stream channels during urban development and population growth, as well as inadequate maintenance can limit the capacity to cope with flood-waters in urban areas.

It is known that the Mediterranean region is subject to flash flood events, as studied numerous times by different scientists. Three heavy rain cases were studied over the western Mediterranean (Doswell et al. 1998), based on the physical processes that drives the precipitation. The synoptic and mesoscale mechanisms of a long-lasting heavy precipitation were discussed for the event that occurred on 12–13 November 2004 in southeastern Italy using observations and numerical outputs (Mastrangelo et al. 2011). The geographical aspects of two flash floods over southern France, one on 12–13 November 1999 and one on 8–9 September 2002, were studied, which caused 35 and 23 fatalities respectively (Vinet et al. 2008). As a Mediterranean country, Turkey also undergoes floods, with its complex topography favoring lift and overflow. Destructive flood events occur in Turkey with an average of 18 cases and 23 fatalities per year (Gurer and Ozguler 2004). The government has paid for a large part of the damage after each event, in addition to losing significant revenue due to the consequences of economic disruption (Gurer and Ozguler 2004). According to flood reports prepared by the General Directorate of State Hydraulic Works, on average, 90 million US$ of flood damage has occurred per year (Kılıçer and Özgüler 2002). The number of floods was 69 in 2007, 42 in 2008 and 125 in 2009. Two of these occurred in the northwest part of Turkey on 8–9 September 2009, which caused 31 deaths and resulted in approximately 90 million US$ of financial damage. According to local news, two days of torrential rain triggered flash floods, sweeping cars into the sea and sending gushing water into homes and businesses. These were considered as the most catastrophic floods in recent history of Turkey, following the 1957 Ankara and 1995 Izmir floods. A number of studies have focused on the synoptic and dynamic analysis of these violent flash flood events (Schipper and Erturk 2009, Kömüşçü et al. 2011, Çelik et al. 2010, Kömüşçü et al. 2010).

Several research centers, universities and institutes are developing models for the prediction of heavy precipitation around the world. WRF-ARW is a community model, developed by many institutes in the United States and elsewhere, widely used in atmospheric sciences both in research and operations (NCAR UCAR, 2018). It is a fully-compressible, Eulerian and non-hydrostatic model, using the Arakawa-C grid system and terrain-following vertical levels. On the other hand, HIRLAM is a Europe-based model, built with the collaboration of national meteorological services (initiated by Nordic countries). It is a hydrostatic model with semi-Lagrangian dynamics and hybrid vertical coordinates. The Arakawa-C grid system is also used in HIRLAM (for more details, see http://hirlam.org). HARMONIE is another Europe-based model, having strong ties with HIRLAM, prepared for mesoscale simulations, with a non-hydrostatic dynamical core.

A high level of horizontal and vertical resolution in physical space is very important when predicting severe weather events, since such weather is often associated with rapidly developing small-scale systems and can be strongly influenced by local terrain characteristics like orographic forcing and land-sea interaction (Chessa et al. 2004). The flood events on 8–9 September 2009 were studied using HIRLAM and HARMONIE models. They ran the models at ECMWF using the default settings with resolutions of 11 km and 2.5 km for these models to investigate whether the NWP models can forecast excessive precipitation in the Istanbul area (Toros et al. 2010). They obtained 24-hour accumulated precipitation forecasts by these models, which were quite high compared to the climatology, but were still far below the observed amounts, and there is a location error for precipitation. In this study, these models and the Weather Research and Forecasting (WRF) modelling system are used to simulate the above-mentioned heavy rain event, and the outputs are compared.

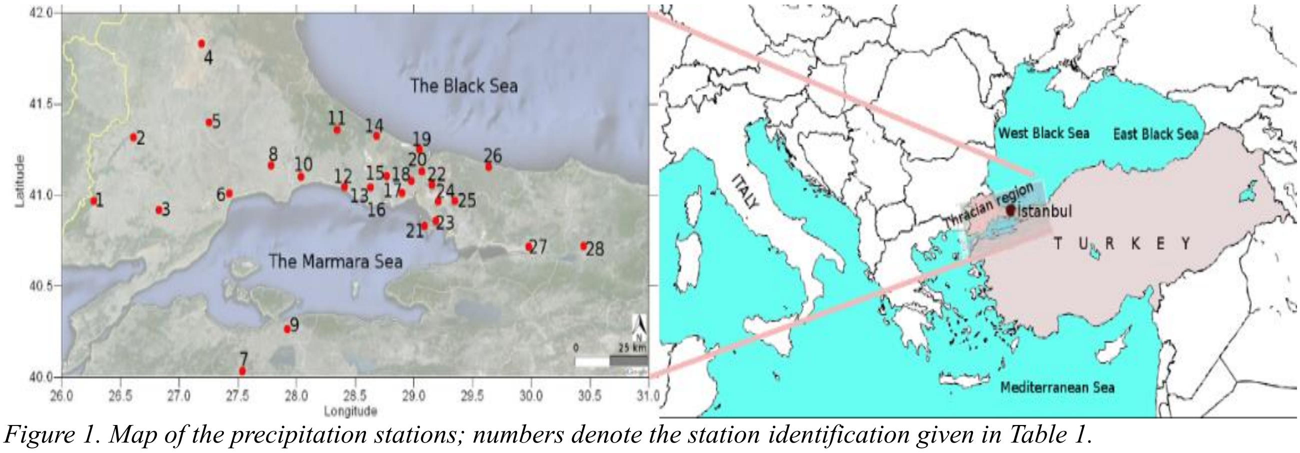

Figure 1. Map of the precipitation stations; numbers denote the station identification given in Table 1.

The performance of the models is evaluated by examining different predicted parameters, such as the upper and lower level circulations, moisture, temperature and precipitation. The goal of the study is to examine the performances of the HIRLAM/HARMONIE/WRF models for the simulation of the severe precipitation event of 8–9 September 2009 over the western part of Istanbul with varying horizontal resolutions.

2. Materials and methods

Twenty four-hour observed precipitation data for the event were obtained from the Turkish State Meteorological Service (TSMS) and Istanbul Metropolitan Municipality (AKOM). Hourly precipitation data from 28 stations in the study area and nearby have been used. The location of these sites can be seen in Figure 1. Numbers in this plot refer to the numbers in Table 1 where the station name and the location in latitude and longitude can be found. Table 1 also provides the 24-hour accumulated precipitation values.

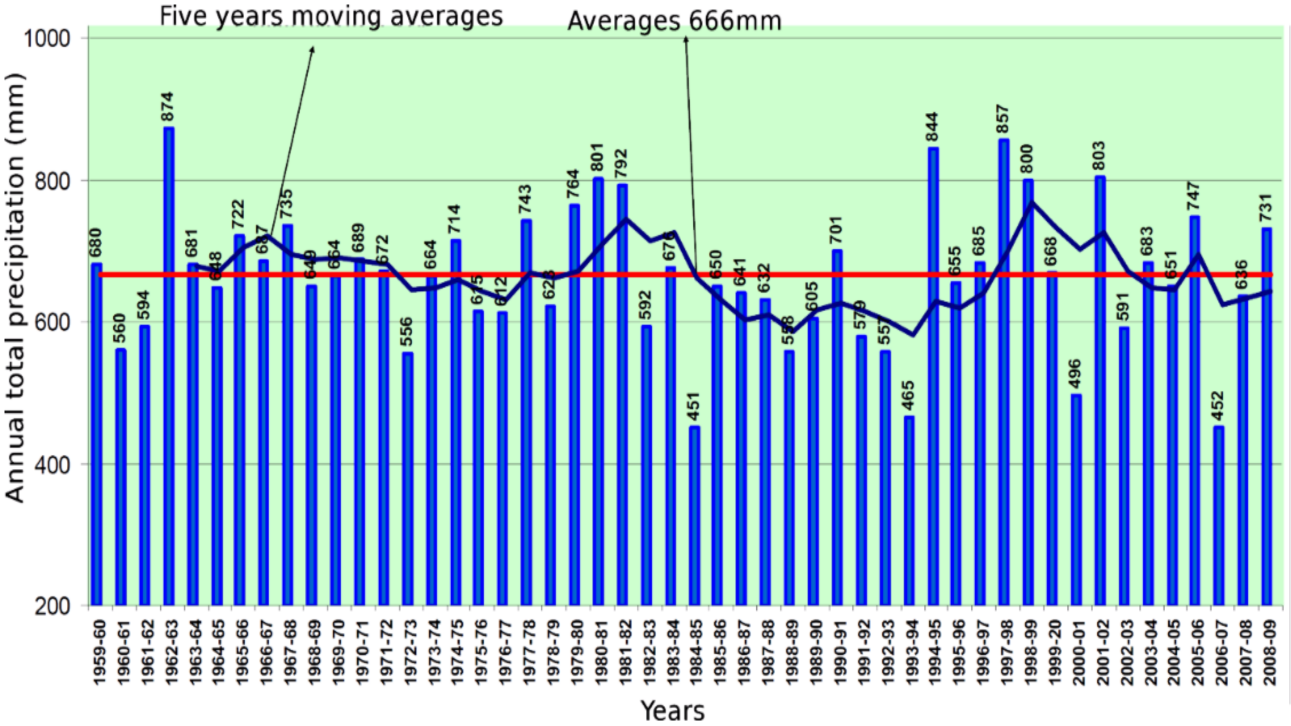

Figure 2. *Long-term annual total precipitation (1959-2009) in the region (TSMS, 2010).*

2.1.Study Area and Climate

Istanbul, as the business and cultural capital of Turkey and home to about 15 million people, has grown rapidly over the last several decades. It has historically been vulnerable to natural disasters. The climate of Istanbul can be characterized as a transition between Mediterranean and temperate. In the summer, the weather is generally warm and humid with very little rain, whereas the winter can be cold and wet with some snow. The spring and autumn seasons are mild. Istanbul covers a large area and has a complex topography with the Bosphorus Seawater Strait extending from the Black Sea to the Marmara Sea and separating the Asian and European sides of the city. The average annual precipitation in the northwestern part of Turkey, the Marmara Region, is approximately 666 mm, with a range from 451 mm–874 mm (Figure 2). For the two-day period of our case study, the 48-h accumulated precipitation values shown in Table 1 are at some observation sites up to 253.8 mm (Bandırma), which is roughly 38% of the annual average.

2.2.Numerical Models Setup for the Run

HIRLAM, non-hydrostatic convection-permitting model (HARMONIE) and Advanced Research Weather Research and Forecasting Model (WRF-ARW) are used for the simulation of this heavy rain case. HIRLAM is a grid-point model using the Arakawa-C grid, developed by the HIRLAM cooperation. It has a hydrostatic dynamic core, with hybrid vertical coordinates. It is based on a semi-implicit semi-Lagrangian discretization of the multi-level primitive equations (Undén et al. 2002). HARMONIE is a spectral model built by HIRLAM and ALADIN, with a two time-level semi-implicit semi-Lagrangian discretization of the fully-elastic equations. It has non-hydrostatic and hydrostatic options. Vertical coordinates are hybrid. The model core is developed by ALADIN, and the parameterizations are adopted from AROME, which has been developed by the meso-NH community. Detailed information can be accessed from http://hirlam.org. The HARMONIE and HIRLAM models were run at ECMWF using the default settings. The model configurations are given in Table 2. WRF-ARW is a widely-used open-source community model. Dynamics are non-hydrostatic with a hydrostatic option. It uses the Arakawa-C grid structure, a third-order Runge–Kutta integration scheme and eta vertical coordinates (Skamarock et al. 2008). Configurations for the WRF model are also shown in Table 2. All of the experiments were started at 00 UTC on 6 September 2009, except for HIRLAM HL2.5/HL11, which started at 0600 UTC on 6 September 2009. HARMONIE, as well as HIRLAM HL11/EC and HL2.5/EC are nested within ECMWF analysis, but HIRLAM HL2.5/HL11 is nested in HL11/EC. The domains used for the simulations can be seen in Figure 3, where 24-hourly precipitation for 7 September 2009 is also plotted.

Table 1. *Station id, name, longitude, latitude, altitude (m) and available daily total observed precipitation (8 September 2009 data for Terkos (id 14) did not include data from 08:00–23:00, so the amount given is for 9 hours only).*

Id	Stations	Long. (º)	Lat. (º)	Alt. (m)	Precipitation (mm)		
					Sep 8	Sep 9	Total
1	Ipsala	26.37	40.92	10	50		50
2	Uzunköprü	26.69	41.25	52	33		33
3	Malkara	26.91	40.89	207	28	5	33
4	Kırklareli	27.22	41.74	232	25	2	28
5	Luleburgaz	27.31	41.35	46	37	11	48
6	Tekirdag	27.49	40.99	4	43	7	50
7	Gönen	27.64	40.11	37	122	6	128
8	Çorlu	27.82	41.15	183	30	18	48
9	Bandırma	27.99	40.33	63	109	144	254
10	Çanta	28.08	41.10	116	44	56	100
11	Çatalca	28.35	41.34	104	204	36	240
12	Kamiloba	28.43	41.05	54	65	97	162
13	Hadimköy	28.63	41.05	183	41	114	155
14	Terkos	28.67	41.32	4	49	80	128
15	Olimpiyat	28.77	41.10	100	50	175	225
16	Florya	28.79	40.97	37	27	79	107
17	Aksaray	28.90	41.03	4	15	11	26
18	Akom	28.97	41.10	88	33	38	71
19	Kumköy	29.04	41.25	38	25	66	91
20	Sarıyer	29.05	41.14	59	65	41	107
21	Büyükada	29.08	40.87	188	42	2	44
22	Çavusbaşı	29.15	41.08	137	8	23	31
23	Kartal	29.18	40.89	28	10	27	37
24	Samandıra	29.20	40.99	123	15	11	26
25	Ömerli	29.33	41.00	153	7	5	12
26	Şile	29.60	41.17	83	3	13	16
27	Kocaeli	29.93	40.77	76	1	5	5
28	Sakarya	30.39	40.77	30	5	69	74
Average					43	41	83

Table 2. *A summary of the characteristics of the models.*

Model feature	**HARMONIE**	**HIRLAM**			**WRF**		
Experiment	$HM_{2.5}$/EC	HL_{11}/EC	$HL_{2.5}$/EC	$HL_{2.5}$/HL_{11}	WRF_{24}/EC	WRF_8/WRF_{24}	$WRF_{2.7}$/WRF_8
Exp. Begin Time (UTC)	2009090600			2009090606	2009090600		
Version	Cy35h1.3	721	721	721	v3.2		
Horizon. resolution (km)	2.5	11	2.5	2.5	24	8	2.7
Vertical levels	60				45		
Projection	Lambert Conformal						
Nodes in x	400	438	406	406	200	196	211
Nodes in y	400	400	400	400	150	196	175
Coordinates (lon; lat)	28.8;41.0	−19.9S, −22.0W, 20N, 21.7E	−4.39S, −4.46W, 4.39N, 4.46E		ref_lat = 45.00, ref_lon = 20.00, truelat1 = 35.0, truelat2 = 50.0, stand_lon = 30.0		
Coordinates of South pole		−50.0;30	−49.0;28.8	−49.0;28.8	-	-	-
Time step fc (s)	60	360	80	80	50	20	15
Time step lower res. DA, (s)	-	1800	396	396	-	-	-
Dynamics	Non-hydrostatic	Hydrostatic			Non-hydrostatic		
Physics	Arome	Hirlam			Kain-Fritsch, WSM6class		
Surface	Surfex	ISBA	ISBA	ISBA	NOAH LSM		
Forecast length, (h)	24	48	24	24	96		
Analysis	3DVAR	4DVAR			ECMWF		
Boundaries	ECMWF	ECMWF	ECMWF	HL_{11}	ECMWF	WRF24	WRF8

3. Heavy Rain Case

3.1. Synoptic Situation

On 6 September 2009, a low pressure system was centered over the Baltic Sea with a long north-to-south-oriented frontal zone affecting Northern and Eastern Europe (Figure 4). The edge of the cold front was related to the system approaching the western part of the Black Sea, while inland areas of Europe were under the effect of a strong high pressure center. As this strong high pressure system moved eastwards on 7 September 2009, the frontal zone was stretched out, reaching the northwestern Marmara Region. On 8 September 2009, the front became quasi-stationary, with a relatively strong northeasterly flow over the region and fractured afterwards on 9 September 2009, favoring severe convective storm environments remaining in the area of interest until 10 September 2009. It seems that heavy precipitation areas observed and simulated in this flash flood event are associated with wind patterns as the cloud band moves eastwards. In Figure 5, the formation of the cut-off low at 500 hPa over the area due to the fracture of the stretched front by anticyclonic forcing could be seen. The evolution of this pattern resulted in a semi-persistent gradient of 500–1000 hPa thickness over the Marmara Region. There was a northeasterly low level jet at 850 hPa reaching 18 m/s over Istanbul on 7–8 September 2009, transporting moisture from the western part of the Black Sea. Cold air aloft and moist air near the surface center favored training storms over the study area, triggered by previous convection outflows, the front and topography. After 9 September 2009, the system lost its strength and dissipated while moving eastwards.

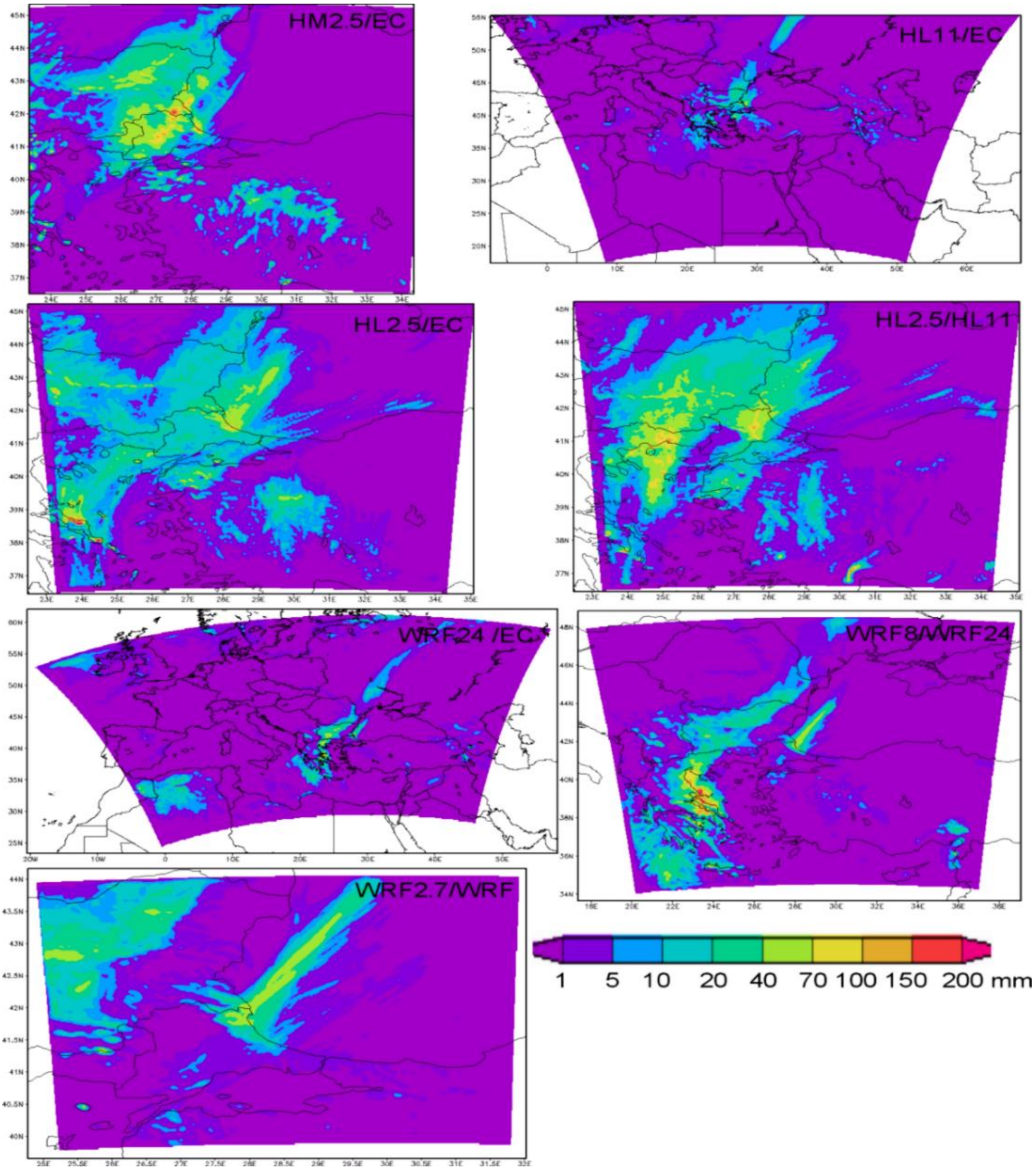

Figure 3. *Domains of all models. Accumulated 0–24-hour precipitation forecast from 00 UTC 7 September–00 UTC 08 September. The plotted area shows: (**a**) HARMONIE HM2.5/EC, (**b**) HIRLAM HL11/EC, (**c**)HIRLAM HL2.5/EC, (**d**) HIRLAM HL2.5/HL11, (**e**) WRF24, (**f**) WRF8, (**g**) WRF2.7.*

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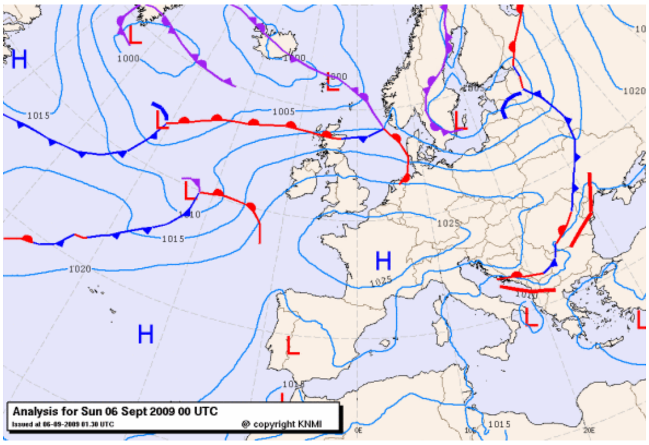

Figure 4. *Weather chart showing the surface analysis for 00 UTC 6 September 2009 based on the operational HIRLAM analysis (courtesy: KNMI operational service).*

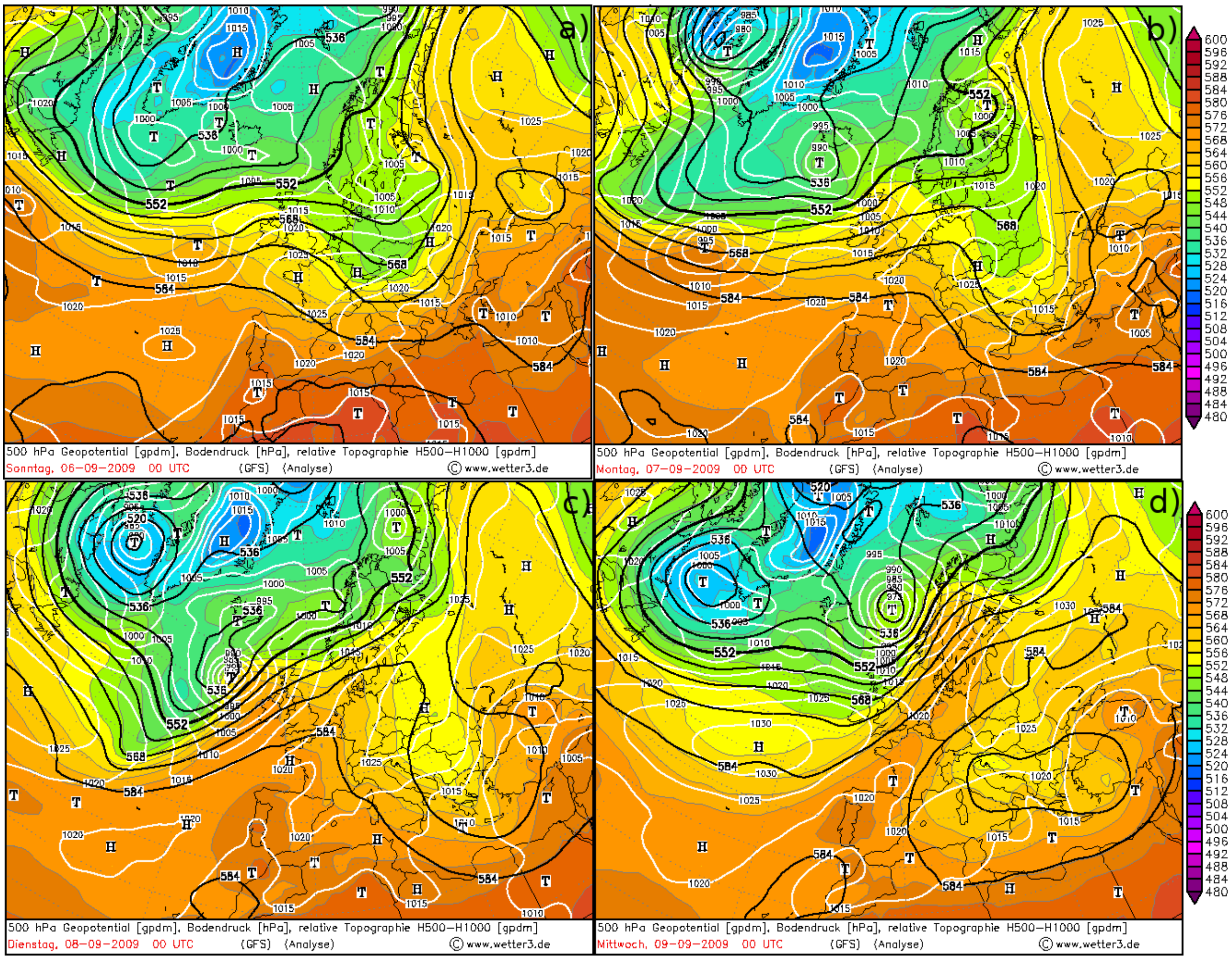

Figure 5. *Mean sea level pressure, 500 hPa geopotential height and 1000–500 hPa thickness analysis of the GFS model between 6 and 9 September 2009 (retrieved from wetter3.de, 2010).*

3.2. Observations

On 8 September, within a span of a few hours, the western parts of Istanbul received exceptionally large amounts of precipitation, with Çatalca, located around 150 km northwest of central Istanbul, recording over 204 mm of precipitation for 8 September. Heavy precipitation of 65 mm was observed at Kamiloba, located on the coast around 60 km southwest of the city center. Sarıyer, located west of the Bosphorus, received 65 mm of precipitation. However, Şile, on the north coast of Asian Istanbul, received less than 3 mm.

On 9 September, heavy precipitation of 175 mm was observed at Olimpiyat, located on the coast around 5 km northwest of the Basın Express highway, which connects two main highways to one another and the most important road leading to Turkey's biggest airport.

Hourly precipitation data from the 28 stations is given in Figure 1. The precipitation in the region in two days was around 83 mm on average, which is about 13% of the mean annual total precipitation, while in Çatalca, it was 240 mm, more than one third of the annual total. (see Table 1).

4. Results and Discussion

Due to some modelling constraints, accurate prediction of precipitation, in terms of both location and amount, is a challenging issue for numerical weather prediction. Primary sources of precipitation forecast errors in complex terrain are the spatial resolution of simulations, model initialization errors, representation of physical processes in clouds and the representation of land use characteristics of the domain in the models. Verification of the predicted precipitation is also a problematic issue, especially for this kind of convective heavy precipitation event, due to the extreme heterogeneity of their spatial distribution and the limited number of available observations; considering the limitation of grid point verification for this kind of convective event, and considering the limitation of Grid 156 point verification for these 157 convective events of this type.

4.1. Discussion for 8 September 2009

The front and the cloud band on 0600 UTC 8 September 2009 can be seen in Figure 6a,b. Daily precipitation observations from stations indicate that the spatial distribution of precipitation is quite inhomogeneous over the study area. On 0600 UTC 8 September 2009, 204 mm of precipitation are observed in Çatalca, in the northern part of western Istanbul, and 3 mm are observed in Şile, on the Black Sea coast of eastern Istanbul, approximately 100 km away from Çatalca (Figure 6d). Gönen and Bandırma in the southern part of the Marmara Sea also observed more than 100 mm of precipitation, demonstrating the low level propagation of the storms with a northeasterly origin. The southern coast of Istanbul, as well as the Bosphorus received around 40 mm of daily precipitation, with values ranging between 7 mm and 65 mm. The flash flood of 8 September 2009 occurred around Silivri, shown in Figure 6d, with precipitation observations of 65 mm to the east (Kamiloba station) and 44 mm to the west (Çanta station). The peak of 204 mm of precipitation is observed at the Çatalca radar site, which has an elevation of 378 m and is approximately 25 km north of Silivri. An image of the daily precipitation amount derived from the Istanbul radar is given in Figure 6c. Compared with the station observations, it is clear that these derived estimates are far below the real precipitation. However, the overall pattern of the precipitation distribution is quite well matched. According to the radar-derived daily precipitation estimate, the highest amount of rainfall is observed in the northern part of western Istanbul. Precipitation in Terkos (49 mm, without data between 0800 and 2300) might be as high as Çatalca, as well as the area between them. The daily peak in the radar image extends to the middle of the peninsula, southeastwards of Çatalca, but there is no station around that region.

In general, the model outputs do not represent the highest amount of precipitation observations. With its 2.5-km grid-size, HARMONIE is the model that has the highest precipitation peaks, reaching 200 mm in the region (Figure 6e). However, the spatial distribution of precipitation is quite different from the observations. According to HARMONIE, the maxima are around downtown Istanbul and the western part of Bandırma. The HIRLAM model, with an 11-km grid-size, has a better spatial distribution of the daily precipitation, but the amount near northwestern Istanbul reaches 40–70 mm (Figure 6f). The 2.5-km HIRLAM with ECMWF input shifts the precipitation farther north, though it gives similar amounts (Figure 6g). On the other hand, the same model with the same horizontal resolution, but with HIRLAM 11-km input depicts a very different distribution of precipitation, carrying most of the rainfall over the Marmara Sea and westwards (Figure 6h). Maximum precipitation amount is higher with this simulation. In general, HIRLAM forecasts the precipitation on the wind side of the hill range. In HARMONIE, on the other hand, advection of a number of hydrometeors enables water to be transported over the top of the hills, in particular if the water is in the form of snow.

Because the top of the hill range is usually the border of a catchment area, this property of being able to advect precipitation to the lee side is essential to predict proper rainfall amounts for flooding (Toros et al. 2010). Nevertheless, although the drag of precipitation in the HARMONIE forecast is considered to be a contributory factor in the shift in the precipitation peaks, this is probably not the only explanation for these patterns. Results from three WRF model runs with horizontal resolutions, ranging from 24 km (Figure 6i), 8 km (Figure 6j) to 2.7 km (Figure 6k), show that the overall distribution of daily precipitation over the domain is quite well estimated, with maxima around northwest Istanbul and southern Marmara. However, the amounts are less than the observations, varying with respect to horizontal resolution by 70–100 mm in the 24-km run and 100–150 mm in the 8-km and 2.7-km runs.

4.1. Discussion for 9 September 2009

Figure 7 shows the observations and model products, as in Figure 6, but for 0600 UTC 9 September 2009. The quasi-stationary front dissipates over the Marmara region (Figure 7a), and the cloud band is fractured (Figure 7b) on this day. The top of storms at 0600 UTC can be seen from the satellite image (Figure 7b). Precipitation observations for this day show a peak of 175 mm at Olimpiyat station, 144 mm at Bandırma station and 114 mm at Hadımköy station. The flash flood occurred around the İkitelli region, shown in Figure 7d. Radar precipitation estimates (Figure 7c) indicate that the highest precipitation is extending onshore on 9 September 2009, over the western part of the flooded catchment area. Radar estimations are again below the observation values.

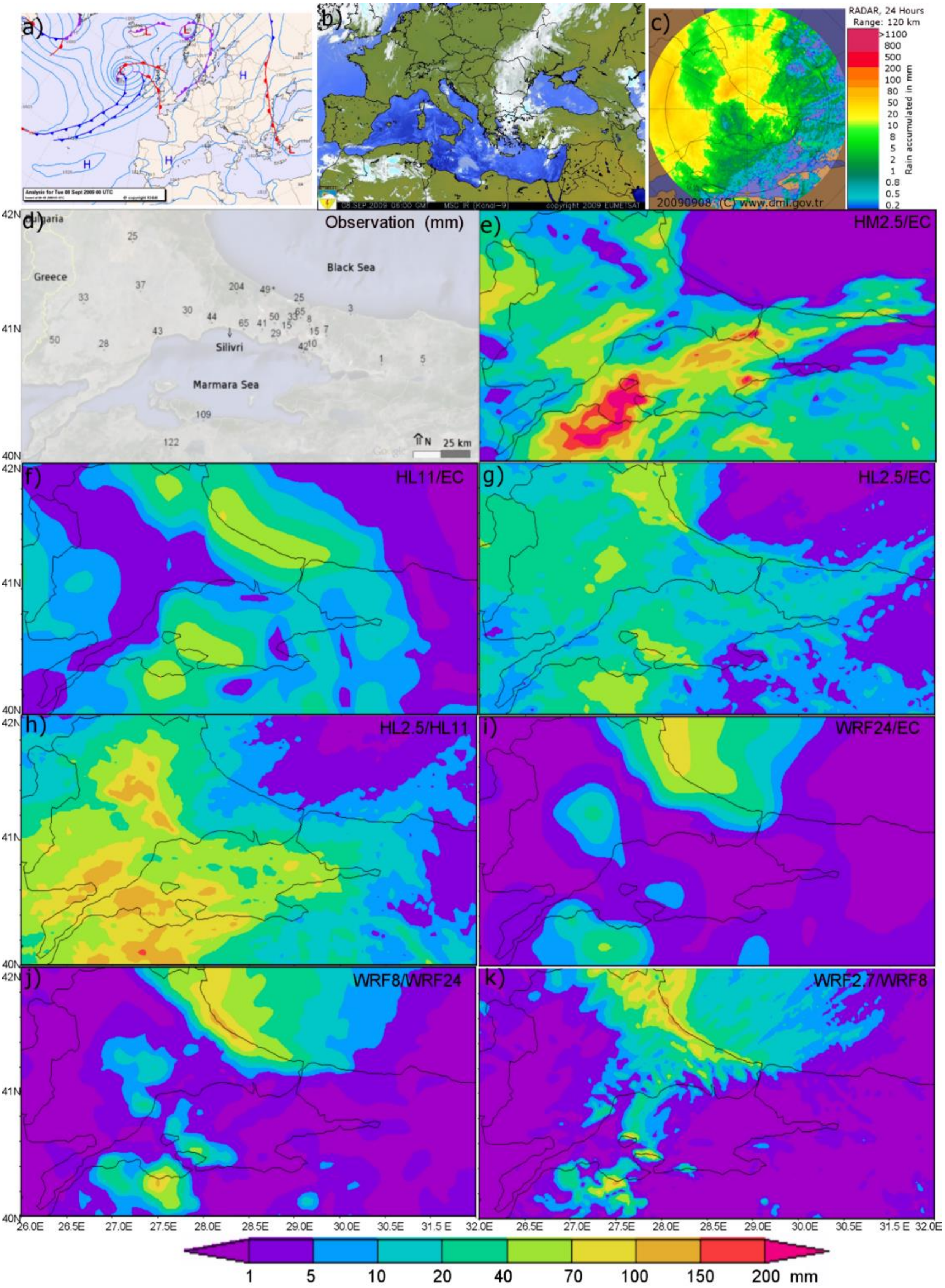

Figure 6. *The 24-hour rainfall totals (mm) in Istanbul and its surroundings on 8 September 2009 (**a**); Meteosat 9 MSG IR images (**b**); weather chart showing the surface analysis for 00 UTC 8 September 2009 based on the operational HIRLAM analysis (courtesy: KNMI operational service) (**c**); SLI_R radar images for every six hours (**d**); the 24-hour forecast from HARMONIE (**e**), HIRLAM HL11 (**f**), HL2.5/EC (**g**), HL2.5/HL11 (**h**), WRF (**i**,**k**). The * in (d) indicates that the Terkos site did not register any data from 08:00–23:00.*

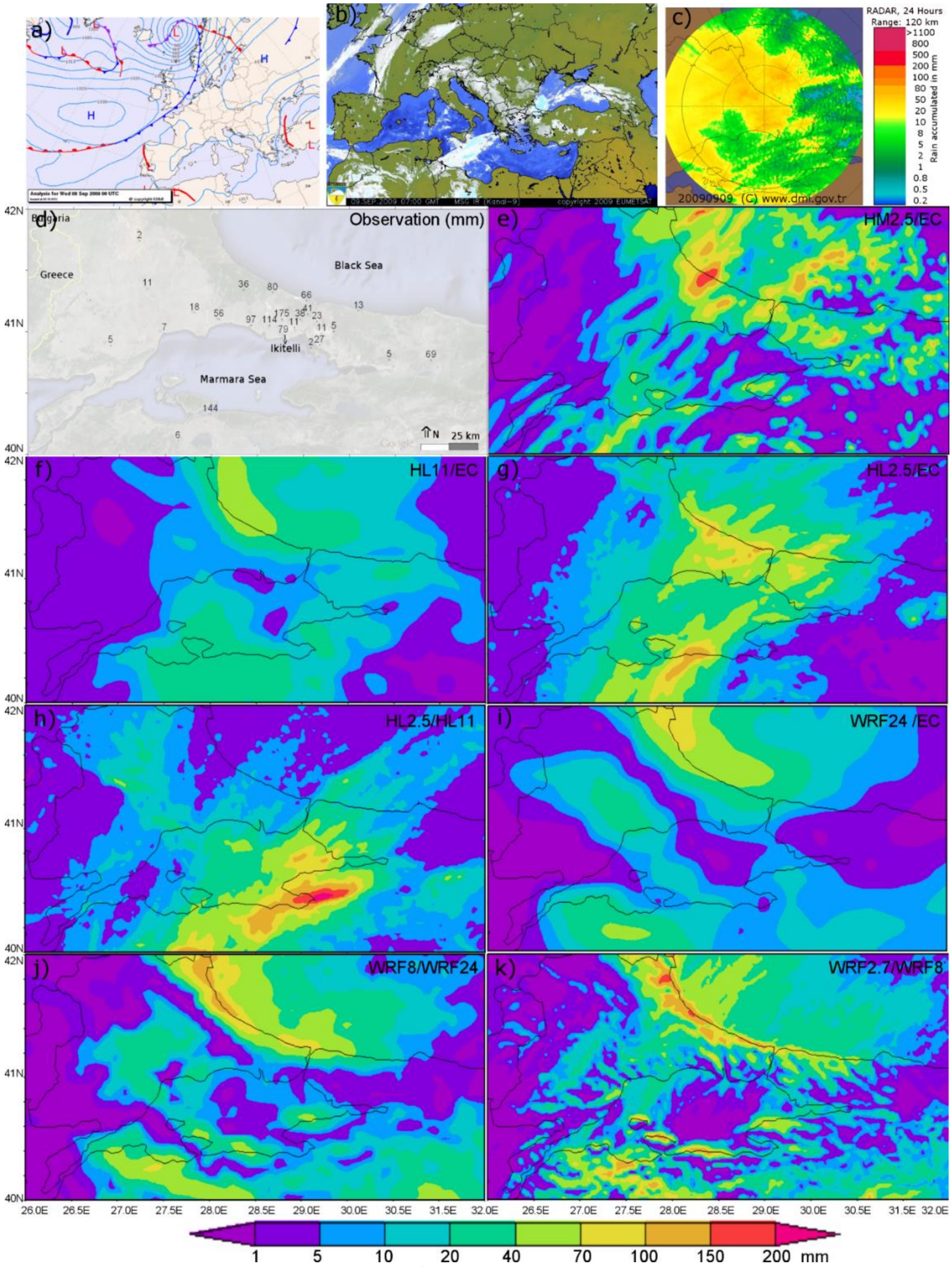

Figure 7. Weather charts as in Figure 6, but for 9 September 2009.

The HARMONIE forecast for 0600 UTC 9 September 2009 (Figure 7e) shows a good spatial distribution of precipitation compared to the radar estimation, with higher amounts over Istanbul and northwards and lesser amounts over the Marmara Sea. The overall high precipitation pattern has shifted a little east. The highest rainfall spots are over the Black Sea coast near Çatalca, exceeding 150 mm. The eastern part of Istanbul also has values up to 100–150 mm, which is not consistent with the radar estimation. Furthermore, the high amount of rain over Edirne and surroundings according to the radar estimation is not present in the HARMONIE forecast. The HIRLAM forecast with the 11-km grid-size (Figure 7f) simulates precipitation amounts that are far less than the observations, with a peak of 40–70 mm in 24 hours over the Black Sea coast. The overall precipitation pattern is acceptable, but still, the western part of the domain does not receive much rain according to the forecast in the HARMONIE case. The HIRLAM 2.5-km forecast with ECMWF input (Figure 7g) has a much higher amount of precipitation, as expected, but the locations of the precipitation maxima are scattered over the entire Istanbul area. It can be seen that the pattern is also further east than the radar estimation. The high precipitation spot to the east of Bandırma on this plot shows good agreement with the radar estimation and station observations. The simulation here represents 100–150 mm of rain, and the Bandırma observation shows 144 mm. On the other hand, the HIRLAM 2.5-km forecast with the HIRLAM 11-km input (Figure 7h) gives a different result. The maximum amount of precipitation on this plot is between 150 and 200 mm over Gemlik Bay. This region does not have high amounts of rain according to the radar estimation and other simulations.

WRF forecasts for the same day with 24-km (Figure 7i), 8-km (Figure 7j) and 2.7-km (Figure 7k) grid-sizes indicate a precipitation peak at the Black Sea coast, shifted slightly northwest compared to the radar estimation. The 24-km run has a peak of 70–100 mm; the 8-km run has a peak of 100–150 mm; and the 2.7-km run has a peak of 150–200 mm of precipitation near the coast. There is a contrast between the southern and northern coasts of Istanbul according to the analysis, and WRF probably underestimates the precipitation on the downwind side of the peninsula.

5. Concluding Remarks

Flash flood forecasting is still an ongoing issue for engineers and scientists. The goal of this study was to investigate how the HARMONIE, HIRLAM and WRF forecast excessive precipitation with an inhomogeneous spatial distribution. For this case, the flooded areas were in different locations on the two studied days. Therefore, the two days can be analyzed as two different events. The catchment areas for both events are quite small (some hundreds of square kilometers).

The 24-hour accumulated precipitation forecast by HIRLAM is quite high compared to the climatological data, but still far below the observed amounts and with a location error. This is explained by the model formulation causing the rain to fall vertically according to the result of some budget for the formulation to consider the way the precipitation falls down. Nevertheless, HIRLAM gives a clear signal that heavy precipitation in the area can be expected. However, interpretation of this signal by a human forecaster with respect to the possible amounts of the precipitation and the location is necessary.

HARMONIE, on the other hand, gives higher amounts, in particular in the catchment areas. Whether the amount and location are good enough to predict flooding should be investigated with a run-off model. WRF simulates a good spatial distribution of precipitation and precipitation amounts, but there is some location shift of the precipitation maxima. Furthermore, the WRF simulations are considered to underestimate downwind rainfall.

Although numerical models are still far from perfectly simulating small-scale precipitation variations, the models used were able to accurately produce excessive precipitation amounts, although with a considerable location error in this case study. Further tests regarding the precipitation rates and locations could be conducted on the use of sea surface temperature or microphysical, as well as convective parameterizations.

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