

EVALUATION OF NUMERICAL WEATHER PREDICTION MODELS FOR
FLASH FLOOD WARNINGS IN TURKEY

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ABSTRACT

EVALUATION OF NUMERICAL WEATHER PREDICTION MODELS FOR FLASH FLOOD WARNINGS IN TURKEY

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Flash floods are among the most destructive natural disasters in both Turkey and world that cause loss of life and property. In this study, monthly distribution of heavy rainfall events in the period of 2015-2019 is examined to show the frequency and distribution of flash floods associated with these heavy rainfall events in Turkey. The monthly distribution of lightning observations for the period of 2015 and 2019 is also studied to release the relationship between heavy rainfall events and lightning flashes during warm season.

Black Sea and Middle East Flash Flood Guidance System (BSMEFFGS) is used for flash floods warnings in Turkey. The system compares rainfall threshold values (Flash Flood Guidance, FFG) with basin-based rainfall estimates and predictions. ALARO, ECMWF and WRF numerical weather prediction (NWP) models provide rainfall predictions within the system. In this study, ten flash flood events resulted from different precipitation characteristics occurred between 2017 and 2019 in Turkey are determined to evaluate the NWP models. The success of the NWP models is measured with whether FFG threshold values were exceeded by rainfall predictions through these flash flood cases.

In this study, it is determined that heavy rainfall events often occur over interior parts of Turkey during warm season due to convective instability conditions especially in May and June. It is proven in this study that lightning observations have the potential to be used for nowcasting flash flood warnings because of similar distribution of heavy rainfall events and lightning flashes during warm season. It is derived from the flash flood case studies that the NWP models within the BSMEFFGS are successful in capturing the flash floods caused by non-convective heavy rainfalls, while the models up to some extent are capable for convective-induced events.

Keywords: Flash Flood, Flash Flood Guidance, Heavy Rainfall, Lightning and Numerical Weather Prediction Models.

ÖZ

TÜRKİYE'DE ANİ TAŞKIN UYARILARI İÇİN SAYISAL HAVA TAHMİN MODELLERİNİN DEĞERLENDİRİLMESİ

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Ani taşkınlar, hem Türkiye’de hem de tüm dünyada ciddi can ve mal kayıplarına yol açan en önemli doğal afetler arasındadır. Bu çalışmada, öncelikle ani taşkınların ülkemizdeki sıklığını ve dağılımını göstermek için şiddetli yağışların 2015-2019 arasındaki dönem içerisinde aylık dağılımları incelenmiştir. Yaz ve bahar aylarındaki şiddetli yağışlarla şimşekler arasındaki ilişkiden dolayı, 2015-2019 arasındaki dönem için şimşek gözlemlerinin aylık dağılımı incelenmiştir.

Karadeniz ve Orta Doğu Ani Taşkın Erken Uyarı Sistemi (BSMEFFGS), Türkiye'deki ani taşkın uyarıları için kullanılmaktadır. Sistem içerisinde yağış eşik değerleri (FFG) havza bazlı yağış hesaplamaları ve tahminleriyle karşılaştırır. ALARO, ECMWF ve WRF sayısal hava tahmini (SHT) modelleri sisteme yağış tahminlerini sağlar. Bu çalışmada, ani taşkın uyarıları için kullanılan SHT modellerini değerlendirmek için Türkiye’de 2017-2019 arasında gerçekleşen, farklı yağış karakter kaynaklı, on adet ani taşkın hadisesi seçilmiştir. SHT modellerinin başarısının ölçütü olarak, ani taşkın vaka çalışmalarında hadisenin gerçekleştiği yerdeki havzada FFG eşik değerlerinin aşılp aşılmasına bakılmıştır.

Bu alıřma kapsamında, řiddetli yaęıřların en fazla konvektif kararsızlık nedeniyle Türkiye'nin i kesimlerinde bahar ve yaz aylarında, zellikle Mayıs ve Haziran, gerekleřtięi belirlenmiřtir. Bahar ve yaz aylarındaki řiddetli yaęıř ve řimřek gzlemlerinin benzer daęılım gstermesi sebebiyle řimřek gzlemlerinin anlık ani tařkın uyarıları iin kullanım potansiyeli olduęu tespit edilmiřtir. rnek ani tařkın vaka alıřmalarında, BSMEFFG sistemi ierisindeki SHT modellerinin konvektif kaynaklı olmayan řiddetli yaęıřların neden olduęu ani tařkınları yakalamada bařarılı olduęu grlrken konvektif kaynaklı hadiselerde kısmen bařarı gsterebildikleri grlmřtir.

Anahtar Kelimeler: Ani Tařkın, Ani Tařkın Erken Uyarı, řiddetli Yaęıř, řimřek ve Sayısal Hava Tahmin Modelleri.



To My Wife...

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LIST OF ABBREVIATIONS

ABBREVIATIONS

ALADIN: Aire Limitée Adaptation dynamique Développement InterNational

ALARO: Meso-scale NWP Model from Météo-France

AROME: Micro-scale NWP Model from Météo-France

ARPEGE: Action de Recherché Petite Echelle Grande Echelle

ASM: Average Soil Moisture

BSMEFFGS: Black Sea and Middle East Flash Flood Guidance System

CMORPH: The Climate Prediction Center Morphing Method

ECMWF: European Centre for Medium-Range Weather Forecasts

FFG: Flash Flood Guidance

FFGS: Flash Flood Guidance System

FFT: Flash Flood Threat

FMAP: Forecast Mean Areal Precipitation

HRC: Hydrologic Research Center

IFFT: Imminent Flash Flood Threat

IMS: Interactive Multisensor Snow and Ice Mapping System

LDNS: Lightning Detection Network System

MAP: Mean Areal Precipitation

MELT: Snow Melt

NAO: North Atlantic Oscillation

NCDC: NOAA National Climatic Data Center

NOAA: National Oceanic and Atmospheric Administration

NOAA-NESDIS: National Environmental Satellite, Data, and Information Service

NWP: Numerical Weather Prediction

NWS: U.S. National Weather Service

PFFT: Persistence Flash Flood Threat

QGIS: Quantum Geographic Information System

QPE: Quantitative Precipitation Estimation

QPF: Quantitative Precipitation Forecast

R: The R Project for Statistical Computing

SAC-SMA: Sacramento Soil Moisture Accounting Model

SCA: Snow Cover Area

SEFFGS: South East Europe Flash Flood Guidance System

SNOW-17: Snow Accumulation and Ablation Model

SWE: Snow Water Equivalent

TSMS: Turkish State Meteorological Service

USAID: U.S. Foreign Disaster Assistance

USGS: U.S. Geological Survey

WMO: World Meteorological Organization

WRF: Weather Research and Forecasting

CHAPTER 1

INTRODUCTION

1.1 Background

Flash flood defined as a rapid rise of water or extreme flow in a relatively small basin usually occurs within minutes to a few hours (less than six hours) as a result of mostly intense rainfall or release of impounded water (NOAA, 2019). Among several flood types such as coastal, river, urban and flash flood, flash and river floods are basic types, while the first generally cause greater loss of life the latter generally cause greater loss of property (USGS, 2020). Flash floods are among the deadliest natural disasters with significant socio-economic impacts and represented with the highest mortality rate (defined as the number of deaths per number of people affected) among the flood types (Jonkman, 2005). Flash flood is one of the most widespread disasters in Turkey and frequently triggered by severe downpour. In recent years, numerous devastating flash floods occurred with high rate casualties. For instance, during September 2009 and August 2015, 32 and 11 people are killed by flash floods in Istanbul (Kömüşçü and Çelik, 2013) and Artvin (Baltacı, 2017) provinces respectively.

The methods for flood damage mitigation can be divided into two namely, structural and nonstructural flood controls. Structural methods usually become expensive precautions while operational flood warning systems are used commonly as a non-structural method. River floods can be forecasted using a river hydraulic model at the downstream of a large basin once upstream flow data is available (Hossain and Katiyar, 2006). The monitoring the observed flow at upstream of a river basin is commonly used within river flooding forecast systems. For instance,

General Directorate of State Hydraulic Works (DSI in Turkish acronym) established an operational system in Ergene Basin through which river flows are monitored and forecasted in real time manner (Erkal and Topgul, 2015). The lag time between rainfall and runoff in a river basin increases with the size of the basin. However, response time is quite short for flash floods. Hence, dependable and suitable flash flood forecasting methods are necessary within the context of flash flood warnings.

National Weather Service (NWS) is responsible for providing flash flood warnings in the United States. In the early 1970s, NWS began producing flash flood guidance (FFG) values to support flash flood warning issuance mission (Schmidt et al., 2007). Sweeney (1992) described the FFG as necessary rainfall volume over a relatively small watershed during a specified period of time to cause flash flood occurrence. As stated by Carpenter et al. (1999), “the basis of FFG is the computation of threshold runoff values, or the amount of effective rainfall of a given duration that is necessary to cause minor flooding”.

The FFG method has been started to use more frequently after the decision of World Meteorological Organization (WMO, 2007) that aims to enhance capacity of effective flash flood warnings issuance globally. Therefore, Flash Flood Guidance System (FFGS) project was initiated worldwide under the leadership of WMO by implementing regional operational systems. The Black Sea and Middle East Flash Flood Guidance System (BSMEFFGS) was established as part of this concept. Turkish State Meteorological Service (TSMS) has been serving as a regional center of the system since 2012 to support flash flood warnings in Turkey and member countries by providing FFG system products.

In the FFG systems, the main idea of estimating sub-basin based threshold values relies on comparison between observed and predicted rainfall for nowcasting and forecasting flash floods (Georgakakos, 2006). The threat of flash flood should be considered if the quantitative precipitation estimation (QPE) or quantitative precipitation forecast (QPF) is greater than the threshold rainfall value (FFG).

Thus, performance of the system depends on both FFG values and precipitation estimations/predictions. Several performance evaluation studies for FFG calculations have been done in various regions over the world (Carpenter et al., 1999; Georgakakos, 2006; Ntelekos et al., 2006; Schmidt et al., 2007; Gourley et al., 2012). In addition, QPE evaluation using radar or satellite (Scofield and Kuligowski, 2003; Yücel et al., 2011; Nikolopoulos et al., 2013; Modrick et al., 2017; Herman and Schumacher, 2018; Özkaya and Akyürek, 2019; Cho and Kurdzo, 2020) and QPF evaluation with different numerical weather prediction models (Vincendon et al., 2011; Yücel et al., 2015[a]; Silvestro et al., 2019; Erickson et al., 2019) are also available in the literature. Numerical weather prediction (NWP) models are used to predict weather conditions by simulating the atmosphere, oceans, land surface and their interactions. TSMS provides NWP model rainfall predictions for using flash flood warnings within the BSMEFFGS.

In Turkey, precipitation mostly in the cold season results from synoptic scale air systems such as deep cyclones but orographic rainfall events initiated by geographic obstacles like mountains can occur during entire year. However, precipitation during the warm season is often guided by meso/small-scale convective processes. Several studies related with flash floods stated (Borga et al., 2011; Gaume et al., 2009; Barredo, 2007) that the intense rainfall events in the Mediterranean area frequently occur in fall season while events in the inland continental region commonly occur in summer. The predictability of intense rainfall-induced flash flood disasters is influenced by the seasonality of extreme precipitation occurrences.

In a nutshell, flash floods are generally resulted from intense rainfall with very short duration events (less than 6 hour) in the relatively small watersheds. Heavy rainfall events occur over Mediterranean areas where non-convective (frontal/cyclonic/orographic) weather systems during cold season are common. Furthermore, convective weather conditions are effective over hot and warm surfaces of coastal and inland areas of continental regions under humid environmental conditions during warm season.

1.2 Precipitation Characteristics of Turkey

Flash floods take place usually as a result of heavy or short term intensity precipitation in Turkey so that understanding of precipitation formation becomes essential. The first condition for precipitation occurrence is to see ordinarily cloud development in the atmosphere. Clouds mostly form as air parcel ascent, cools, and condense. A lifting mechanism which can be through convection, orography, convergence by low pressure and weather fronts is required to move air parcel upward (Ahrens, 2007). Cloud is not adequate always for precipitation process therefore there are a few theories that happen inside of the cloud and help growing cloud droplets through collision-coalescence and ice-crystal process. The ice crystal process is also known as the Bergeron-Findeisen process, after the meteorologists Tor Bergeron and Walter Findeisen, who suggested and further developed that all raindrops originate from ice crystals and liquid rain droplets (Bergeron, 1935; Findeisen, 1938). However, precipitation type can be classified as convective and non-convective (orographic and cyclonic, frontal) which are effective in different seasons and regions depend on climatic and meteorological conditions.

Arid (B), temperate (C), cold (D), and polar (E) climate conditions are mostly dominant around Central Anatolia, coastal areas, East of Anatolia and small part of north eastern Turkey respectively. Minor climate classes change quickly due to special conditions of Turkey such as distribution of land and water, topography with altitudes, existence of dynamic pressure systems (Icelandic, Siberian and Azores), shifting Hadley Cell and North Atlantic Oscillation (NAO) elements.

Turkey is located mainly in the sub-tropical zone between the humid mid-latitude zone and dry/hot tropical zone. The climate in Turkey is strongly influenced by the coupled dynamic and thermal pressure systems that occur over Iceland (low), Azores (high) and Siberian (high) (see Figure 1.1).

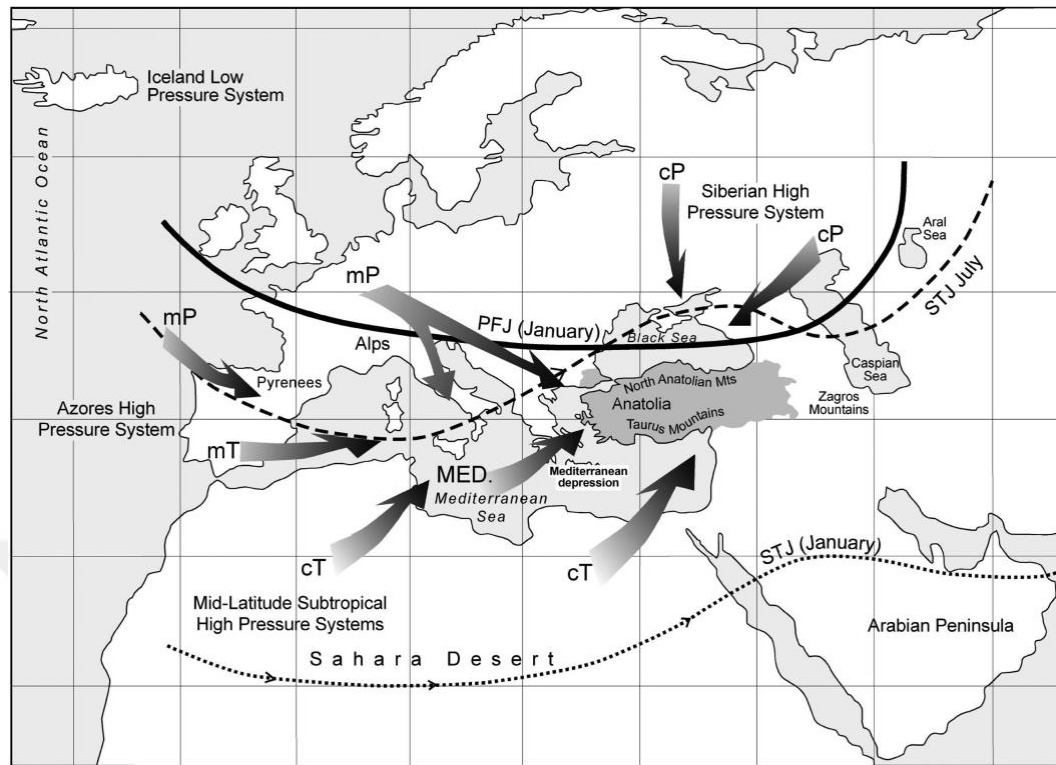


Figure 1.1 Schematic diagram of air masses influencing winter and summer climate of the eastern Mediterranean region (Sarış et al., 2007).

In generally, Icelandic and Mediterranean based low pressure cyclones are effective during winters but Azores high pressure systems become more effective during summers over Mediterranean coast of Turkey. Mediterranean depressions (low) control climate of Turkey during winter. These low pressure cyclones cause frontal systems which bring steady and heavy rainfall during winter and autumn seasons.

In Central Anatolia, less rainfall occur than coastal region because of continental effects and less moisture. Icelandic Low and Siberian High pressure systems are effective over this region in a way that low pressure systems bring snow and high pressure systems cause cold, misty and cloudless weather conditions during winter months. On the other hand, during summer convective instability conditions may cause short and intensity downpour.

In East of Anatolia, the altitudes change between 2000 and 2200 meters. During spring and summer season convective and orographic systems may cause extreme rainfall due to overheated surface air and height. In this region, Siberian high pressure systems support the cold and snowy weather conditions once it mixed with humid based frontal systems over high topography. Since snowfall is the main water source of this region rapid snow melting is one of the flood reasons in the beginning of spring.

According to Sariş et al. (2007), cP air mass causes orographic rains if it becomes saturated while crosses the Black Sea while mP air mass causes rainfall in coastal areas (Black Sea and Marmara) and snowfall at higher elevations which originates from the Atlantic Ocean and travels across Balkans.

Annual long term (normal) areal average rainfall is 574 mm across the Turkey for the period of 1981–2010 (TSMS, 2019[a]). On the other hand, this average rainfall disperses not homogeneously since precipitation shows great variability in timing, intensity and localization. In general, coastal regions are wetter than the interior parts of Turkey, especially eastern Black Sea coasts.

Western Turkey, located in the eastern Mediterranean extending between 26° and 38° E, is a region where plenty of cyclonic (low pressure area) precipitation occurs because of its geographic and topographic conditions. The cyclonic systems with heavy rainfall are more common between autumn and winter seasons for Mediterranean coast of Anatolia. The density of cyclonic systems shows inter-monthly variations over eastern Mediterranean, maximum in January and minimum in July. The track of cyclonic frequency decreases after May and tends to increase in October (Flocas et al., 2010).

Convective rainfall events are more common over inland parts of Turkey due to convenient instability conditions. According to a recent study which investigates severe convective environment of Turkey (Kahraman et al., 2017); complicated topography is suitable for creating local severe storm environments by modifying low-level winds and severe hail is widespread for interior parts of Turkey.

However, Mediterranean rainfall regime shows an important decreasing trend but summer rainfall regime has a significant increasing trend for continental Mediterranean and central Anatolia regions of Turkey in last several decades (Türkeş et al., 2009). On the other hand, Black Sea region is the wettest area of Turkey. The mountains facing north on the eastern Black Sea coasts receive excessive amount of precipitation due to their coastal formation and orographic lifting (Kadioglu, 2000). In this way, flash flood and landslide events occur very frequently in Black Sea coastal parts due to heavy rainfall which causes considerable loss of life and property.

Climate change is one of the most major environmental concerns facing humanity in the twenty-first century. Climate change does not mean only warmer weather or melting polar glaciers, it also causes increasing frequency of extreme heavy precipitation in the 21st century (Beniston et al., 2007). Many studies show that average temperature is increasing not only globally but also regionally due to the climate change. In Turkey, the warming from 1960s or 1970s to the 2000s is close to 1.5°C (Şen, 2019). According to Demircan et al. (2017), the average annual temperature rising for the period of 2016-2099 in Turkey is expected to vary between 1°C and 5°C.

Figure 1.2, 1.3 and 1.4 indicate annual average temperature anomalies, total rainfall anomalies and heavy rainfall events in Turkey for the period of 1961-2019, 1981-2019 and 1940-2019 respectively. The annual temperature and rainfall anomaly graphs are published in “Climate Assessment for 2019” document by TSMS (2019[a]). The annual heavy rainfall events plot is prepared by TSMS and published in “Meteorological Disasters in 2019” (TSMS, 2019[b]). The data of graphs was taken from involved TSMS divisions and plotted over again with R scripts in the scope of this study. The anomaly is calculated as the average for the present year minus the average for the long term period (1981-2010). The long term (normal) temperature average is 13.5°C for Turkey. In recent years near-surface temperature of Turkey has been increasing significantly as shown in the anomaly plot (Figure 1.2).

Figure 1.3 indicates anomaly of annual total precipitation in percentage between 1981 and 2019 for Turkey. In this figure, year to year variability appears while the year 2008 is direst with twenty two percent decreases and the year 2009 is the wettest with twenty five percent increases. On the other hand, flood occurrence is not only related with the amount of precipitation but also precipitation intensity, soil properties and socioeconomic factors are critical.

In Turkey, severe-weather/extreme-event reports are issued by local TSMS meteorological offices for the purpose of their own internal usage. These records are performed by local observers of TSMS who generate them not just for heavy rainfall events but also for other extreme meteorological events such as heavy snowfall, heat wave, hail, thunderstorm etc. However, there is no specific flash flood record in Turkey. Thus, heavy rainfall observations are used in place of flash floods in this study since heavy rainfalls often result in flooding.

Globally, economic losses due to floods exceeded 19 billion \$ in 2012 and it is obvious that damages are rising exponentially (Ward et al., 2013). The frequencies of heavy rainfall events have indeed increased in Turkey for last two decades remarkably (Figure 1.4). This increasing of extreme rainfall events shows that damages caused by floods are increasing in Turkey too.

The predictability of intense rainfall-induced flash flood disasters is influenced by the seasonality of extreme precipitation occurrences. Rapid snow melt is another case for flash flood occurrence at the beginning of warm season. Borga et al. (2011) refer the seasonality effect on the occurrence of flash flood events. They stated that the events in the Mediterranean area frequently occur in fall season while events in the inland continental region commonly occur in summer. In relation to different climatic variability, the spatial extent and duration of the flash floods for the inland area are ordinarily smaller than those in the Mediterranean area. Under these circumstances, heavy rainfall events over Mediterranean and inland continental regions are associated with non-convective and convective weather conditions as one of the most efficient reason of flash flood occurrence.

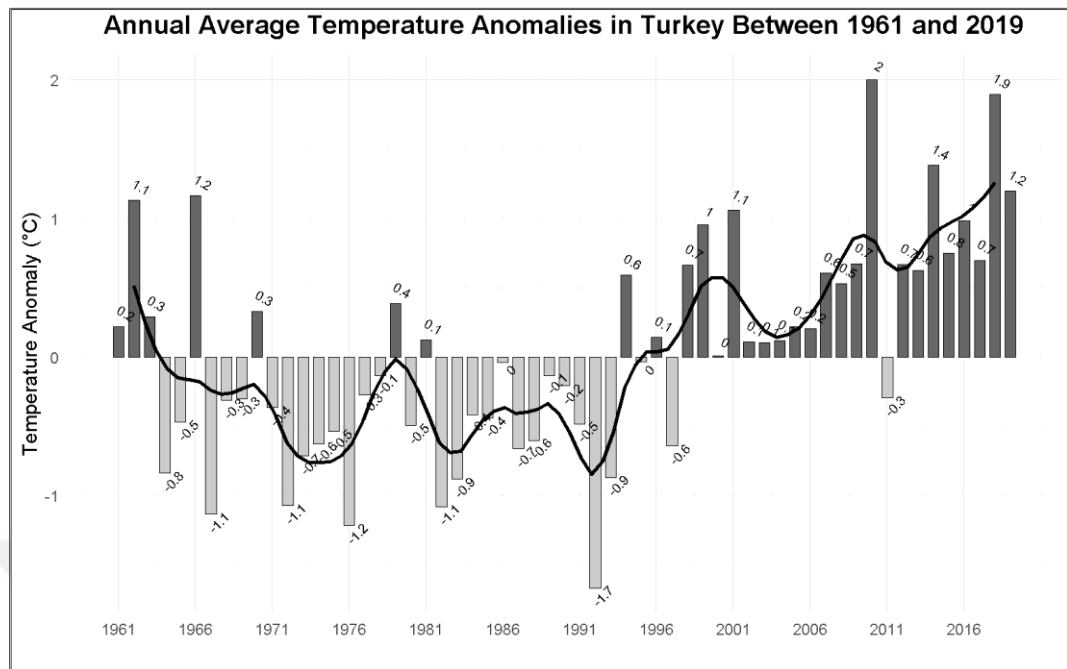


Figure 1.2 Annual average temperature anomalies in Turkey (TSMS, 2019 [a]).

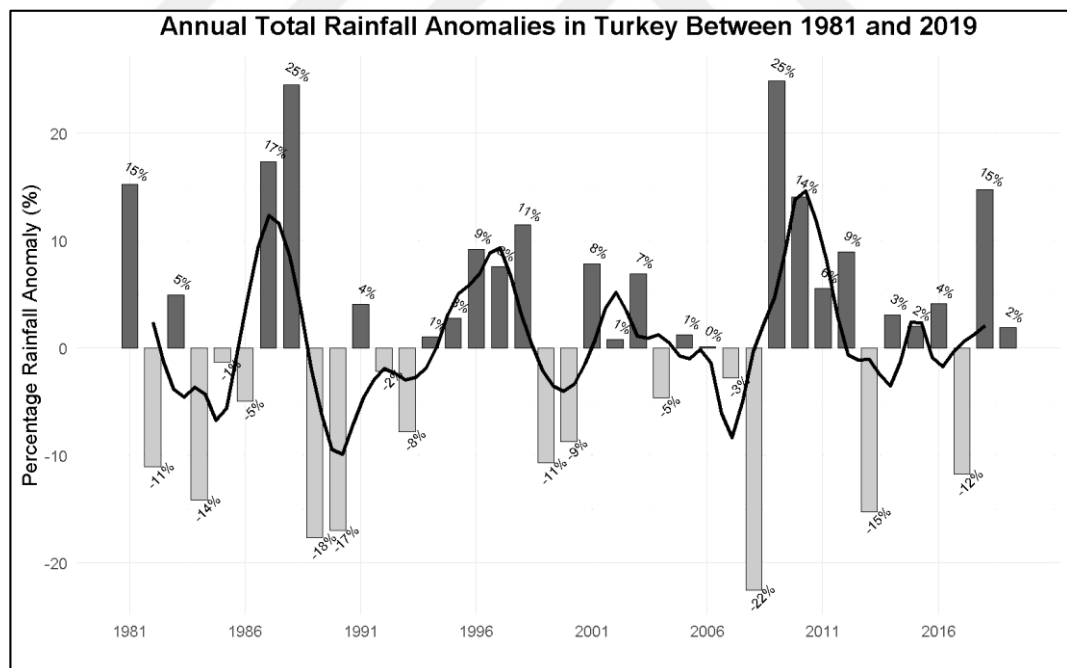


Figure 1.3 Annual total rainfall anomalies in Turkey (TSMS, 2019[a]).

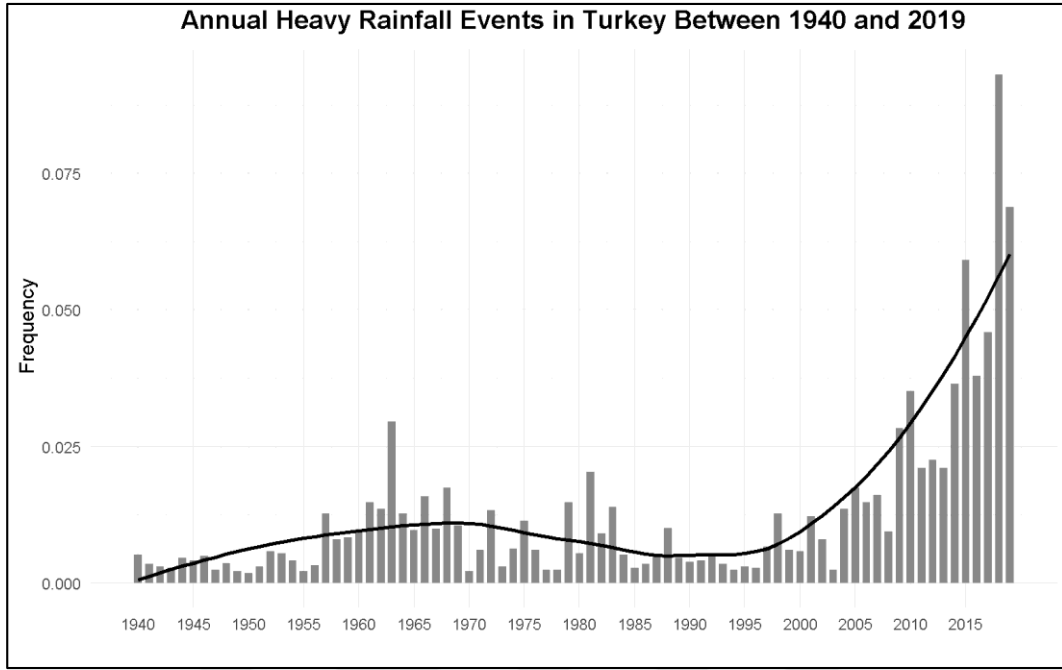


Figure 1.4 Annual heavy rainfall events in Turkey (TSMS, 2019[b]).

1.3 Problem Statement

Issuing the reliable warning with the use of operational BSMEFFG system depends on many factors that are basin geometry, snow melting, soil moisture accounting, FFG calculation and the accuracy of the spatiotemporal QPE and QPF. Satellite- and radar-based precipitation systems provide data at the lead time less than 1 hour. However, the NWP models are the only sources provide precipitation outputs at much longer lead times. Therefore, the utilization of NWP outputs (QPF) in issuing the warning for possible flood/flash flood events is crucial. However, these models have also many limitations in precipitation forecast because the accuracy of the outputs from these models relies on initial and boundary data, the solutions of the number of appropriate model physics, and dynamics. On the other hand the systems originated from a convective structure triggered over complex topographical terrain make the model simulations more challenging. BSMEFFGS uses operational products of QPF from three different NWP models namely;

ALARO, ECMWF and WRF over Turkey. Comprehensive comparison among these three models in issuing the flash flood warning from BSMEFFGS for different rainfall systems is missing.

According to NWS, overall threat scores in terms of QPF have increased consistently over the past 50 years but the majority of this improvement was for the cold season with fewer achievements during the warm season (Barthold et al., 2015). Therefore, different approaches are necessary for precipitation forecast during warm season in terms of flash flood warnings.

Additionally, verification of the FFG systems and evaluation of their products are lacking in spite of its worldwide prevalence for flash flood warning such as in the U.S., Asia, and Europe (Gourley et al., 2012). Thus, it is important to evaluate the NWP models and BSMEFFGS products to increase the performance of the system further. It is also necessary to include added values of supportive tools (satellite, radar and gauge based precipitation) besides the NWP models for more reliable flash flood warnings.

1.4 Scope of the Study

The aim of this study is to test and evaluate the success of precipitation forecasts from three different NWP models applied for different weather system signatures for promoting the flash flood warnings in the BSMEFFGS. In the evaluation, the NWP model predictions averaged over each sub-basin within the system are compared with updated FFG values (rainfall threshold) acquired from a soil moisture accounting model available in the system.

In this study, the spatial and temporal distributions of extreme rainfall events is also prepared to show the occurrence of flash floods resulted from heavy rainfall throughout Turkey between the years 2015 and 2019. As a supporting data, the distribution of lightning flashes for the same period is also assessed because severe

weather conditions such as thunderstorms, heavy rainfall and hail factors are highly related with lightning strikes.

Since the success of the system depends on accuracy of NWP model outputs besides FFG values, three different model (ALARO, ECMWF and WRF) outputs have been evaluated with different case studies in this thesis. For the evaluation, ten flash flood events occurred at different locations and seasons across Turkey between 2017 and 2019 are selected. The criterion of selecting flash flood case studies is determined as heavy rainfall induced by convective (four cases) or non-convective (five cases) weather conditions. There is also one extra case study to show importance of snow melting for flash flood occurrence.

This study consists of five chapters. Chapter 1 introduces the study, provides insights into precipitation characteristics of Turkey and describes the content of the thesis. Chapter 2 describes background of BSMEFFG system with its technical components and products. Chapter 3 presents data and methodology in the study. Chapter 4 provides the analyses and results including extreme rainfall events, distribution of lightning flashes and flash flood case studies in Turkey. Finally, Chapter 5 presents the conclusions and recommendations.

CHAPTER 2

BSMEFFG SYSTEM

At the Fifteenth Congress of the WMO in 2007, it was decided to enhance National Meteorological and Hydrological Services capacity to issue effective flash flood warnings and alerts (WMO, 2007). Therefore, a Memorandum of Understanding was signed in February 2009 among the World Meteorological Organization (WMO), the U.S. Agency for International Development/Office of U.S. Foreign Disaster Assistance (USAID), the U.S. National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS) and the Hydrologic Research Center (HRC) to work together under a cooperative initiative to implement the Flash Flood Guidance System (FFGS) worldwide.

The FFGS was designed and developed for interactive use of meteorological and hydrologic forecasters by HRC which is a non-profit public benefit corporation located in San Diego/USA and responsible for technical issues in the FFGS. A number of regional FFGS projects have been implemented, while others are under implementation, currently more than sixty countries are covered and serve more than two billion people worldwide (WMO, 2017). For instance, Black Sea and Middle East, South East Europe, Central America, Southern Africa, Central Asia South Asia and Southeast Asia FFGS are one of the systems among the regional FFGS projects (see Figure 2.1).

Flash Flood Guidance System (FFGS) with Global Coverage

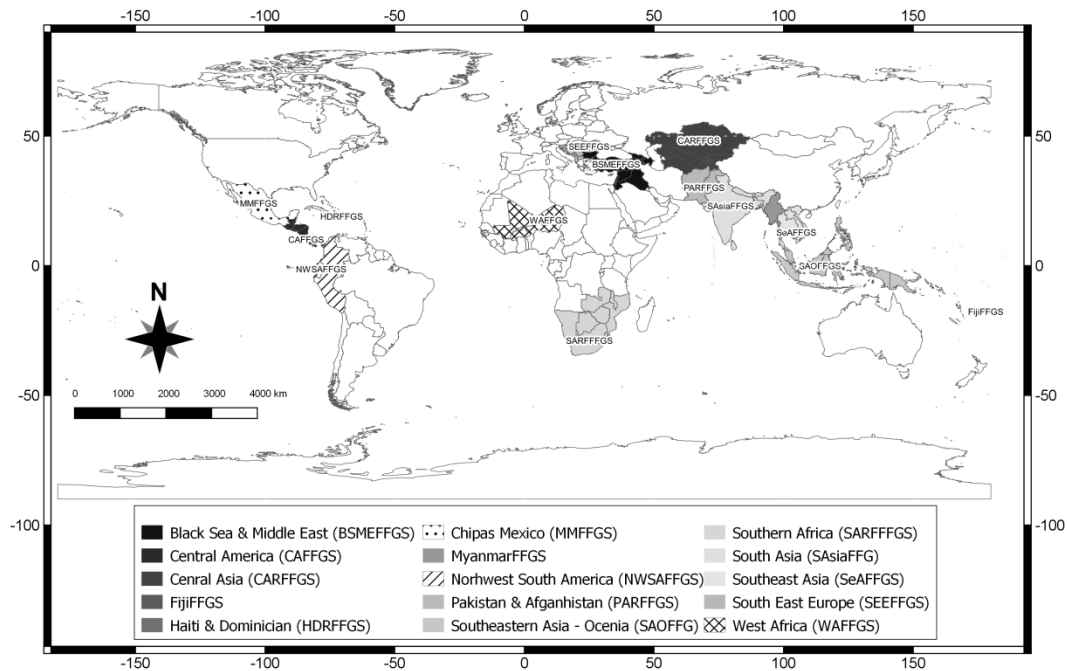


Figure 2.1 Flash Flood Guidance System with global coverage (adopted from WMO, 2017).

The Black Sea and Middle East FFG System (BSMEFFGS) was designed and developed as part of this concept with the implementation initiated in 2010. In the present, the system covers many countries such as Armenia, Azerbaijan, Bulgaria, Georgia, Iraq, Israel & Palestinian Authority, Jordan, Lebanon, Syria and Turkey (see Figure 2.2). Turkey is both the regional center of Black Sea and Middle East and South East Europe FFG Systems (SEEFFGS) and systems have been established in own servers of TSMS.

The implementation of the BSMEFFG system can be considered into three phases. First, spatial data such as digital elevation model, soil, vegetation cover, streams, lakes, reservoirs and hydro-meteorological observations are processed using GIS applications to a priori estimate of the model parameters. Second, the selected meteorological and hydrological data are used to calibrate model.

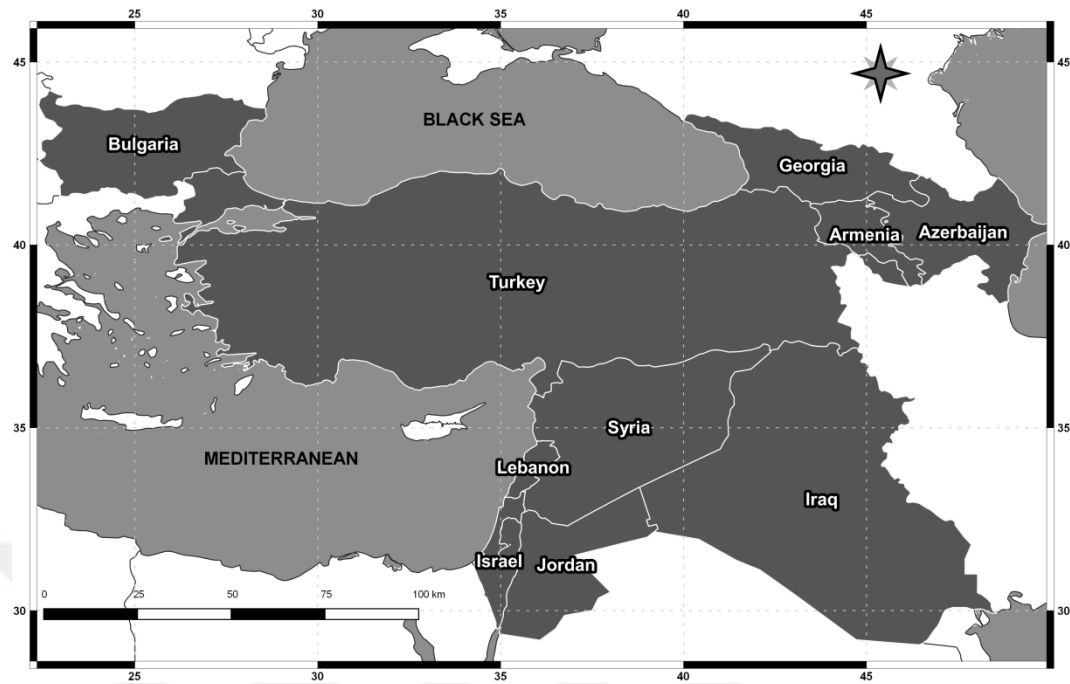


Figure 2.2 Black Sea and Middle East Flash Flood Guidance System (adopted from WMO, 2017).

Most of the spatial and observational data were provided to Turkey from related institutions but open source global data are used for remaining countries (TSMS, 2015). In the last phase, the system run and disseminates the products dynamically on the BSMEFFG server. Forecasters from member countries of the system can reach products of the system via a web interface with an individual password and username. However, the system is not public because it was created for operational using.

The BSMEFFGS is considered as a semi-distributed model with the hydro-meteorological model configured and the parameters estimated for each sub-basin. Figure 2.3 shows the sub-basins for Turkey in the BSMEFFGS. HRC delineated the sub-basins by using through GIS spatial analysis of digital elevation data with 30 meters resolution (TSMS, 2015). There are 11888 sub-basins with special identification number for each basin and an average drainage area of 50 – 150 square kilometers.

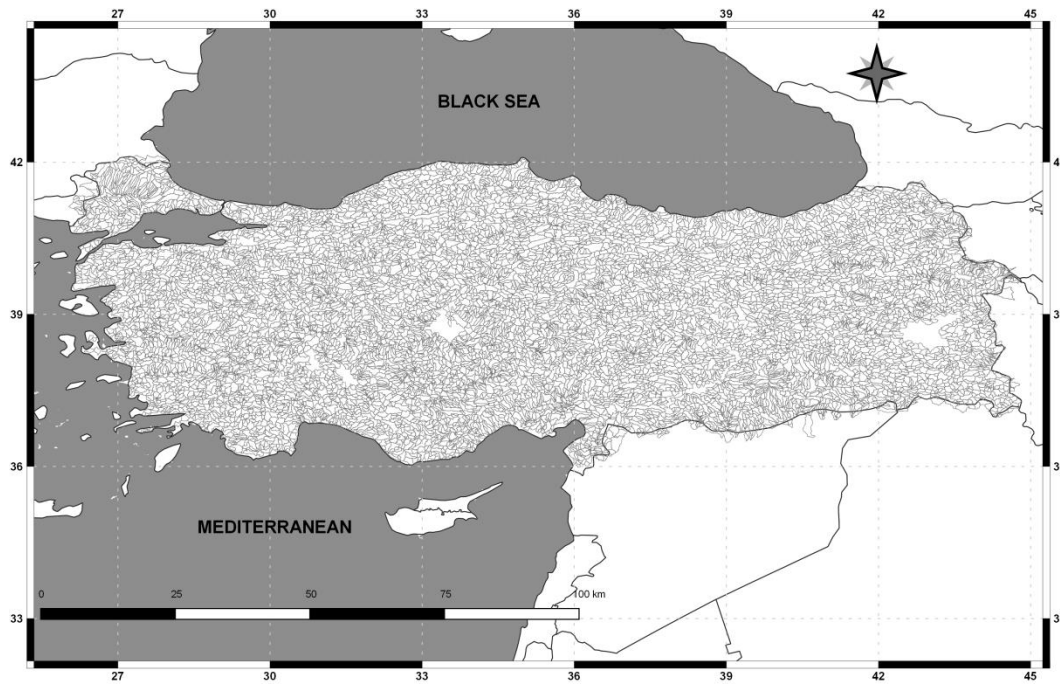


Figure 2.3 BSMEFFGS sub-basins for Turkey (adopted from TSMS, 2015).

2.1 Technical Components of the BSMEFFG System

The technical components of the BSMEFFGS utilize the available real-time data from gauge measurements and remote sensing platforms. Flash flood guidance (FFG) estimates of various durations over small catchments are produced based on soil moisture and snow models and suitable bias corrections. The BSMEFFGS technical components and flow of information are demonstrated in Figure 2.4 (HRC, 2019). Threshold Runoff Model is used to estimate threshold runoff volume which causes bankfull conditions at the outlet of catchment and computed once for each sub-basin. Soil moisture accounting model (SAC-SMA) for accounting soil moisture conditions and snow model (SNOW-17) for modeling snowpack for each catchment are also used in the system. These components promote the flash flood guidance estimates (FFG). FFG is defined as the characteristic volume of rainfall in a given duration which is needed to produce flash flood for a given sub-basin. In other words, it is the volume of rainfall causes bankfull conditions at the outlet of catchment (Modrick et al., 2014).

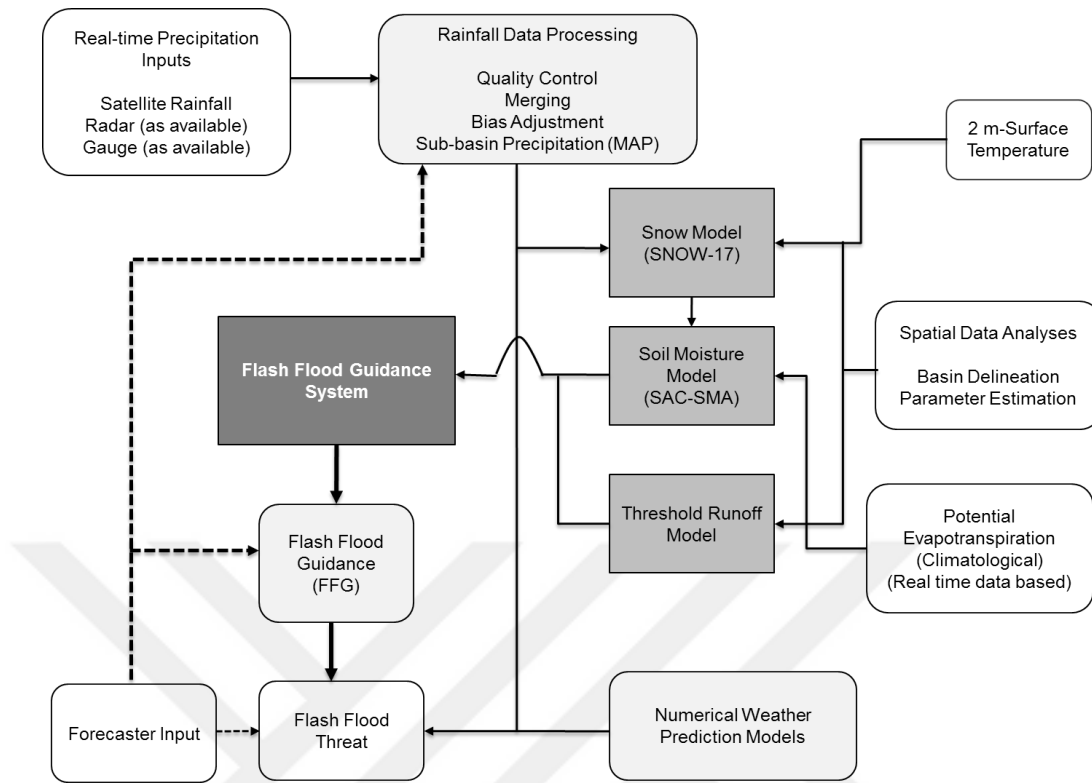


Figure 2.4 BSMEFFGS technical components (adopted from HRC, 2019).

Products from BSMEFFGS merged mean areal precipitation (MAP) and forecast mean areal precipitation (FMAP) products are derived by using real-time precipitation inputs and numerical weather prediction model outputs into the BSMEFFGS, respectively. The basic reason of the FFG estimation is that comparison of observed (nowcasting, MAP) or predicted (forecasting, FMAP) rainfall volume to characteristic volume of rainfall for given duration and over sub-basin which cause bankfull flow conditions at the outlet of catchment (Georgakakos, 2006).

If the observed or predicted rainfall volume is greater than the characteristic threshold then flash flooding is quite possible. The flash flood threat (FFT) is the amount of rainfall of a given duration that is greater than the FFG value for a basin; meaning that it is the difference between the FFG value and the corresponding estimated or forecast precipitation for the same duration and basin. BSMEFFG

system generates two different type flash flood threat products such as imminent-persistence and forecast flash flood threat (IFFT-PFFT and FFFT). Therefore, performance of the system depends on both FFG values and precipitation estimations/predictions.

2.1.1 Threshold Runoff Model

The threshold runoff is defined as the effective rainfall of a given duration that is just enough to cause bankfull conditions while effective rainfall is the residual rainfall after the infiltrative or evaporative losses are extracted. The threshold runoff model is used to compute the threshold runoff volume for just once during the initial phase of BSMEFFGS (HRC, 2013[a]). The FFG estimates are derived from threshold runoff calculations and relationship between FFG and threshold runoff is a function of the current soil moisture conditions, which are estimated in real time by operational soil moisture accounting model (SAC-SMA) (Carpenter et al., 1999).

Threshold runoff can be mathematically expressed as:

$$R = Q_p/q_{pR}A \quad (2.1)$$

R (m³) is the threshold runoff, Q_p (m³/s) is the flooding flow which means bankfull discharge at the outlet of the stream, q_{pR} is the unit hydrograph peak for a specific duration t_R normalized by catchment area (m³/s/km²/m³) and A (km²) is the watershed area (eq. 2.1). There are different options for estimation of bankfull discharge (Q_p) as described by Carpenter et al. (1999) in Table 2.1. The first method based on Manning's steady flow resistance formula and using two-year return period flow as flooding flow is the other one. The first method needs measurements of cross-sectional parameters. The two-year return period flow method is used to estimate threshold runoff for Turkey due to data availability (HRC, 2013[b]).

Table 2.1 Options for threshold runoff computation (Carpenter et al., 1999).

	Flooding flow definition		Unit hydrograph options	
Options	Two-year return period flow, Q_2	Bankfull discharge Q_{bf}	Snyder's synthetic unit hydrograph	Geomorphologic unit hydrograph
Data required	Regional relationship for Q_2 (historic flow record)	Regional relationship for channel cross-sectional parameters (cross-sectional data)	Regional estimates of empirical coefficients	Regional relationship for channel cross-sectional parameters (cross-sectional data); regional estimates of R_L

“In each method, GIS is utilized to process digital terrain data and compute catchment-scale characteristics, such as drainage area, stream length and average channel slope” (Carpenter et al., 1999). The catchment-scale characteristics are derived with GIS applications by HRC for the BSMEFFGS (see Figure 2.5a and 2.5b). Regional relationships are created for Turkey based on two-year return period flow and catchment properties by HRC such as basin area. Published surveys (mostly surveys done in USA) were used to develop regional regression relationships based on similar climatological conditions (HRC, 2013[a]). In this way, BSMEFFG region was divided into the sub-regions.

Figure 2.5[c] represents the 10 bias regions identified for the BSMEFFGS and the currently used standardized relationships for the estimation of bankfull flow. Figure 2.5[d] is shown for linear regression relationship between two-year return period flow and area for a bias region of Turkey as an example. Figure 2.6 indicates the estimated threshold runoff values for BSMEFFG for six-hour rainfall duration. The relationship between FFG estimates and threshold runoff (R) is a function of the current soil moisture conditions. Therefore, a linear relationship is created with the threshold runoff and FFG for each catchment and durations (e.g., one, three and six hours) by considering soil moisture deficit (Georgakakos, 2006). The soil moisture deficit for upper level is computed dynamically by using SAC-SMA model.

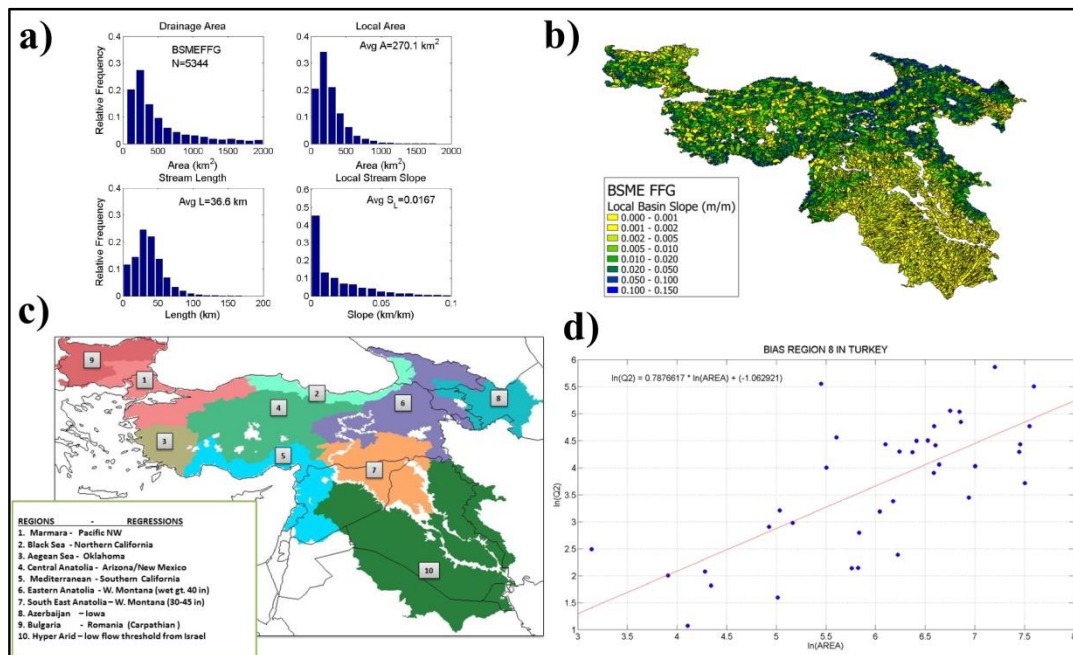


Figure 2.5 For the BSMEFFG System, catchment properties (a), catchment slope (b), bias regions (c) and linear regression relationship example in Turkey (d) (HRC, 2013[a] and [b]).

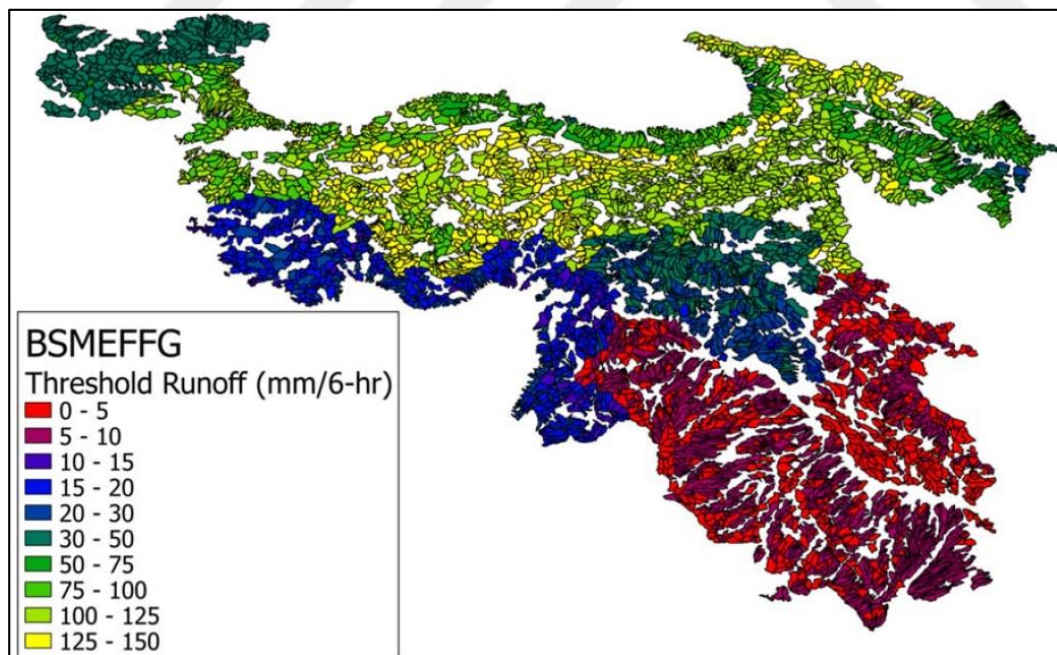


Figure 2.6 Six-hour threshold runoff values for BSMEFFG (HRC, 2013[a]).

2.1.2 Sacramento Soil Moisture Accounting Model (SAC-SMA)

The Sacramento soil moisture accounting (SAC-SMA) model is a conceptual, continuous and aerial-lumped model that describes moisture condition in the soil. The SAC-SMA model is used by most of the NWS forecast centers to simulate the rainfall-runoff processes within their operational modeling system (Burnash, 1995).

The SAC-SMA model simulates a soil column within two layers such as an upper and a lower zone. Each layer includes tension and free water storages, which interact to generate soil moisture states and five runoff components (Koren et al., 2000). The main components of the SAC-SMA are tension water, free water, surface flow, evapotranspiration and percolation. The SAC-SMA model components are illustrated in Figure 2.7. Ajami et al. (2004) described the interaction of soil moisture in various layers particularly and the parameters are listed in Table A. 1 (in Appendices).

Soil, terrain and land cover data are used to a priori estimate the model's time invariable parameters (Shamir et al., 2013). In the BSMEFFGS, soil, terrain and land cover data are obtained from Ministry of Forestry and Water Affairs for Turkey (TSMS, 2015). The SAC-SMA model is run in BSMEFFGS by using six-hour mean areal precipitation, potential evapotranspiration and snow melt real-time data and simulates the state of the soil moisture. Merged mean areal precipitation (MAP) is produced in the BSMEFFGS. Potential evapotranspiration is calculated dynamically with Thornthwaite method in the BSMEFFGS (HRC, 2013[a]). HRC calibrated estimated evapotranspiration values with observations by using one hundred and seventy nine stations in Turkey for a period of twenty six years (TSMS, 2015). Snow melt is derived from SNOW-17 model which is one of the outputs of the model.

Average soil moisture (ASM) product is output of SAC-SMA model and it shows six hour water deficit for given date and time. ASM product indicates the upper soil moisture content and used for dynamical FFG threshold values estimation.

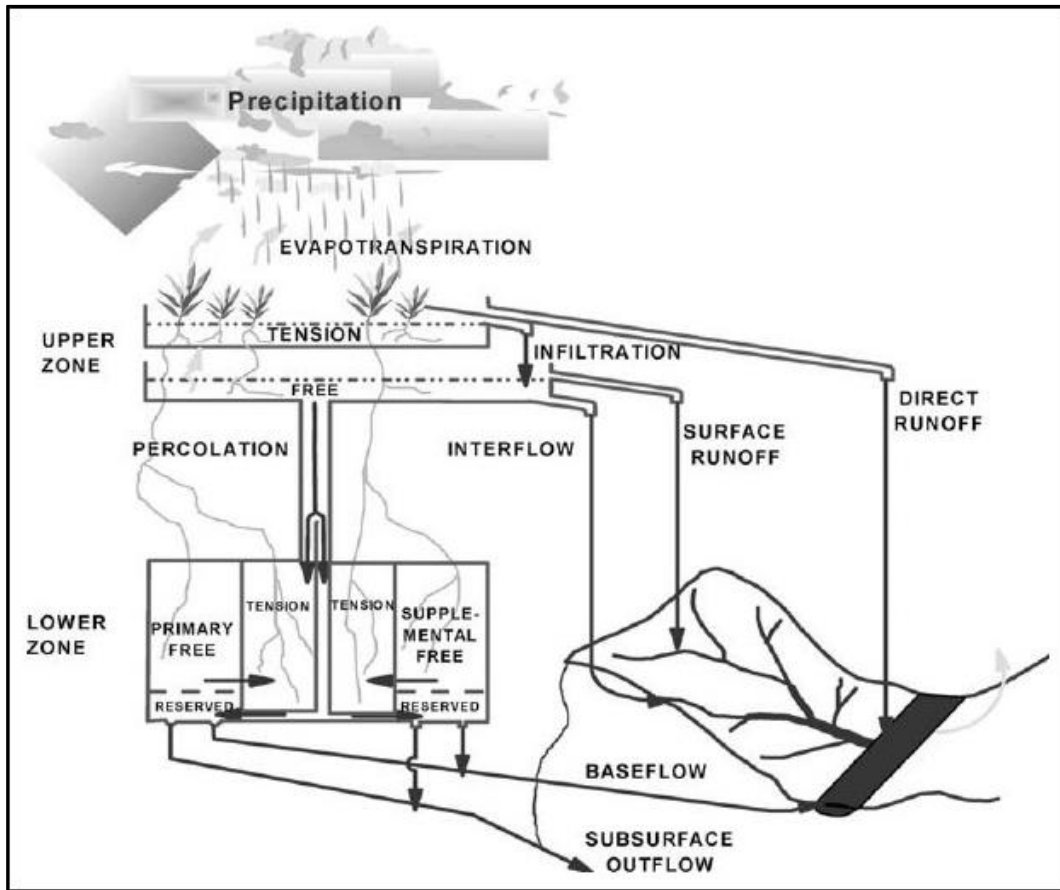


Figure 2.7 Components of the SAC-SMA model (Ajami et al., 2004).

2.1.3 Snow Accumulation and Ablation Model (Snow-17)

The Snow-17 snow accumulation and ablation model is used and coded in NWS River Forecast System for its snow products. The Snow-17 is an index model using air temperature to determine the energy exchange between the snow cover and air (Anderson, 2006). In addition to temperature, the other input parameter is precipitation. Air temperature is used as an indicator for snowmelt and its measurement is simple. An energy balance equation is used to simulate physical processes of a snow cover and the equation is given in Figure A. 1 (in Appendices) (Anderson, 2006). Figure 2.8 indicates flowchart of the Snow-17 model.

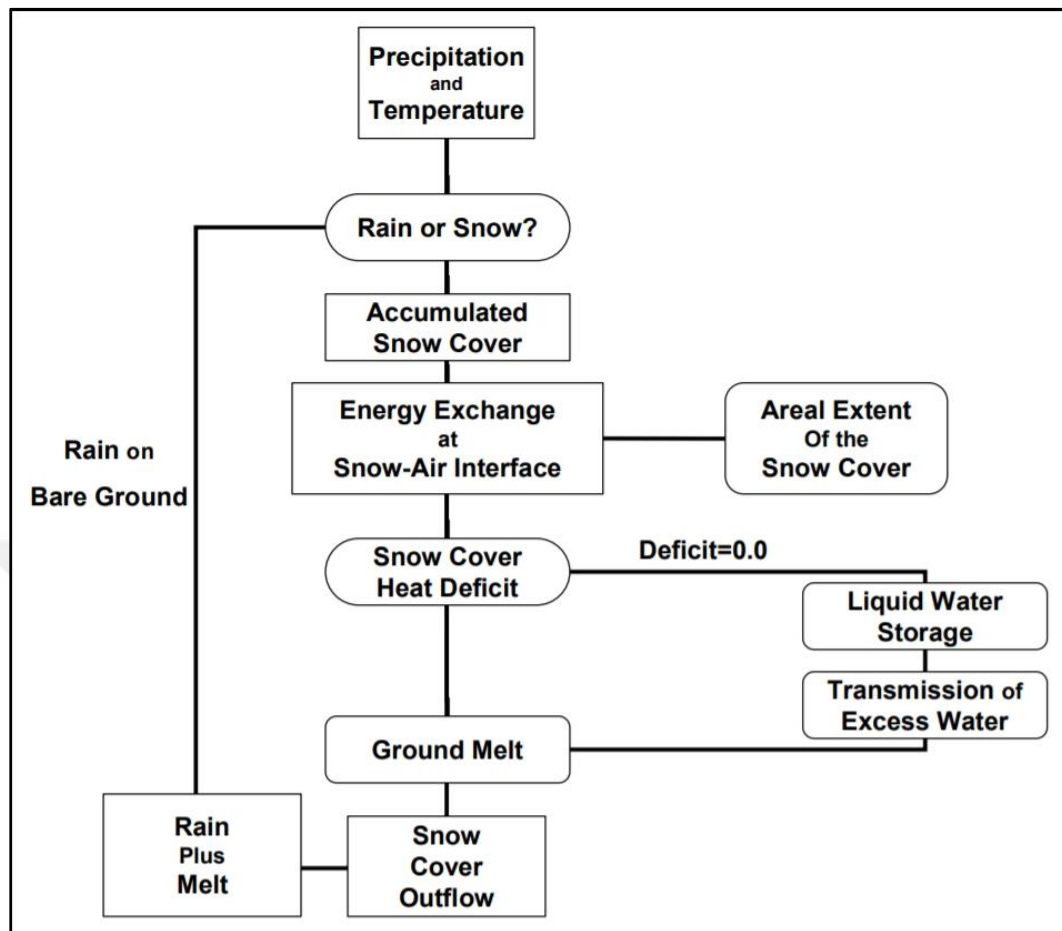


Figure 2.8 Flowchart of the SNOW-17 model (Anderson, 2006).

In the SNOW-17 model, physical processes that occur in a column of snow approach is used and applied to an area. The main physical processes in the model are; form of precipitation, accumulation of the snow cover, energy exchange at the snow-air interface, internal state of the snow cover, transmission of water through the snow cover and heat transfer at the soil-snow interface (Anderson, 2006).

A single threshold temperature ($PXTEMP \sim \text{about } 1.5^{\circ}\text{C}$) is used to distinguish between rainfall and snowfall events in the model. If the air temperature is less than or equal to $PXTEMP$, all the precipitation is assigned as snow for the given duration. If the air temperature is greater than $PXTEMP$, all the precipitation is assumed to be rain. In the BSMEFFGS, NOAA/NESDIS Interactive Multisensor

Snow and Ice Mapping System (IMS) product is used for its areal extent of the snow cover.

The melt factor is used for ablation processes in the model. In the model, M_f (mm °C⁻¹ 6 h⁻¹) regulates the production of snow melt during non-rainy periods:

$$M = M_f(T_a - T_{base}) \quad (2.2)$$

where M is the melt (mm 6 h⁻¹); T_a (°C) is surface air temperature and T_{base} (°C) is a threshold parameter that represents the temperature above which melt occurs (Shamir, E., et al, 2006). The maximum and minimum melt factor parameters are estimated for BSMEFFG region by HRC (Shamir et al, 2012). Historical on-site precipitation, temperature, snow depth and snow water equivalent data were taken from NCDC for the each country of the BSMEFFG region. SNOW-17 model outputs for BSMEFFG region are calibrated and validated with historical data by HRC (Shamir et al, 2012).

Merged mean areal precipitation and mean areal temperature values are used as input for snow model within BSMEFFGS. SNOW-17 model produces two snow products; SWE and MELT. SWE means snow water equivalent source from current snow cover and MELT shows melted amount of snow in mm for each sub-basin.

2.2 SAC-SMA and SNOW-17 Model Outputs and Flash Flood Guidance Product in BSMEFFGS

SAC-SMA model is used in BSMEFFGS for developing six-hour average soil moisture (ASM) product. The dynamic inputs of model are gauge mean areal temperature (GMAT) and merged mean areal precipitation (MAP). ASM product shows six hour water deficit for the upper zone (approximately 20-30 cm depth) of each catchment in the system for given date and time. ASM product is updated each six hour interval (00, 06, 12, and 18 UTC) in BSMEFFGS.

SNOW-17 model produces two snow products in BSMEFFGS such as snow water equivalent (SWE) and snow melt (MELT). The real-time inputs of model are gauge mean areal temperature (GMAT), merged mean areal precipitation (MAP) and snow cover area (SCA). SWE is produced each six hour (00, 06, 12, and 18 UTC) and reflects the state of the snowpack in millimeters (mm) for each watershed in the BSMEFFGS. MELT product indicates cumulative snow melt in millimeters (mm) over the period of twenty four and ninety six hours for each sub-basin.

SCA product in the BSMEFFGS indicates that the fractions of each watershed area with snow cover. SCA product is generated in the BSMEFFGS by using the Interactive Multisensor Snow and Ice Mapping System (IMS) from NOAA-NESDIS. SCA is derived from various geostationary and polar orbital satellite images with 4 km spatial and daily (at 00:00 UTC) temporal resolution.

Gauge mean areal temperature (GMAT) product in the BSMEFFGS shows sub-basin average temperature over a six hour period ending at 00, 06, 12, and 18 UTC. GMAT is generated by using interpolation of six-hour temperature gauge data for each watershed in °C. There are 839 in-situ temperature gauges which are well distributed in Turkey.

The primary indicator used by forecasters at hydrological and meteorological services around the world to predict the onset of flash flooding is when rainfall predictions (forecasting) or estimates (nowcasting) exceed FFG values over

durations of one, three or six hours. FFG values can be considered as threshold values to show potential of flash flood occurrence. FFG is defined as the characteristic volume of rainfall in a given duration which is needed to produce flash flood for a given sub-basin. In other words, it is the volume of rainfall causes bankfull conditions at the outlet of catchment (Modrick et al., 2014). Soil moisture accounting model (SAC-SMA) for accounting soil moisture conditions and snow model (SNOW-17) for modeling snowpack for each catchment are also used in the system. These components promote the flash flood guidance estimates (FFG) as described in section 2.1 of this study. Gourley et al. (2012) explained in their study that “threshold runoff is defined very similarly to FFG, but it is the amount of rainfall excess required to cause flooding at the basin outlet; rainfall excess is the effective volume of rainfall that is transformed into surface runoff at the basin scale”. The amount of rainfall excess is mostly less than the actual rainfall because of losses such as infiltration, interception and evaporation etc. These hydrological processes are simulated in real time by using Snow 17 and SAC-SMA. However, threshold runoff values are assumed to be constant and computed once before the initiating the system. The computation of threshold runoff values for basins in Turkey are explained in section 2.1.1 of this study. The FFG estimates are derived from threshold runoff calculations and relationship between FFG and threshold runoff is a function of the current soil moisture conditions, which are estimated in real time by operational SAC-SMA model (Carpenter et al., 1999).

Figure 2.9 is shown for as an example of for daily SCA, six-hour GMAT, six-hour SWE and MELT products, at 00:00 UTC on 25 December 2019, in BSMEFFGS. It can be interpreted form the figure that eastern and some parts of southern Anatolia are covered by snow and water potential is more than one hundred mm for many basins over there. Figure 2.10 is given as an example for ASM and FFG products of BSMEFFGS for Turkey at 00:00 UTC on 25 December 2019. The ASM product shows that the basins are highly saturated for last six hours in southern coastal Anatolia. Additionally, FFG values are noticeably low (purple basins) for these basins which mean that these basins have hazardous in terms of flash flooding.

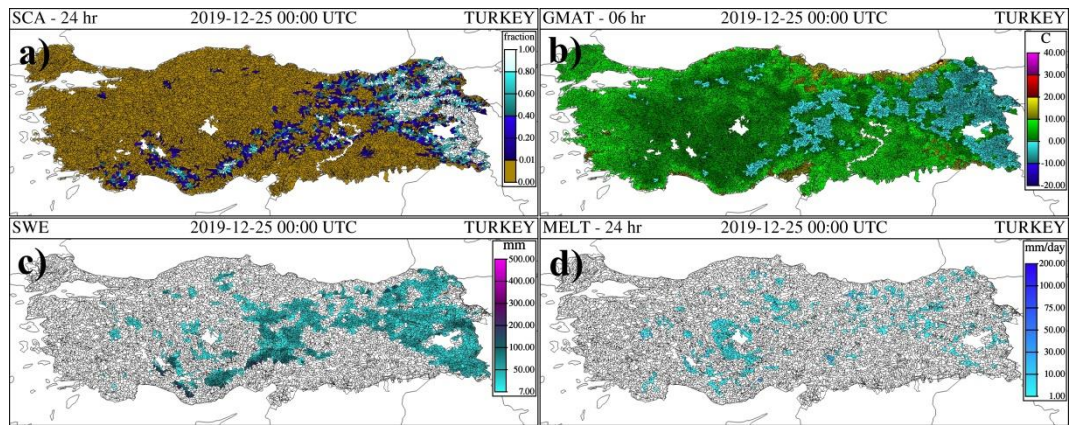


Figure 2.9 Sample BSMEFFG products for daily snow cover area (SCA) (a), six-hour gauge mean areal temperature (GMAT) (b), six-hour snow equivalent (SWE) (c) and daily snow melt (MELT) (d) at 00:00 UTC on 25 December 2019.

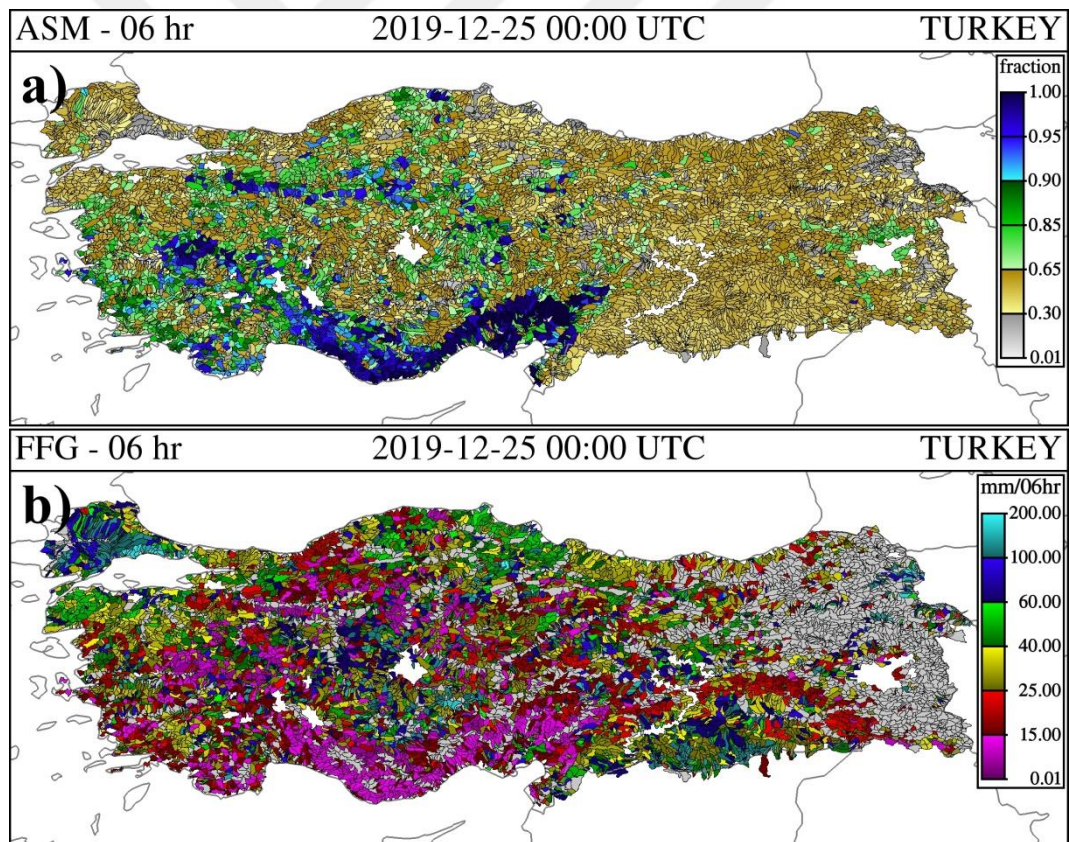


Figure 2.10 Sample BSMEFFG products for six-hour average soil moisture (ASM) (a) and six-hour flash flood guidance (FFG) (b) at 00:00 UTC on 25 December 2019.

2.3 Precipitation Estimates in BSMEFFGS

There are different sources for estimation of precipitation in the BSMEFFGS such as radar, satellite and gauges. Figure 2.11 is shown for sample of six-hour rainfall estimates within BSMEFFGS for Turkey at 00:00 UTC on 25 December 2019. These products are called as RADAR, GHE, MWGHE, GMAP and MAP in the BSMEFFGS. RADAR, GHE and MWGHE remotely sensed rainfall estimates are available in gridded format. GMAP and MAP are available in areal format. Additionally, it is possible to download all rainfall estimation data for given date and duration from the BSMEFFGS server.

As indicated Figure 2.11a, radar based gridded precipitation data is available in the BSMEFFG system, which is provided from Doppler weather radar network of TSMS. There is 10 C-band radar in the system while covering mostly the coastal regions although TSMS has 17 C-band radar currently. These C-band radar systems collect the data in a 7-min sampling frequency with a 720-meter range interval along a 120 km radius from the radar location (Yücel, 2015). However, a radar mask study has been carried out for TSMS radars by HRC in order to reduce measurement-related errors and uncertainty (TSMS, 2015). RAIN1 product is used to represent realized rainfall in BSMEFFGS for last one, three, six and twenty-four hour time steps. The radar rainfall estimates are displayed in the system with a latency of approximately 10 minutes, without any bias correction except TSMS implementations, over a background of the sub-basin boundaries.

The quantitative precipitation estimation techniques by satellites can be divided into two based on infrared (visible) and microwave. These techniques also involve cloud indexing, temperature-threshold and cloud growth methods. Thus, two different satellite precipitation products are available in the BSMEFFGS such as Global Hydro Estimator (GHE) and Microwave-adjusted Global Hydro Estimator (MWGHE). NOAA-NESDIS provides satellite-based precipitation estimates operationally for flash flood analyses. Hydro Estimator precipitation estimate technique is based on infrared window (10.7 μ m) channels from geostationary

operational environmental satellites (GOES) from which cloud-top infrared (IR) brightness temperature is derived. In this way, GHE provides gridded global (60°S to 60°N) 15-min quantitative precipitation with high spatial resolution of 4 km (Scofield and Kuligowski, 2003). 15-min rainfall estimates are aggregated to hourly quantitative precipitation values in the BSMEFFGS. As shown in Figure 2.11b, the GHE rainfall estimates are provided on a grid without any adjustment which is displayed over a background of FFGS sub-basin boundaries with latency of up to twenty five minutes.

The second satellite based rainfall product of BSMEFFGS is Microwave-adjusted Global Hydro Estimator (MWGHE) which is produced by HRC as indicated Figure 2.11c. The GHE data is available with high temporal and spatial resolution in BMSEFFGS but infrared channel measure cloud top temperature which does not always correlate well with rainfall. Since rainfall is not just associated with cold clouds ($-40^{\circ}\text{C} >$), incorrect estimations are probable if infrared data alone is used. For example, cirrus clouds are classified as high and cold; however, these clouds are mostly associated with clear sky and non-precipitating systems. In contrast to the infrared, passive microwave signals sense scattering of radiation that coming inside of the cloud, which means better rainfall estimations because of adding into account raindrops and ice particles (Joyce et al., 2004). However, microwave sensors are not applied on geostationary platforms because of the technical challenges so that polar orbiting satellites are in used and it cause longer latency times. In the BMSEFFGS, CMORPH algorithm is used for microwave based estimations which is provided from NOAA/Climate Prediction Center. Microwave based rainfall estimations are not used directly in the system but it is used for adjusting the GHE data. Because of the latency issues as explained above, the adjustments are not performed consistently. Previously calculated climatological bias adjustments are implemented for the BMSEFFG region by HRC. The MWGHE product is updated every hour with a latency of approximately 45 minutes in the BSMEFFGS.

The interpolation of the gauge precipitation is the last source for rainfall estimates in the BSMEFFGS. Gauge mean areal precipitation (GMAP) is performed on the observations made by 839 on-site rainfall observations which are well distributed in Turkey. The GMAP product is derived for all sub-basins from the interpolated six-hourly station observations by using inverse distance weighting deterministic method. Figure 2.11d is shown for a sample of GMAP product in BSMEFFGS.

Merged mean areal precipitation (MAP) is a bias corrected product within BSMEFFGS that exhibits estimated rainfall for 1, 3, 6 and 24 hour time steps. Figure 2.11e is shown for a sample of MAP product in BSMEFFGS. The MAP is generated from surface rain gauges and remote sensing platforms such as radar and satellites. Figure 2.12 indicates merged mean areal precipitation production procedure with using various precipitation sources. MAP product is derived for each basin from first radar then bias-adjusted MWGHE or GHE or the gauge interpolation based on the best available sources. The remote sensed estimates are available in the system without any correction but bias-adjustment processes are performed for just MAP calculations. Climatological and dynamic bias adjustments of MAP are explained by Georgakakos et al. (2013). Shamir et al. (2012) explained climatological bias adjustment procedures and results for the BSMEFFG region for the period of 2008-2010. The MAP product can be considered as the best precipitation estimate of available in real-time and it is used as input for flash flood threat products besides the hydrological model components (HRC, 2019).

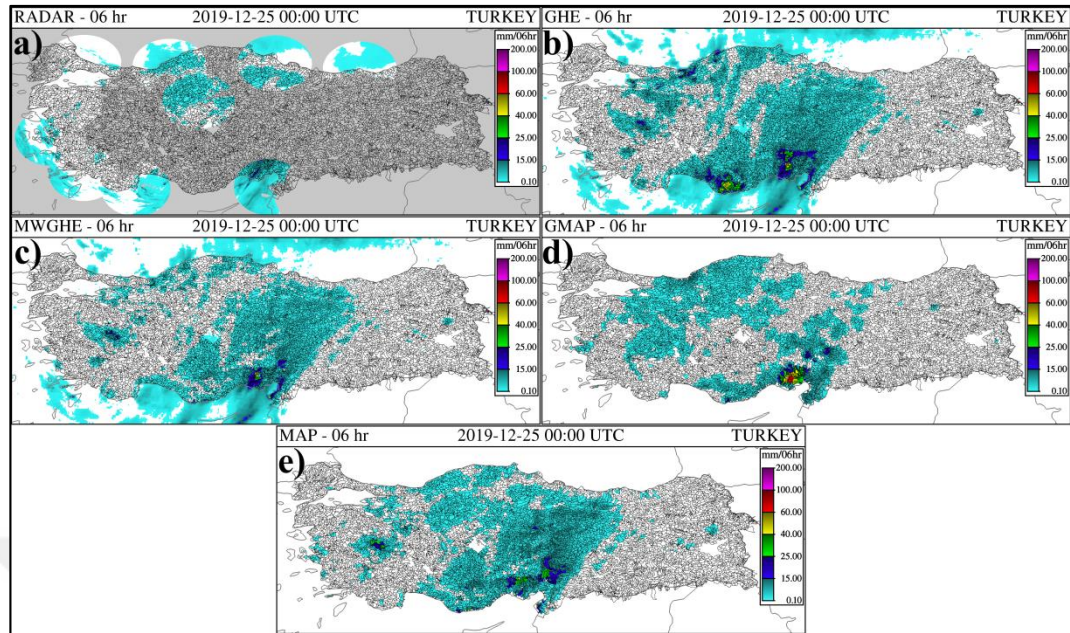


Figure 2.11 Sample of six-hour rainfall estimates within BSMEFFGS for Turkey at 00:00 UTC on 25 December 2019; Radar (a), GHE (b), MWGHE (c), GMAP (d), and MAP (e).

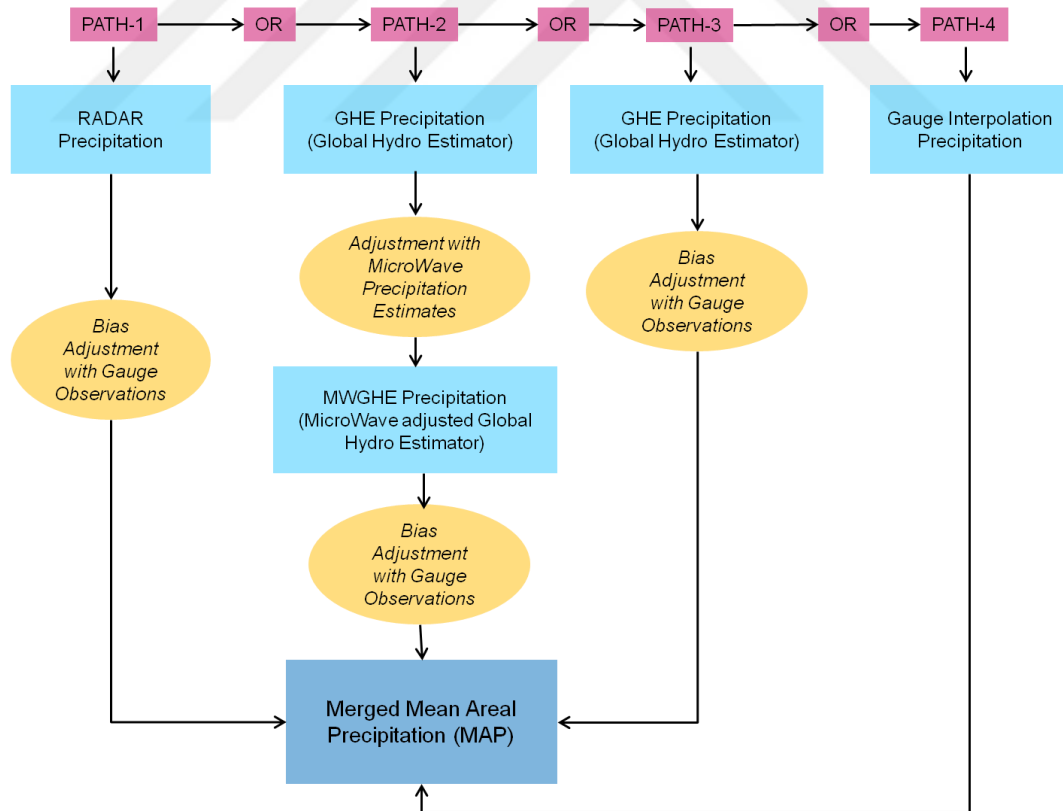


Figure 2.12 Flow chart of MAP production.

2.4 Numerical Weather Prediction Models in BSMEFFGS

Numerical weather prediction (NWP) models use mathematical models of the atmosphere and oceans with their interactions among themselves to predict the weather. Mathematical models based on the same physical principles can be used to generate either short-term weather forecasts or longer-term climate predictions. For an example, hydrostatic equation is one of the basic physical principles which describes pressure gradient with density of the air and gravity. However, the Earth's atmosphere is not only physical but also dynamical and chemical system. NWP models have to contain solution of all dynamical, physical and chemical equations but it is almost impossible to solve these equations exactly because of chaotic nature of these partial differential equations. The model dynamics can be listed as conservation of momentum, mass, energy and moisture. Physical terms are vital due to properly model the atmosphere such as friction, radiation, heat flux and condensation parameters and solved in boundary layer, radiation transfer, land surface layer, microphysics (large-scale precipitation) and convection schemes respectively. These physical processes, given in Figure 2.13, need to be approximated in models because of huge simulation computer time which is called as parameterization. Therefore, different models use different numerical methods for solution or ignore someone and it is the reason why different models have different predictions.

NWP models have been started using for many decades earlier to forecast precipitation besides other atmospheric variables. Nevertheless, prediction of precipitation is challenging for many reasons; such as discontinuity, changing rapidly in space and time features of precipitation. The precipitation process depends not only on the synoptic conditions, but also on processes that are not explicitly considered by NWP models, including condensation, vertical convective transport of heat and moisture and phase transitions of water between vapor, clouds and ice (Damrath et al., 2000).

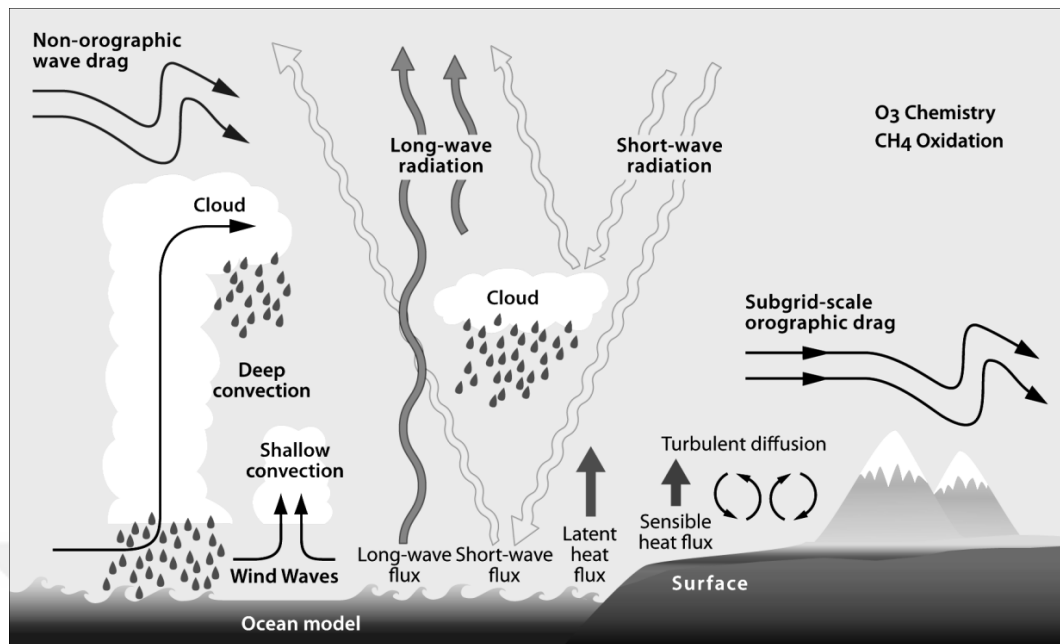


Figure 2.13 Physical processes in the atmosphere referred as the physical parametrization in NWP models (ECMWF, 2020).

Increased computing power and improving NWP models led to a significant advance in precipitation forecast. However, the ability to predict precipitation of NWP models is comparatively low, especially for very short lead times (eg <12 hours), long lead times (eg > 5 days) and local-regional convective systems (Cuo et al., 2011).

Prediction of precipitation can be very useful for not only synoptic forecasts but also for operational and research uses in hydrological studies. Accurate precipitation forecasts can reduce forcing uncertainty in hydrological models and can greatly improve the quality of their outputs. Hydrological models are sensitive to uncertainty in the precipitation forecasts, which are propagated to the model outputs because of stochastic processes. However, NWP precipitation forecasts are inherently uncertain and subject to three types of error; localization, timing and intensity of precipitation events, which potentially limit their usefulness for stream flow forecasting (Shrestha et al., 2013).

There are several NWP models exist in TSMS for almost two decades to predict precipitation and other atmospheric variables such as ECMWF, ALARO (ALADIN), AROME (ALADIN), WRF and WW3; each of them has different horizontal/vertical resolution, run time and domain. Nevertheless, ECMWF, ALARO and WRF models are in use within BSMEFFGS for hydrological purposes starting from different periods.

Figure 2.14 indicates that NWP model domains within BSMEFFGS; ALARO model domain is the narrowest, ECMWF has the largest domain and WRF model has moderate coverage area. Therefore, some parts of the region are not covered by ALARO such as south of Jordan, Israel and east of Azerbaijan. ECMWF and WRF model cover the entire region of BSMEFFGS.

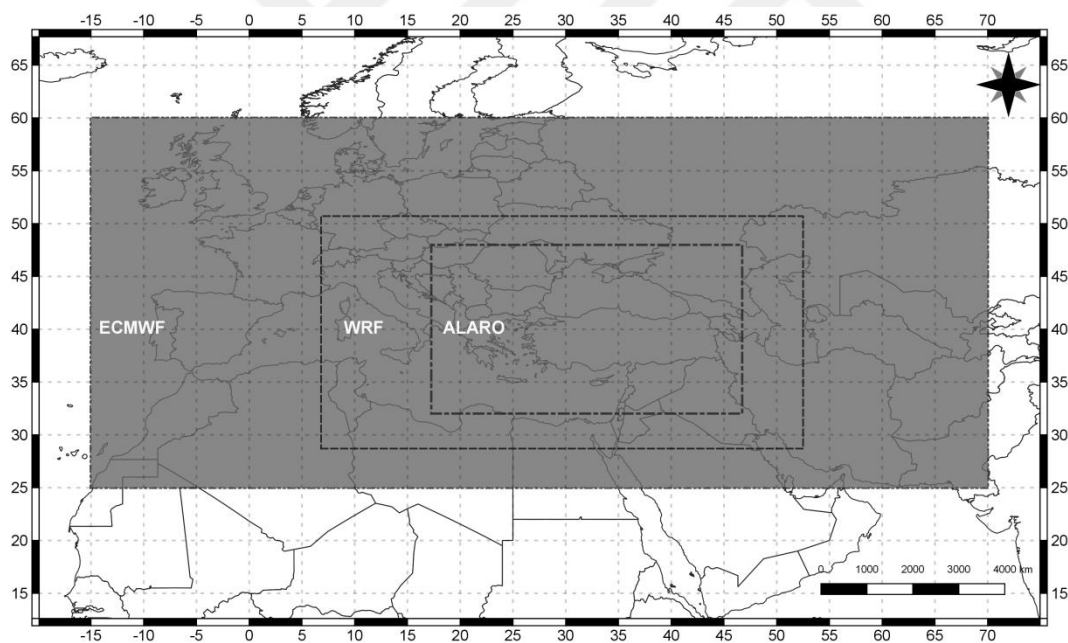


Figure 2.14 NWP model domains for precipitation forecast within BSMEFFGS.

The gridded prediction values of NWP models are converted to areal for each sub-basin by taking average of the pixels over a basin within BSMEFFGS. Forecast mean areal precipitation (FMAP) products of BSMEFFGS are derived for varied

hour accumulations by using each NWP model. The FMAP product represents predicted amount of precipitation over each sub-basin for multiple durations such as one, three, six and twenty-four hours.

Figure 2.15 is shown for sample of six-hour both gridded and areal NWP products within BSMEFFGS for Turkey at 00:00 UTC on 25 December 2019. Figure 2.15a and b indicate gridded and areal ALARO rainfall predictions for next six hours respectively. Figure 2.15c and d indicate gridded and areal ECMWF rainfall predictions for next six hours respectively. Figure 2.15e and f indicate gridded and areal WRF rainfall predictions for next six hours respectively. In the figure, each NWP model shows precipitation forecast over southeast Mediterranean coastal parts of Turkey but rainfall amounts are different for the period 00:00 UTC and 06:00 UTC 25 December 2019.

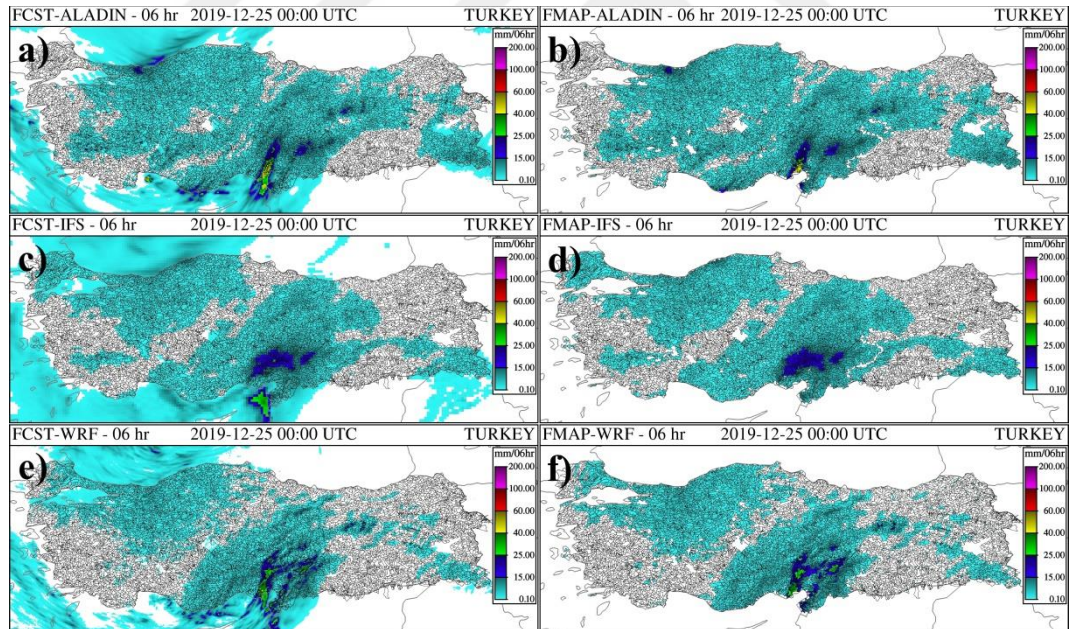


Figure 2.15 Sample of six-hour NWP products within BSMEFFGS for Turkey at 00:00 UTC on 25 December 2019; FCST-ALARO (a), FMAP-ALARO (b), FCST-ECMWF (c), FMAP-ECMWF (d), FCST-WRF (e) and FMAP-WRF (f).

2.4.1 ALARO

ALADIN is a system and developed by the international ALADIN consortium for operational weather forecasting and research studies. Being developed by the international consortium of European and North African countries under the leadership of Meteo-France it is widely employed by various national meteorological services particularly in Central and Eastern Europe (Farda et al., 2010). Therefore, ALADIN is very popular among Mediterranean countries as a mesoscale numerical weather prediction model. The system based on a code which is shared with the global circulation model IFS of the ECMWF and the ARPEGE model of Meteo-France (Termonia et al., 2018).

Global models are insufficient in local weather forecast due to their low horizontal and vertical resolutions. In order to overcome this issue the limited-area model (LAM) configurations operated at higher resolutions than global models were needed. Today, there are three different LAM configurations exist in the ALADIN system which are called as ALADIN, AROME, and ALARO. AROME and ALARO models are running in TSMS for weather forecasting purposes currently. ALARO is a hydrostatic version of ALADIN and operationally run with the forecast input data from Action de Recherche Petite Echelle Grande Echelle (ARPEGE) as a limited area model in TSMS.

The primary relevant features of the ALARO are given in Table 2.2 as operationally runs in TSMS. The basic physics parameterizations of the ALARO with references are listed which are the most related with precipitation formation. The large-scale precipitation (microphysics) scheme is used for resolved precipitation estimation (Lopez, 2002) and includes prognostic variables such as liquid and solid water etc. ACRANEB2 is the second version of radiative transfer scheme in ALADIN system (Masek et al., 2016) and it is used to calculate cloud-radiation interaction. The ISBA surface parametrization scheme (land surface) is used for accounting surface fluxes of energy interactions between sub-surfaces such as land, urban, water, and inland waters (Noilhan and Planton, 1989). Davies

scheme (Davies, 1976) has been chosen as boundary layer in the ALARO system for calculation of momentum and energy exchanges between lowest model level and ground. 3MT and TOUCANS schemes are used in ALARO for deep and shallow convection type precipitation respectively (Gerard et al., 2009; Duran et al., 2014).

Table 2.2 Physics options of ALARO model as operationally using in TSMS.

<i>Category</i>	<i>Scheme</i>	<i>References</i>
Microphysics	Lopez	Lopez (2002)
Radiation	ACRANEB2	Masek (2016), Galeyn (2017)
Land Surface Layer	ISBA	Noilhan & Planton (1989)
Boundary Layer	Davies Scheme	Davies (1976)
Cloud (Convection)	3MT (Deep) TOUCANS (Shallow)	Gerard (2009), Duran (2014)

ALARO model is the first NWP model in BSMEFFGS and it has been used operationally since April, 2013 for precipitation forecast. The horizontal resolution of ALARO is 4.5 km, forecast period is 72 hours and model is updated for each six hours (00/06/12/18 UTC) in TSMS. ALARO provides hourly quantitative precipitation forecast so that 1-hour, 3-hour, 6-hour and 24-hour accumulation precipitation forecast outputs are available in BSMEFFG System.

2.4.2 ECMWF

The European Centre for Medium-Range Weather Forecasts (ECMWF) was officially established on 01 November 1975 as an independent international agency to overcome medium-range forecast problem. Turkey officially became a member of the ECMWF since 1975. ECMWF makes a forecast to ten days ahead and

distributes to members via a dedicated telecommunication network (Persson, 2001). The missions of ECMWF can be summarized as follows; produce numerical weather forecasts and monitor, carry out scientific and technical research to improve forecast skill and maintain an archive of meteorological data.

ECMWF uses a global general circulation model known as the Integrated Forecasting System (IFS) to produce probabilistic ensemble forecasts. IFS consists of several components that are coupled together in various ways such as an atmospheric model, ocean wave model, ocean model, land surface model and four-dimensional data assimilation analysis (ECMWF-IFS). The version of the IFS is often referred to as the ECMWF and it is used in this study in the same way.

The primary relevant features of the ECMWF are listed in Table 2.3 with their references (Tiedtke, 1993; Forbes, 2011; Mlawer, 1997; van den Hurk and Viterbo, 2003; Koehler, 2011; Tiedtke, 1989; Bechtold, 2008). These schemes are used to fulfill the requirements of model physics, for instance microphysical and convection schemes are convenient to calculate convective and non-convective precipitation processes.

Table 2.3 Physics options of ECMWF model as operationally using in TSMS.

<i>Category</i>	<i>Scheme</i>	<i>References</i>
Microphysics	Forbes -Tompkins	Tiedtke (1993), Forbes (2011)
Radiation	RRTM	Mlawer (1997)
Land Surface Layer	TESSEL	van den Hurk & Viterbo (2003)
Boundary Layer	Monin-Obukhov (MO)	Koehler (2011)
Cloud (Convection)	The Moist Convection	Tiedtke (1989), Bechtold (2008)

ECMWF model has been used operationally since August, 2016 for its 3-hr, 6-hr and 24-hr accumulation precipitation forecast outputs in BSMEFFG System. The horizontal resolution of ECMWF model is 9 km, forecast period is 240 hours and model is updated for each twelve hours (00/12UTC) in TSMS. 3-hr rainfall estimates are provided by ECMWF and these estimates are aggregated to six and twenty-four hourly values in the BSMEFFGS.

2.4.3 WRF

The Weather Research and Forecasting (WRF) model is a next-generation open source mesoscale numerical weather prediction system. As it is open source, it has a very flexible structure that allows it to be used by met-offices, universities and atmospheric research centers. The effort to develop WRF began in the latter 1990's and was a collaborative partnership of the National Center for Atmospheric Research (NCAR), the National Oceanic and Atmospheric Administration (NOAA), the U.S. Air Force, the Naval Research Laboratory, the University of Oklahoma, and the Federal Aviation Administration (WRF web page). WRF operationally run with the forecast input data from Integrated Forecast System – IFS as limited area model in TSMS (Karadavut, 2015).

The physics options of the WRF are given in Table 2.4 as operationally run in TSMS. The basic physics parameterizations of the WRF with references are listed which are the most related with precipitation formation (Hong, 2004; Dudhia, 1989; Mlawer, 1997; Dudhia, 1996; Hong, 2006). It is noted that there is no parameterization for convection unlike other NWP models but remained various features are available in WRF. Convective tendencies are usually resolved within 1–4 km grid scale and therefore convective scheme is generally not used lower 4-km grid resolution in WRF modeling (Yücel, 2015).

Table 2.4 Physics options of WRF model as operationally using in TSMS.

<i>Category</i>	<i>Scheme</i>	<i>References</i>
Microphysics	Single Moment 3 Class and 5 Class	Hong (2004)
Radiation	Dudhia, RRTM	Dudhia (1989), Mlawer (1997)
Land Surface Layer	5 Layer Thermal Diffusion	Dudhia (1996)
Boundary Layer	Yonsei University	Hong (2006)
Cloud (Convection)	No Parameterization	

WRF model has been used operationally since August, 2016 for its 1-hr, 3-hr, 6-hr and 24-hr accumulation precipitation forecast outputs in BSMEFFG System. The horizontal resolution of WRF is 3 km, forecast period is 72 hours and model is updated for each six hours (00/06/12/18 UTC) in TSMS. WRF provides hourly quantitative precipitation forecast so that 1-hour, 3-hour, 6-hour and 24-hour accumulation precipitation forecast outputs are available in BSMEFFG System.

CHAPTER 3

DATA AND METHODOLOGY

3.1 Severe Weather Reports and Lightning Observations

TSMS provides a database of severe (exceptional) weather event reports, including extreme rainfall events that eventuate along Turkey. These reports are performed by local observers of TSMS who generate them not just for rainfall events but also include other extreme meteorological events such as heavy snowfall, heat wave, thunderstorm etc. The reports for extreme rainfall events mostly trigger flooding occurrence frequently. There is no flash flood record specifically in Turkey. Therefore, extreme rainfall events are used in this study in place of flood events. These reports include valuable information such as beginning and ending time of an event, direct and indirect damages, loss of life and property -if it is available-, an event narrative, images of event and location of the event. The locations are stored as province and district. Unfortunately, the reports are not open for public using but can be obtained from TSMS by applying for scientific studies.

TSMS has been used the Lightning Detection Network System (LDNS) operationally since the ending of 2014 for nowcasting of severe weather warnings with 41 passive sensors on the ground across Turkey (TSMS, 2016). The system provides lightning data in split-second level with their current values. The location of accuracy of LDNS is 200-meter. The number and locations of cloud-to-cloud and cloud-to-ground lightning flashes are obtained from the LDNS in the scope of this thesis. Lightning data assist forecasters to assess the evolution of thunderstorm activities, flashes are mostly related with cumulonimbus clouds which are formed by convection and cause severe weather conditions and downpours over a region. Thus, the lightning data of the LDNS is used in this study to show usage capacity of lightning flashes for heavy rainfall events during warm season in Turkey.

3.2 Data for Event Cases

Criteria for selecting case studies are determined as follows: whether convective or non-convective intense rainfall caused flash flooding, occurrence in different seasons and distributed homogeneously in Turkey. Figure 3.1 shows the province of selected case studies. There are ten different cases; non-convective (five), convective (four) and snowmelt (one) induced cases. The success of each NWP model is tested in capturing and issuing flash flood warning for different event signature, geographical location, and season.

The main BSMEFFGS products for the case studies are flash flood guidance (FFG) as threshold and forecast mean areal precipitation (FMAP) obtained from ALARO, ECMWF and WRF numerical weather prediction models. Rainfall estimates within BSMEFFGS are also used in the cases such as merged areal precipitation (MAP), gauge mean areal precipitation (GMAP), radar, GHE and MWGHE. Snow products of BSMEFFGS are snow cover area (SCA) and snow melt (MELT) which are used in the cases if they are necessary. FFG, FMAP, MAP, GMAP, SCA and MELT products are available in areal format in BSMEFFGS. However, satellite based (GHE and MWGHE) and radar rainfall estimates are gridded in the BSMEFFGS. Thus, the grid data of radar, GHE and MWGHE remotely sensed precipitation estimations are downloaded from system server and extracted with selected basins by using an R script. Remaining rainfall and FFG threshold products are in areal format within the BSMEFFGS, the data are just downloaded from the system server.

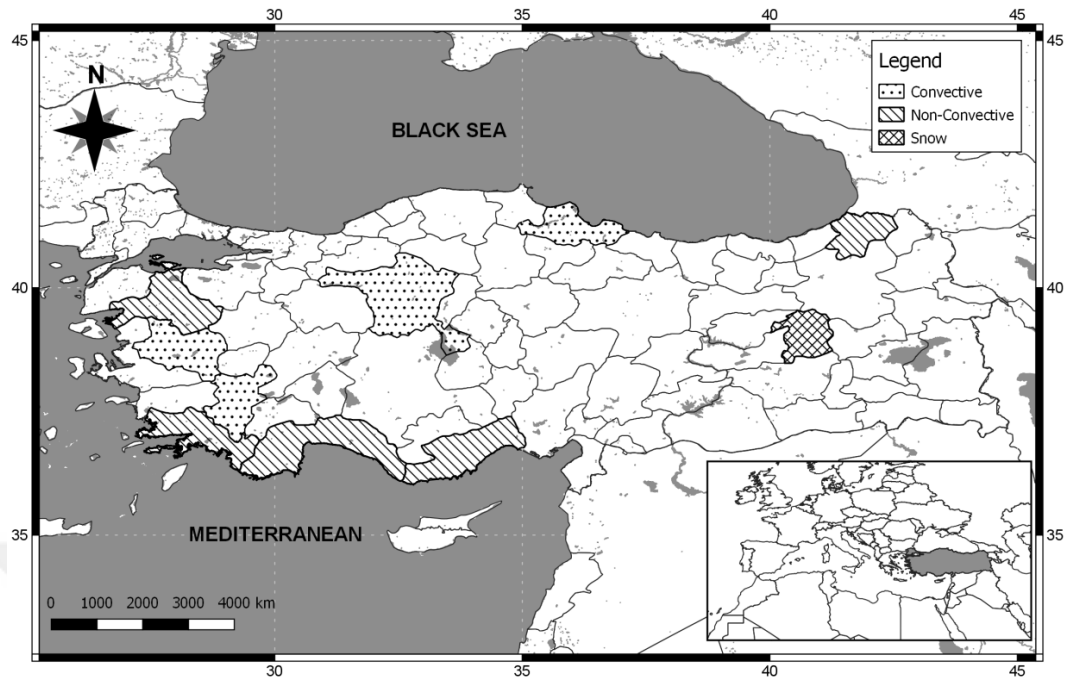


Figure 3.1 Selected case studies across Turkey for the period of 2017 and 2019.

There are many data source used in these case studies beside BSMEFFGS products such as observed daily rainfall, TSMS severe weather reports and web news for verification of flash flood events, observed hourly rainfall - dew point temperature – surface temperature and lightning flashes.

In the cases, R programming is used for simple inverse distance weighting interpolation of daily rainfall amounts to distribute and visualize.

Observed hourly rainfall, dew point temperature and surface temperature data are used in the non-convective rainfall induced cases. The hourly data during an event period are plotted to detect signature of rainfall. The plots are generated by using R programming with creating a script.

Distribution of lightning flashes map during an event is given in each non-convective rainfall induced cases. It is aimed to show that lightning flashes have a potential for flash flood warning during warm season.

3.3 Methodology

In the most general form, the flow chart of the analyses in this study is presented in Figure 3.2. Distribution of extreme rainfall events and lightning flashes are performed primarily. Subsequently, event-based flash flood case studies are implemented for evaluation of NWP models.

Severe weather reports of TSMS are used to show distribution of heavy rainfall events across Turkey between 2015 and 2019. Furthermore, lightning data is also used to show distribution of lightning flashes across Turkey between 2015 and 2019.

The success of FFG method is depending on both FFG threshold values and forecasted/estimated precipitation. Thus, NWP precipitation predictions within BSMEFFGS are evaluated by case studies in this thesis. Precipitation predictions, precipitation estimates and FFG threshold values within BSMEFFGS are used in flash flood case study analyses. Comparison of NWP results with FFG products are presented in the last part of each study.

Assessment of extreme rainfall events is given to show importance and frequency of events which mostly cause flash flooding. Additionally, distribution of lightning flashes over Turkey for recent years is performed because lightning is related with intense rainfall events. In total 10 event-based flash flood cases, occurred along Turkey for the period of 2017 and 2019, were selected to evaluate the NWP models on a smaller scale.

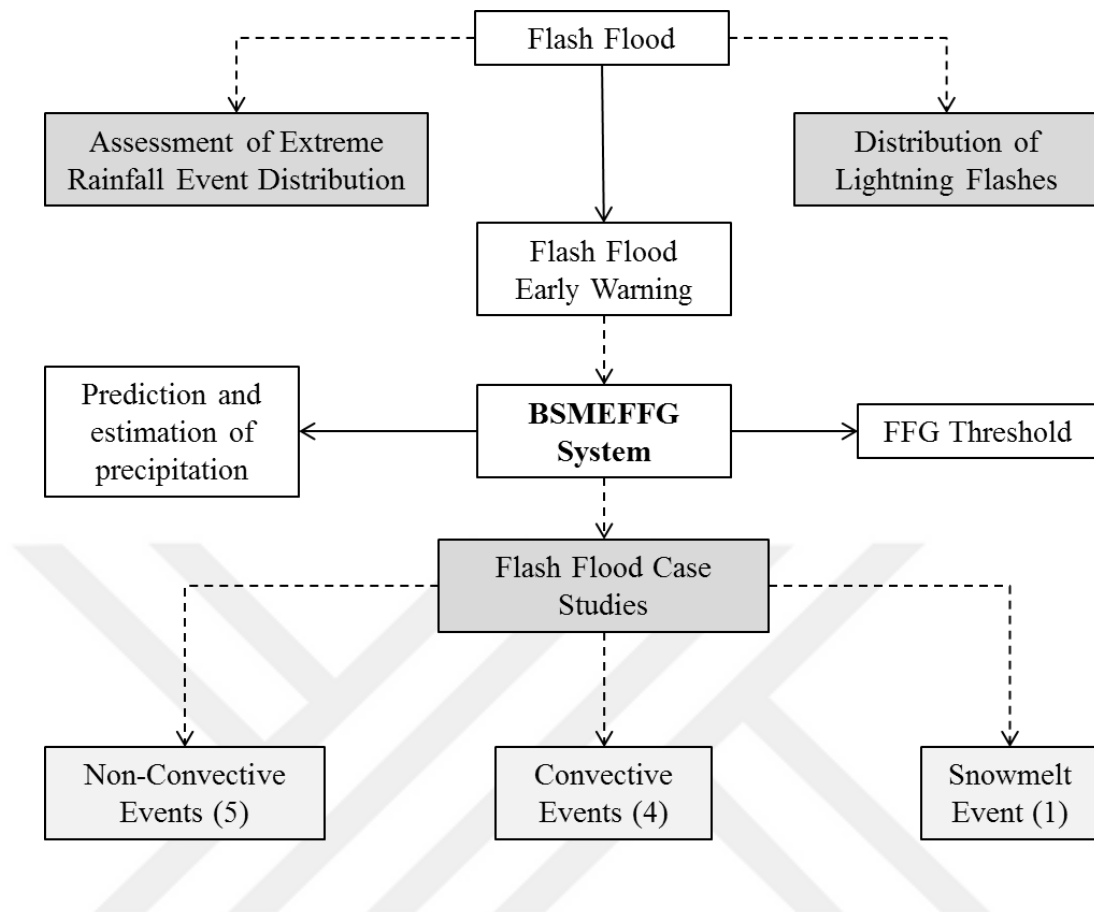


Figure 3.2 Flow chart of the analysis performed in this thesis.



CHAPTER 4

ANALYSES AND RESULTS

The MAP and FMAP products (ALARO, ECMWF, WRF) of BSMEFFGS have been evaluated for an overall performance evaluation of NWP models before the analyses within the scope of this thesis. The monthly distribution of six-hour MAP and FMAP products for the period of 2017 and 2019 are given in Appendices (see Figure B.1 and B.2). In addition to, correlation coefficient and root mean square error calculations between six-hour MAP and FMAP products are performed for the same period (see Figure B.3 and B.4). These analyses were done by creating R scripts specifically for this thesis.

In this chapter, precipitation forecast used in the BSMEFFGS for flash flood warning is discussed. Firstly, assessment of extreme rainfall events for the period of 2015 and 2019 is done by using TSMS severe weather reports. Then, distribution of lightning flashes over BSMEFFG sub-basins (for Turkey) for the period of 2015 and 2019 is given. Finally, through event based flash flood case studies a more detailed assessment to measure performance of NWP outputs with the comparison of threshold (FFG) values is performed.

4.1 Assessment of Extreme Rainfall Event Distribution in Turkey

Investigating temporal and spatial distribution of heavy rainfall events can be very useful to understand the causes and occurrence of flash flood events. The most common reason for flash flood occurrence is attributable to heavy and intense rainfall while the type of precipitation formation is not always unique. For instance, frontal activities are more effective over coastal regions but convective instability is more favor over inland parts of Anatolia. Under these circumstances, flood

events should be studied with their temporal and spatial distributions under climatic and meteorological phenomena.

Thus, temporal and spatial distribution of extreme rainfall events are examined by using TSMS severe weather reports between the years 2015 and 2019 in this study. The reports for the period of 2015 and 2019 were downloaded from database of TSMS in the scope of this study.

An event list is prepared for each year by using these reports which contains date and location information. Monthly distribution maps and graphs are performed for last five years with using this list. A script is created for producing these plots in R programming which is an open source script language. R programming has several libraries to solve various issues. For instance, “ggmap” library was used (Kahle and Wickham, 2013) to create poly maps in one plot.

Figure 4.1 is shown for spatiotemporal distribution of extreme rainfall events in Turkey during 2015, 2016 and 2017. Figure 4.2 indicates the same analysis for 2018, 2019 and the period of 2015 – 2019. Legend of maps represents number of events for same location and period.

In 2015, during winter and autumn months extreme rainfall events occur mostly over coastal regions as a result of frontal or Mediterranean based low pressure cyclones effects (Figure 4.1a). In June 2015, extreme events show homogeneous scattering over west of Turkey because of the possibility of convective short term downpours.

In 2016, there are fewer events in winter and autumn months than previous year while scattering of extreme events are dominant over Mediterranean coasts (Figure 4.1b). May, June and August are abundant in terms of flood; events are spreading homogeneously in May and June. On the other hand events take place mostly over Black Sea coast during August where mountainous area allows for formation of orographic precipitation.

In 2017, there is a similar pattern with previous years for winter and autumn seasons. June and August are the top months in case of flooding (Figure 4.1c).

In 2018, there are few events appeared in winter and autumn seasons but also most of the flood events occurred on coastal regions (Figure 4.2a). For example, most of the blue points fall over Aegean and Mediterranean shores but multiplicity and well-scattered of events are remarkable in May and June months.

In 2019, during winter and autumn months events occur mostly over coastal regions as a result of frontal or Mediterranean based low pressure cyclones (Figure 4.2b).

The same analysis is performed over 5 year period from 2015 to 2019 to drive more meaningful spatiotemporal distribution of extreme rainfall occurrence in Turkey. Figure 4.2c shows the monthly distribution of extreme rainfall events occurred between 2015 and 2019. May through August heavy/intense rainfall events more spread over the inland parts of Anatolia due to the fact that convective instability is more dominant while other months generally flooding can be seen over coastal regions as a result of frontal systems. Most of the events took place over Aegean and Mediterranean coastal regions because of low pressure based cyclonic depressions except September. In August and September, Black Sea coast is the most affected region between these years because of the coupled frontal, convective and orographic based systems. However, May and June are the top months with respect to heavy/intense rainfall events considering the fact that convective instability conditions are effective during these months

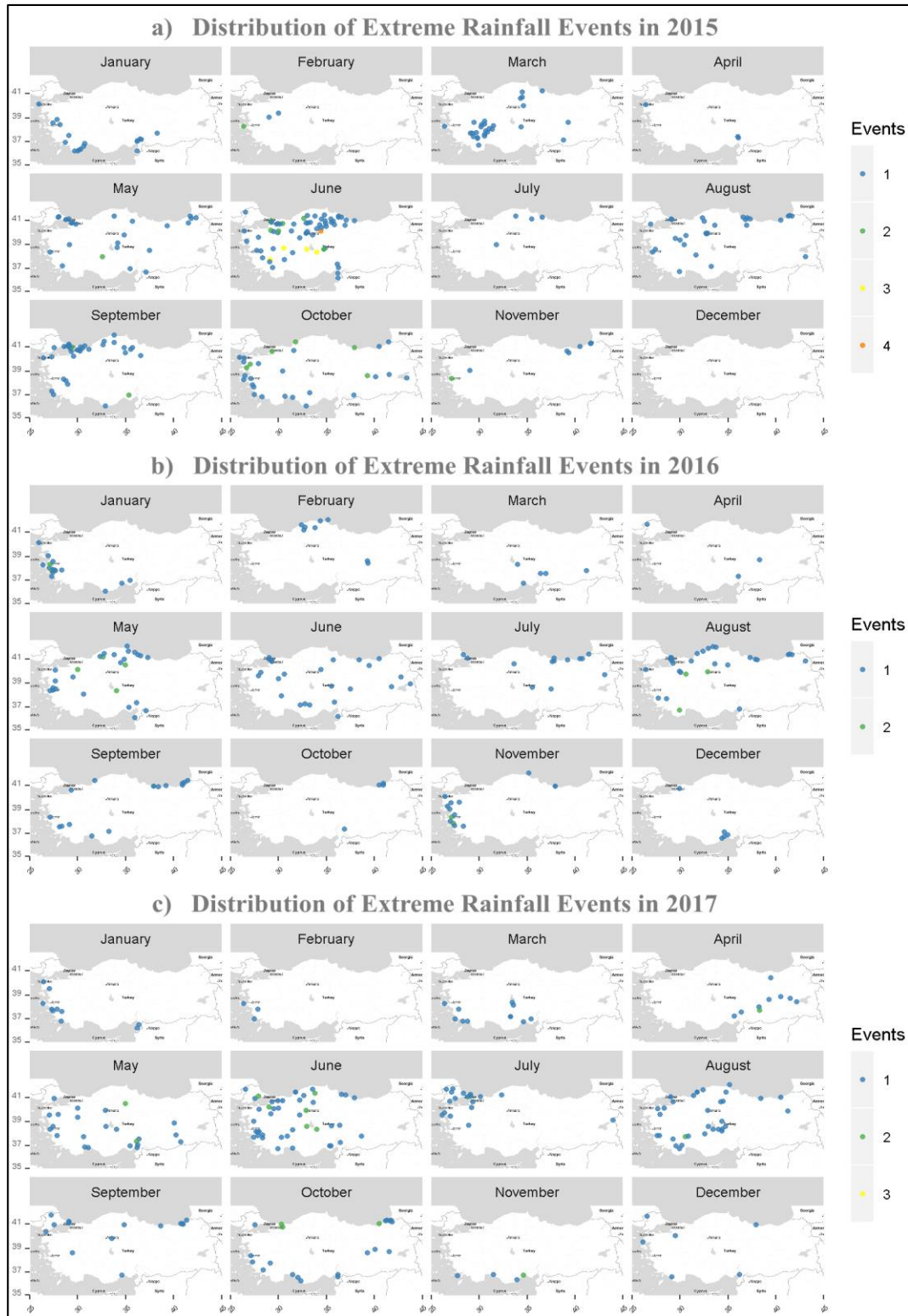


Figure 4.1 Spatiotemporal distribution of extreme rainfall events in Turkey during 2015 (a), 2016 (b) and 2017 (c).

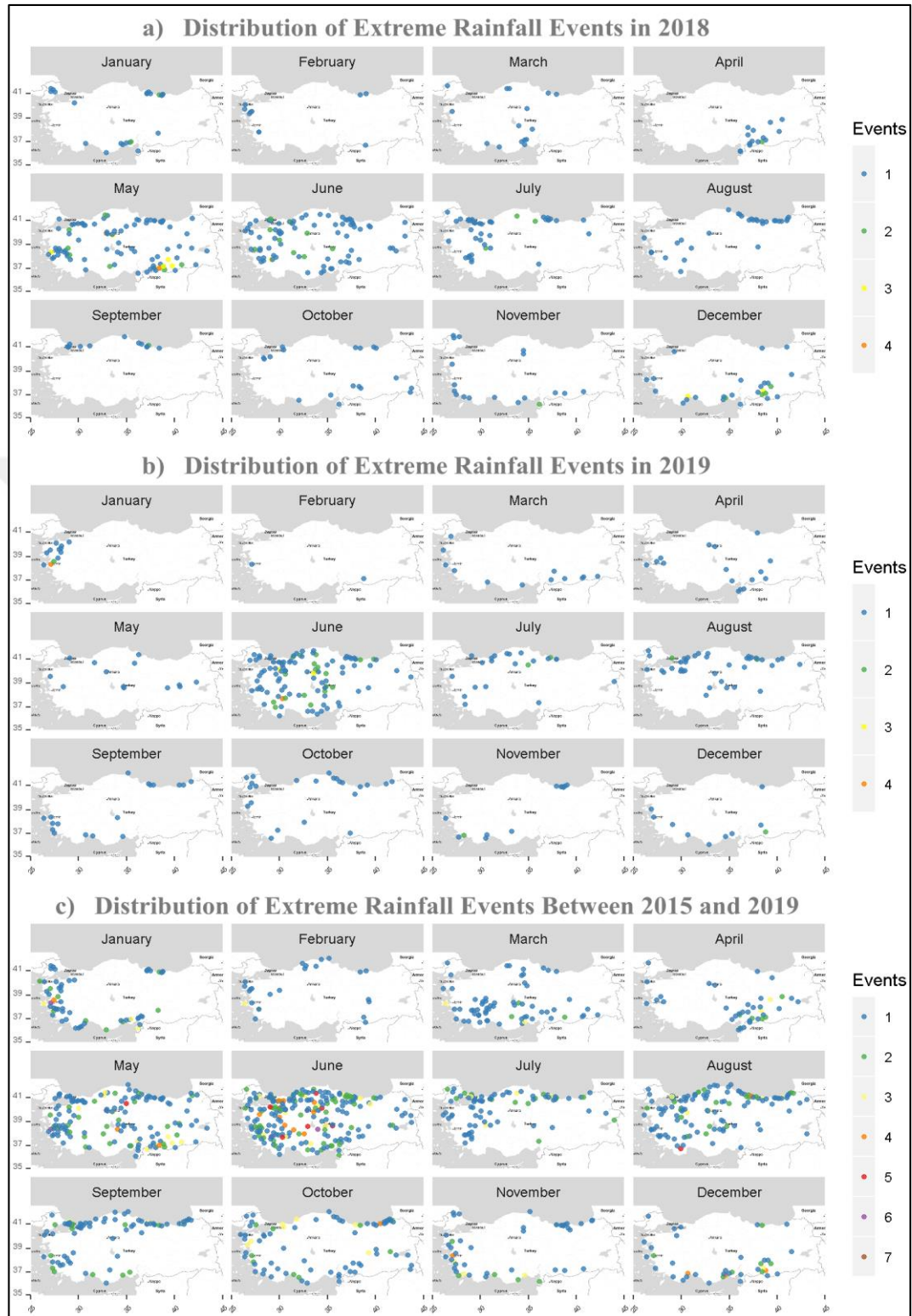


Figure 4.2 Spatiotemporal distribution of extreme rainfall events in Turkey during 2018 (a), 2019 (b) and for the period of 2015-2019 (c).

Figure 4.3 and 4.4 indicates monthly occurrences of extreme rainfall events in Turkey for the five-year period from 2015 to 2019. These bar plots are created by using the event list and the R script which are generated for this thesis. The horizontal axes of plots represent months of the current year and vertical axes show the relative frequency of events. The relative frequency is calculated by dividing each monthly total event to the annual total number of events.

Among total 229 extreme rainfall events occurred in 2015 throughout Turkey, June is the month with the highest occurrence while August, September and October also show remarkable high values in Figure 4.3a. Sum of extreme rainfall events is 134 in 2016. Furthermore, the highest frequency rates occur in May, August and June in terms of flooding events in Figure 4.3b. Number of total extreme rainfall events is 186 in 2017. The highest frequency rate is observed in June during 2017 (Figure 4.3c).

The year 2018 is the extreme year for Turkey with respect to TSMS extreme rainfall events records (TSMS, 2019[b]) since 1940. 331 extreme events occurred in total and May is the month with the highest event occurrence during 2018 (Figure 4.4a). Sum of extreme events is 245 in 2019 and the highest frequency rates appear for June clearly (Figure 4.4b). However, May and June are the top months with respect to extreme rainfall events considering the fact that convective instability conditions are effective during these months. According to the TSMS reports, sum of the extreme rainfall events is 1125 between 2015 and 2019 periods. June and May months have the highest frequency rate as compared to the remaining months (Figure 4.4c).

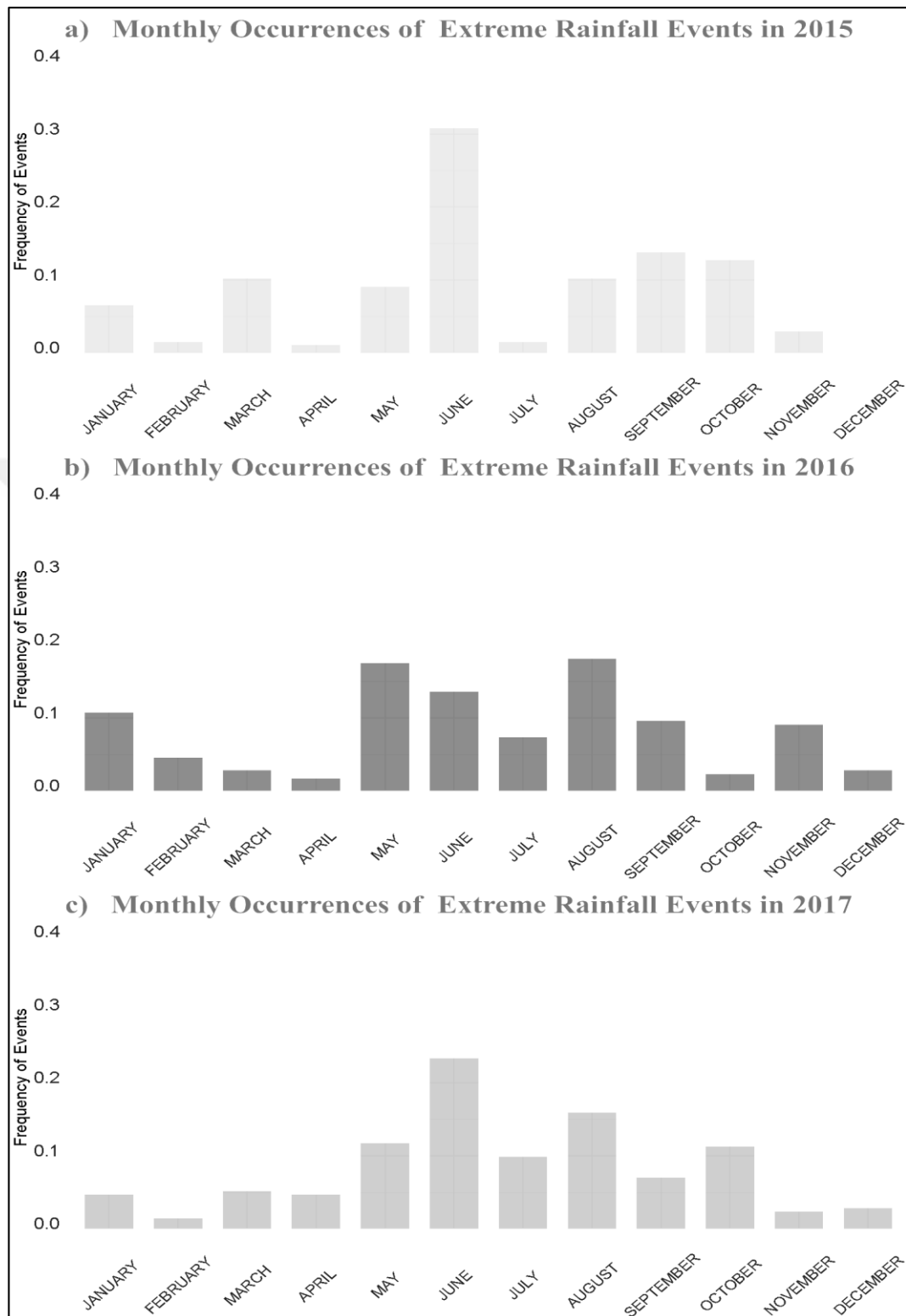


Figure 4.3 Monthly occurrences of extreme rainfall events in Turkey during 2015 (a), 2016 (b) and 2017 (c).

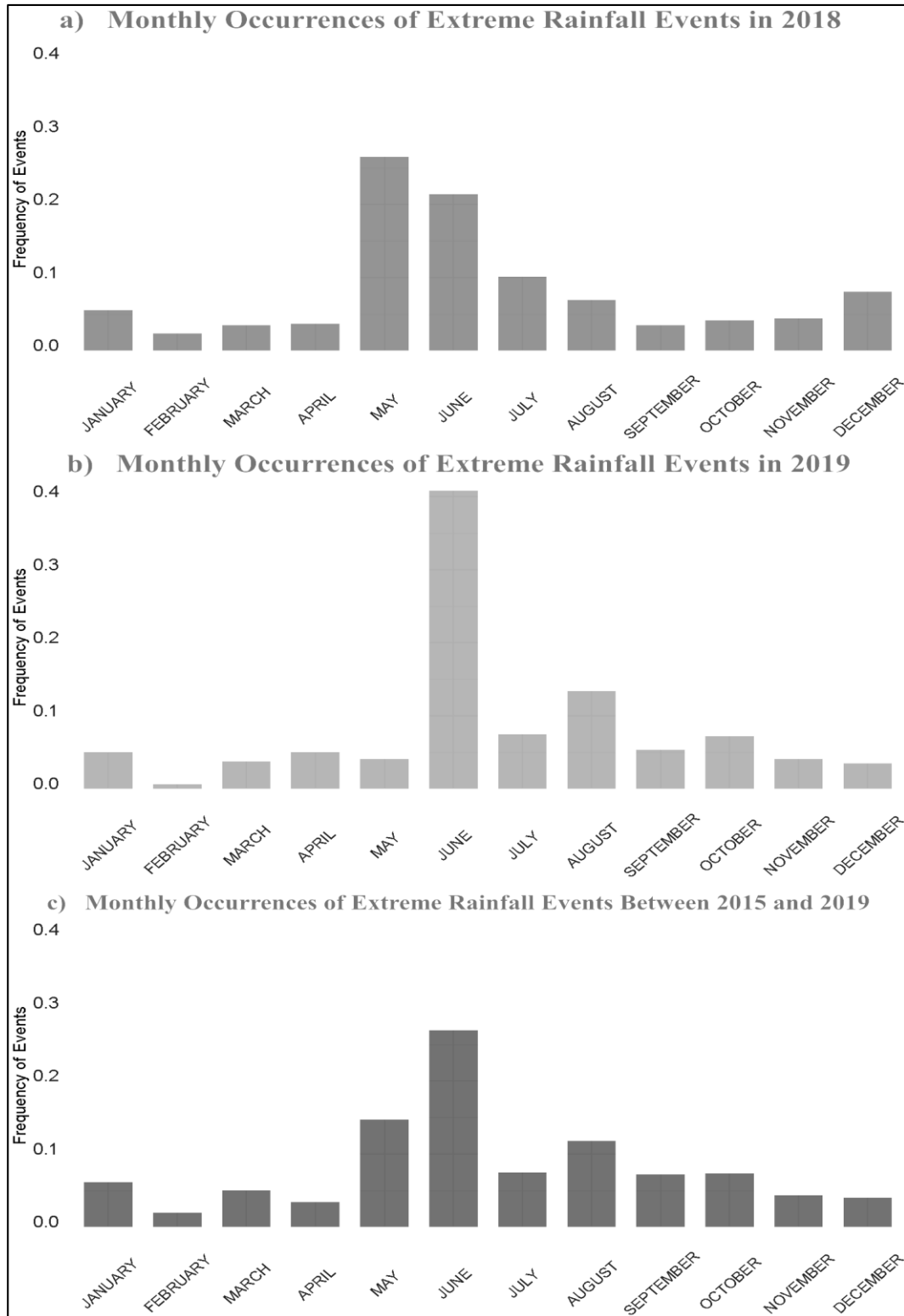


Figure 4.4 Monthly occurrences of extreme rainfall events in Turkey during 2018 (a), 2019 (b) and for the period of 2015-2019 (c).

Under these circumstances, it is clear that Turkey faces the extreme rainfall events often throughout the year but it generally concentrates during spring to autumn months depending on the system signature of precipitation and the geographical location. Frontal influence is dominant over coastal regions during winter and autumn months. Orographic upward is effective over north east of Anatolia where reasonably a mountainous region and convective instability is more common during spring and summer seasons.

It should not be ignored that heavy rainfall may be the main reason for flood but it is not sole; remaining reasons can be listed as snowmelt, landslide, disputes of dam operation and etc. A flood caused by snowmelt runoff is common in eastern Turkey at the beginning of the spring season where heavy snowfall occurs during winter. Yücel et al. (2015[b]) show that the peak timing of snowmelt runoff is shifted to earlier times significantly in the eastern basins of Anatolia because of warming resulted from climate change. This may also turn in increasing the probability of sudden flooding. Nevertheless, the analyses of spatial and temporal distribution of extreme rainfall events show that convective induced intense precipitation has primary importance in terms of flooding.

4.2 Distribution of Lightning Flashes over Turkey

Cumulonimbus is the only cloud type that can produce hail, thunder or lightning. These type clouds and super cells are associated with severe weather conditions such as heavy torrential downpours. The lightning detection also shows presence of huge amount of energy, explaining the intense precipitation activity. It has been proven by many studies that rainfall estimates derived from lightning observations are of potential use for short-term prediction of flash floods.

There are several studies in the literature which have been investigated the relationship with lightning and rainfall amount. Tapia, Dixon and Smith (1998) developed a technique to use lightning flashes for estimating convective rainfall

which includes the ratio between lightning and rainfall, spatial and temporal distribution of both lightning and rainfall. Pineda et al. (2007) used Tapia method successfully for estimating summer season rainfall over northeastern Spain. Gungle and Krider (2006) proved that lightning observations can be used to estimate the location and intensity of convective rainfall over Florida. A lightning-based nowcast-warning method also developed and tested for short-term storms during the warm season which cause intense rainfall and flash flood events (Wu et al., 2018). Lightning observations were also used in the studies for improvement of radar (Rigo et al., 2010) and satellite (Xu et al., 2013) precipitation estimations.

In this study, cloud-to-ground and cloud-to-cloud lightning flashes data is provided from the LDNS which has been used by TSMS since 2015. The lightning data for the five-year period from 2015 to 2019 was taken from TSMS within the scope of this study. The data includes date, location, elevation, direction and current information in point scale.

An R script is created for reading the data and counting the flashes which are fallen inside of the BSMEFFG basins. The flashes data are classified as monthly and visualized by using the script. There are more than eleven thousand sub-basins available in the BSMEFFGS for Turkey. The basin border data exist in shapefile format in the system that is derived by HRC. In addition to basins, approximately more than three million lightning strikes exist for each year. Computing time for counting the flashes over catchments and visualizing it monthly is huge due to size of the data. Thus, ten percent of lightning data was selected randomly for each year and the five-year period by the R script.

The spatiotemporal distribution of lightning flashes over BSMEFFG watersheds for the period of 2015 and 2019 are presented in Figure 4.5 and 4.6. Legend of maps represents the frequency of lightning flashes. The frequency is calculated by dividing monthly number of flashes to monthly maximum value for each basin. The distribution of lightning strikes between 2015 and 2019 has a similar pattern in each year. During cold season (winter and autumn) lightning flashes mostly placed

over coastal regions. However, flashes show homogeneous scattering over Turkey during warm season, especially in May, June and August. The lightning flashes are denser over northwestern Anatolia. These situations were mostly caused by effectiveness of instability conditions. Thus, lightning flashes are denser during warm season than cold one as a trace of intensity rainfall. Oztopal (2017) found similar results in his study which is performed for Turkey between 2010 and 2014.

Figure 4.7 and 4.8 indicates monthly occurrences of lightning flashes in Turkey for the five-year period from 2015 to 2019. In the bar plots, horizontal axes of plots represent months of the current year and vertical axes show the relative frequency of flashes. In each year, monthly occurrences of lightning flashes show a similar pattern. May and June are top months in terms of flashes for each year and all period. It is the fact that convective instability conditions are the most effective during these months. Approximately twenty five million strikes are calculated in total from 2015 to 2019 over Turkey. However, five and seven million flashes were occurred during same period for May and June respectively. It shows that May and June are the top months in terms of convective instability conditions for Turkey (see Figure 4.8c). Additionally, instability conditions are more effective over western and northeastern part of Turkey during these months (see Figure 4.6c).

There is a remarkable similarity between lightning observations and extreme rainfall events during warm season both spatially and temporally between 2015 and 2019 (distribution of the extreme rainfall events in Turkey is given in Figure 4.1 and 4.2). May and June are the top months for both extreme rainfall events and lightning strikes. Extreme rainfall events and lightning flashes are more frequent over western inland and northeastern part of Turkey in May, June and August. There is no doubt that cloud to ground or cloud to cloud lightning flashes have insights for warm season intense rainfall events. Thus, lightning flashes should be considered for rainfall estimation during warm season in Turkey. Eventually, lightning topic should be investigated for nowcasting flash flood warnings in future research.

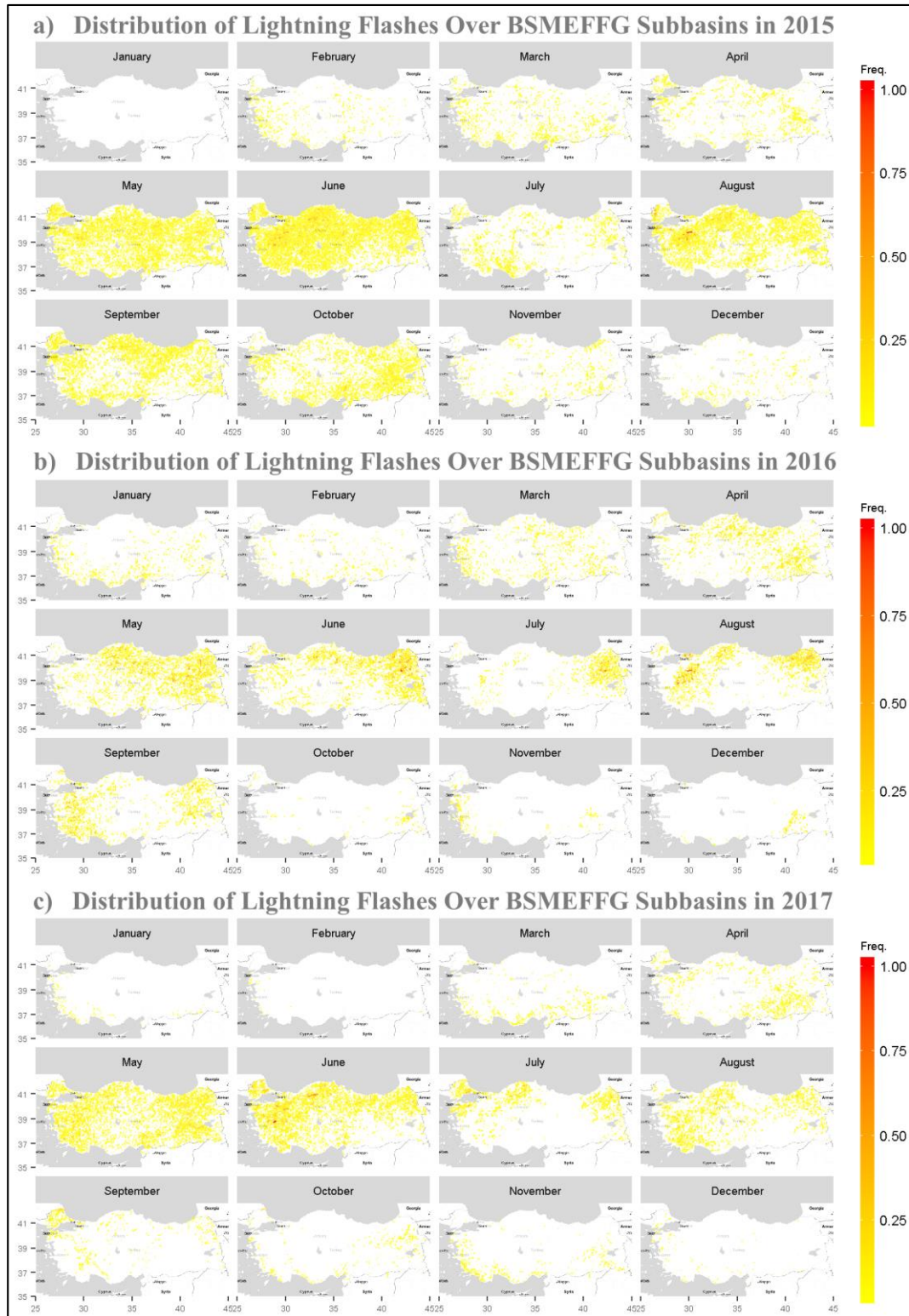


Figure 4.5 Spatiotemporal distribution of lightning flashes over BSMEFFG subbasins for Turkey during 2015 (a), 2016 (b) and 2017 (c).

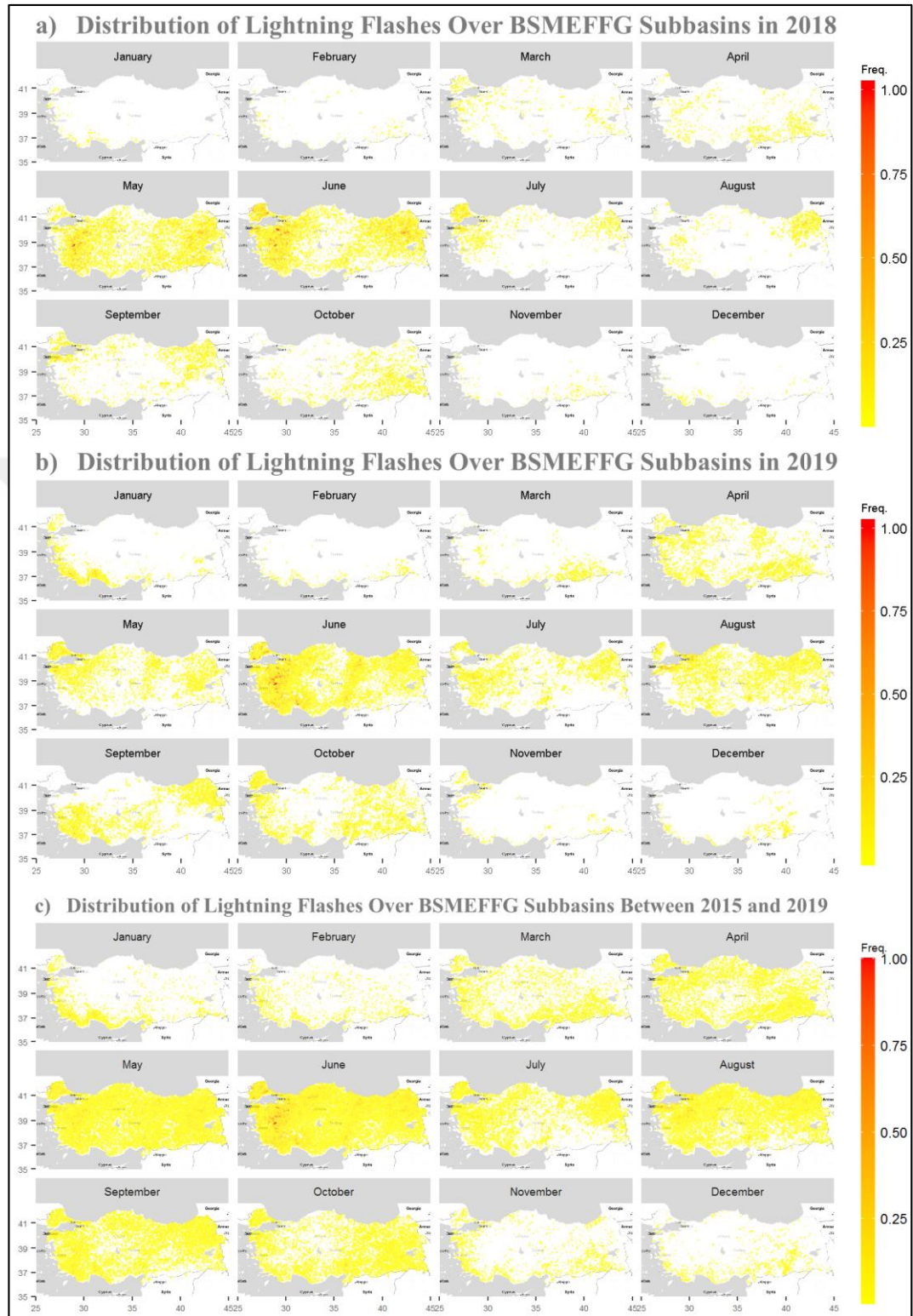


Figure 4.6 Spatiotemporal distribution of lightning flashes over BSMEFFG subbasins for Turkey during 2018 (a), 2019 (b) and for the period of 2015-2019 (c).

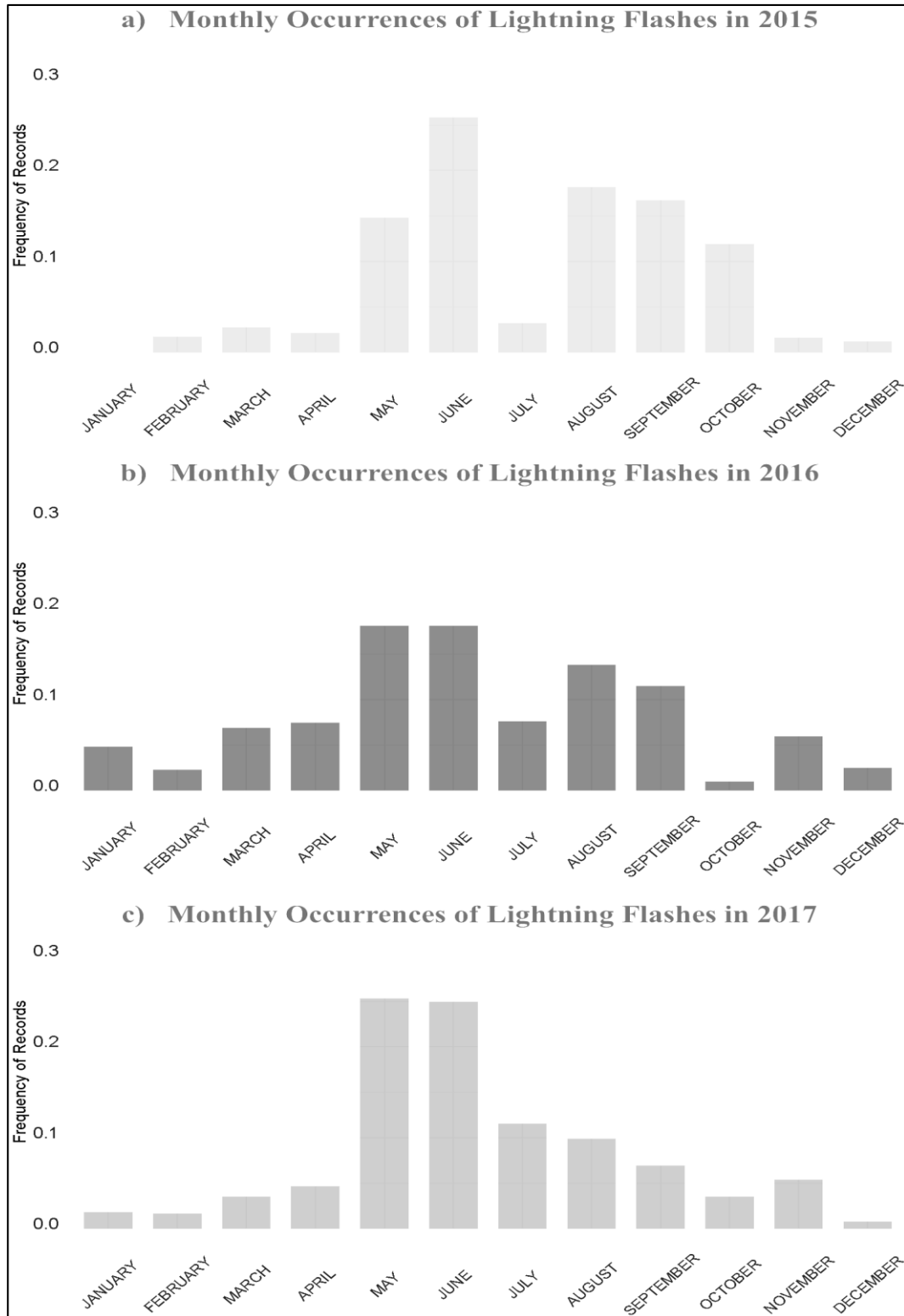


Figure 4.7 Monthly occurrences of lightning flashes in Turkey during 2015 (a), 2016 (b) and 2017 (c).

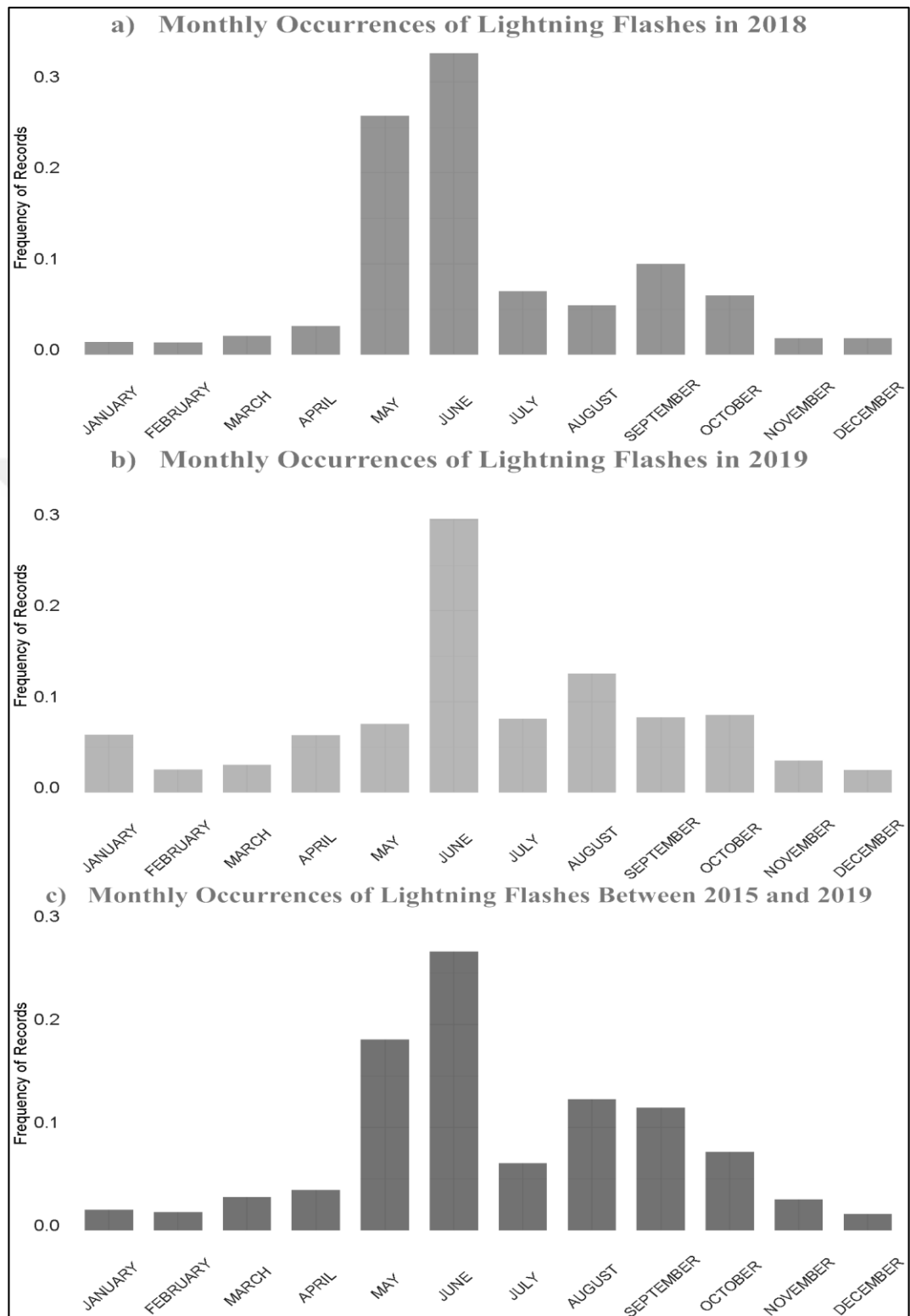


Figure 4.8 Monthly occurrences of lightning flashes in Turkey during 2018 (a), 2019 (b) and for the period of 2015-2019 (c).

4.3 Non-Convective-Induced Flash Flood Case Studies

4.3.1 Flash Flood Events of 16-17 December 2018 in Kemer and Antalya

Mediterranean Sea behaves as storage of energy and moisture for the coastal surface of southwestern Turkey, especially from the beginning of autumn to end of winter when frontal systems related deep troughs are effective. These synoptic formations mostly cause flash flood events by generating large amounts of precipitation in the city. Antalya province is located in southwestern Mediterranean coast of Turkey. Antalya was hit by a low pressure storm during a period of two days of December, 2018. A low pressure depression was displaced over southwestern Mediterranean coast on 16 December and continued to move over Antalya on 17 December. Kemer district and downtown of Antalya city were affected by flash flood events due to heavy rainfall. Figure 4.9 indicates location of study area, selected sub-basins from BSMEFFGS for comparing NWP model rainfall predictions with FFG thresholds and in-situ rainfall gauges in Antalya.

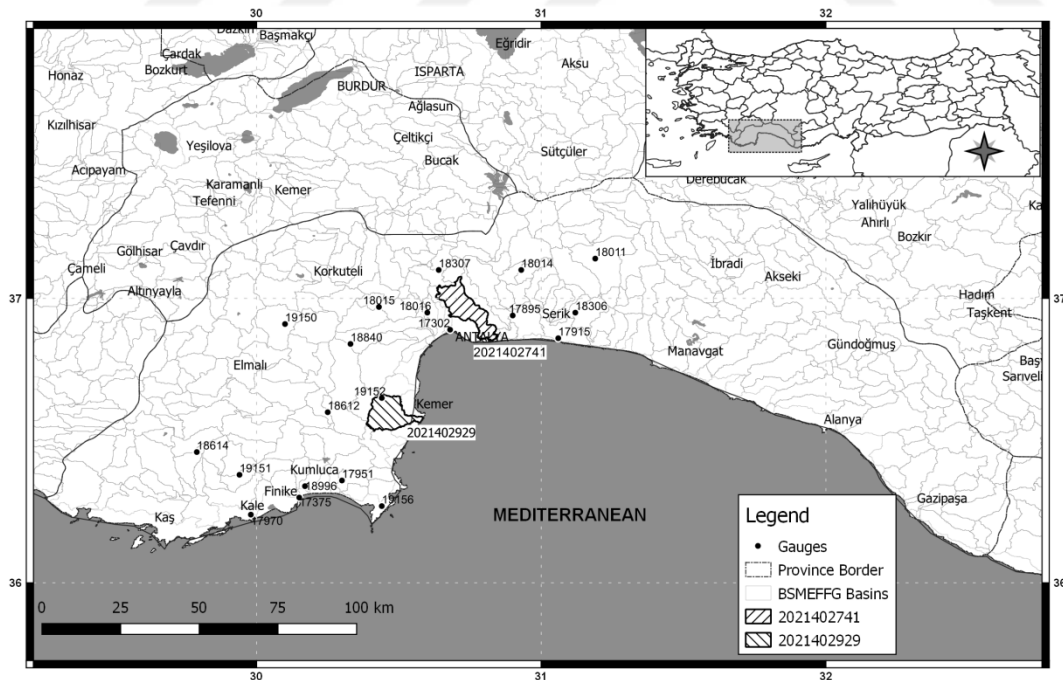


Figure 4.9 Location of Antalya province, rainfall gauges and selected watersheds.

The appropriate sub-basins are selected within the BSMEFFGS to perform individual analysis for this case. Identification numbers 2021402741 and 2021402929 are used for these basins in the BSMEFFGS. The basins are located in Antalya and Kemer borders respectively.

The surface and upper atmosphere charts are used to define rainfall signature for this case (see Figure C.1 and C.2 in Appendices). Flash flood events are verified by related severe weather report from TSMS and newspaper articles (WEB1 and WEB2). The images of flash flood events for Kemer and Antalya can be seen in Figure 4.10.



Figure 4.10 Flash flood event images for Kemer (a) (WEB1) and Antalya (b) (WEB2).

Figure 4.11 and Figure 4.12 are shown to define spatial distribution of observed rainfall on 16 and 17 December. Daily precipitation data from meteorological stations in the region were used to create the maps. At 06:00 UTC on 16 December 2018, heavy rainfall observed over southwest of Turkey, especially amount of rainfall values are higher than 200 mm in Kemer district. At 06:00 UTC on 17 December 2018, observed rainfall values are much higher than previous day and exceed 100 mm in Antalya.

Rainfall gauges in the region and observed daily amounts during the event are given in Table 4.1. The highest daily quantities were observed at station Antalya Bolge (17302), Dosemealti (18307) and Kemer-Ovacik (19152) on 17 December with 124.2, 168.0 and 491.5 mm respectively.

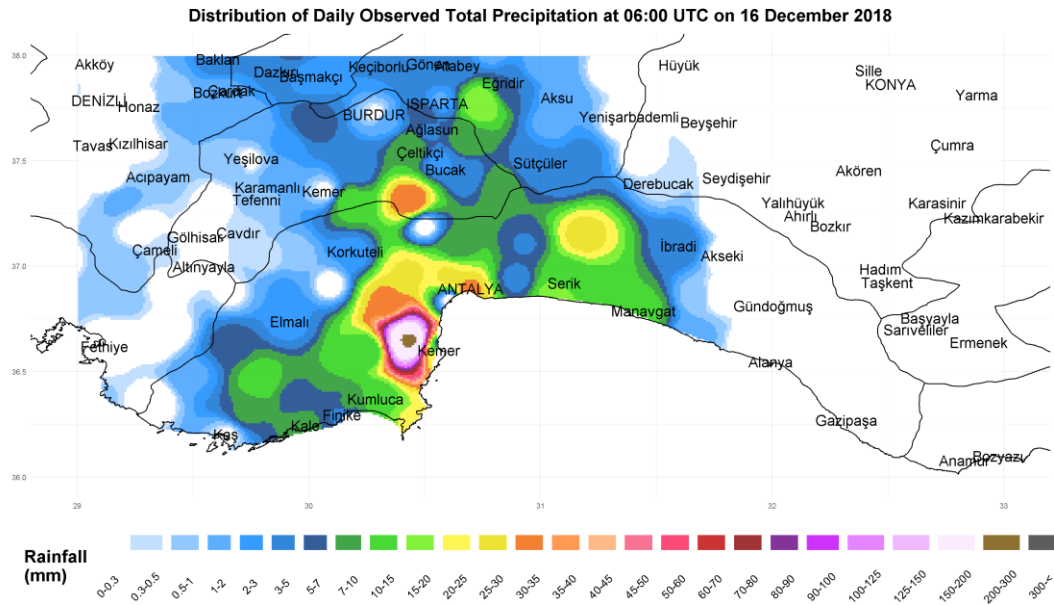


Figure 4.11 Distribution of daily total precipitation at 06:00 UTC on 16 December.

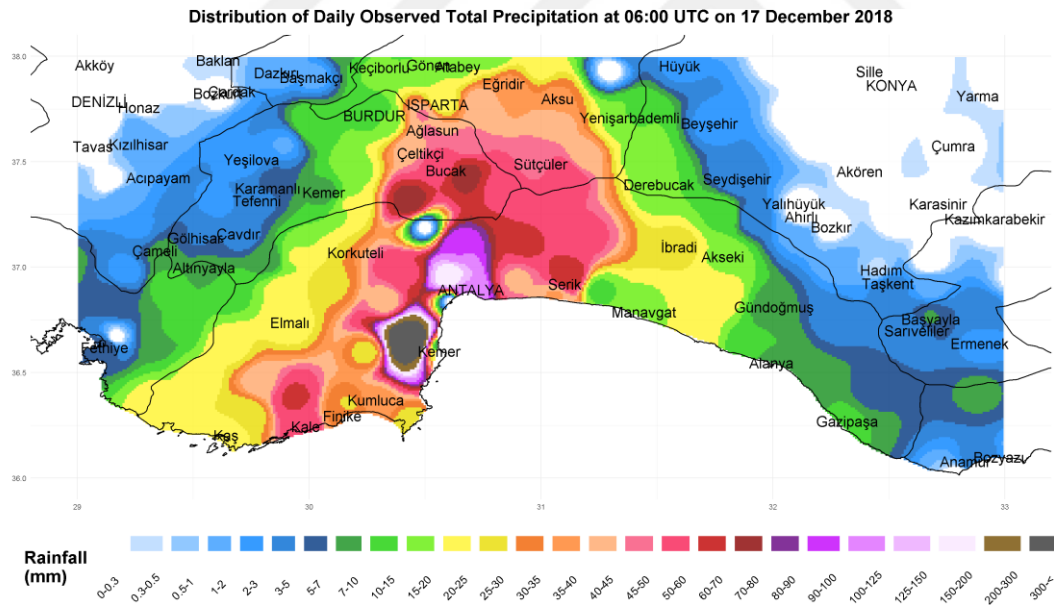


Figure 4.12 Distribution of daily total precipitation at 06:00 UTC on December 17.

Table 4.1 Rain gauges in Antalya province and daily precipitation amounts throughout the event period.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height.m.</i>	<i>Dec15</i>	<i>Dec16</i>	<i>Dec17</i>	<i>Dec18</i>	<i>Total</i>
Antalya Bolge (17302)	36.89	30.68	47	0.10	31.90	124.20	0.00	156.20
Finike (17375)	36.30	30.15	2	0.00	4.50	32.20	0.00	36.70
Aksu/Boztepe Tigem (17895)	36.94	30.90	10	0.00	4.40	44.00	0.40	48.80
Serik/Belek (17915)	36.86	31.06	6	5.80	16.80	39.60	0.10	62.30
Kumluca (17951)	36.36	30.30	60	0.00	11.20	38.20	0.00	49.40
Kale-Demre (17970)	36.24	29.98	25	0.20	7.40	55.60	0.20	63.40
Manavgat/Beşkonak Orman Sahası (18011)	37.14	31.19	142	17.60	27.00	52.00	0.70	97.30
Serik/Gebiz Orman Sahası (18014)	37.10	30.93	78	0.90	4.90	60.90	0.70	67.40
Korkuteli/Bük Orman Sahası (18015)	36.97	30.43	489	0.00	25.60	58.70	0.30	84.60
Döşemealtı/Nebiler Orman Sahası (18016)	36.95	30.60	266	0.00	25.60	168.00	0.30	193.90
Serik (18306)	36.95	31.12	94	14.00	12.90	69.70	0.10	96.70
Döşemealtı/Karain Havacılık (18307)	37.10	30.64	308	0.60	8.00	99.70	0.10	108.40
Kumluca/Akdağ Kovucak Mevki (18612)	36.60	30.25	1001	0.00	10.80	27.90	0.00	38.70
Kaş/Ortabağ Mevki (18614)	36.46	29.79	1423	10.50	12.40	43.40	0.40	66.70
Korkuteli/Saklıkent Kayak Merkezi (18840)	36.84	30.33	1880	0.60	30.90	42.10	0.10	73.70
Finike/Saklısu (18996)	36.34	30.17	52	0.00	7.30	29.60	0.00	36.90
Korkuteli/Beğiş Köyü (19150)	36.91	30.10	1340	0.00	0.00	29.00	0.00	29.00
Demre/Çağman Köyü (19151)	36.38	29.94	753	1.40	6.40	61.70	0.00	69.50
Kemer/Ovacık Köyü (19152)	36.65	30.44	1131	0.10	201.50	491.50	10.50	703.60
Kumluca Radar Sahası (19156)	36.27	30.44	955	0.00	20.40	28.10	0.00	48.50

Cumulative hourly precipitation plots are given in Figure 4.13 for stations 17302 (Antalya) and 19152 (Kemer) respectively. Shape of the both curves are similar except amounts, it can be interpreted that the rainfall signature for both stations is same frontal system since lines are rising gradually. The slope of curves indicates that the highest intensity of precipitation observed at station 17302 between 18:00 UTC December 16 and 00:00 UTC December 17. Additionally, the highest intensity was recorded at station 19152 between 12:00 - 18:00 UTC December 16. The duration of rainfall is longer than six hours so it may lead to the interpretation that the event is not a flash flood. Nevertheless, the highest rainfall intensity was observed in six hours therefore this event was considered as flash flood.

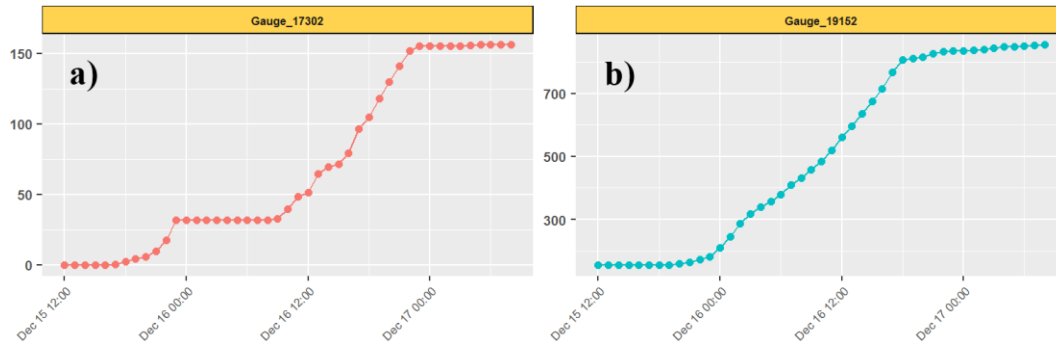


Figure 4.13 Cumulative hourly rainfall curves between 12:00 UTC 15 and 17 December 2018 for station 17302 (a) and 19152 (b).

The both selected sub-basins are covered by Antalya Radar so that radar rainfall estimation is used while MAP calculation within the BSMEFFGS for these basins. Figure 4.14 and Figure 4.15 show that comparing FFG threshold values with six-hour forecast and estimated precipitation amounts between 12:00 UTC 15 December and 00:00 UTC 18 December for catchments 2021402741 (Antalya) and 2021402929 (Kemer) respectively.

For both basins the remotely sensed precipitation shows under-estimation but particularly MAP values are very small for Kemer basin even though on-site gauge data is used for bias adjustment of MAP. However, station 17302 is available in the BSMEFFGS and GMAP value exceed FFG threshold for catchment 2021402741 at 00:00 UTC on 17 December. Unfortunately, GMAP values don't exceed FFG threshold for watershed 2021402929 because station Kemer-Ovacik (19152) is not included within the BSMEFFGS where extreme precipitation is recorded and less rainfall amounts are observed by rain gauges near the watershed. FFG values are lower than ECMWF and ALARO rainfall predictions at 00:00 UTC on December 17 for sub-basin Antalya (2021402741). However, WRF precipitation forecasts never exceed the threshold for this period and it means that ALARO and ECMWF models can be assumed as convenient to prepare flash flood warnings for this watershed in contrast to WRF model. When similar analyses are implemented for sub-basin Kemer (2021402929), each NWP model predictions are higher than threshold at 18:00 UTC on December 16. The analysis shows that ECMWF and ALARO models are very functional to prepare flash flood warnings for this case.

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021402741 (2018-12-15 12:00 UTC - 2018-12-18 00:00 UTC)

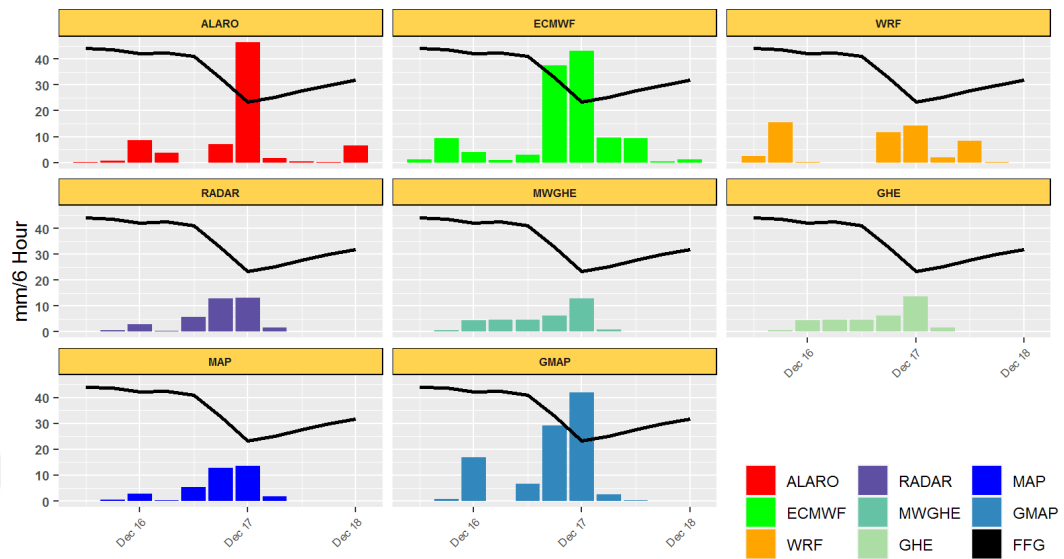


Figure 4.14 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021402741 (Antalya).

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021402929 (2018-12-15 12:00 UTC - 2018-12-18 00:00 UTC)

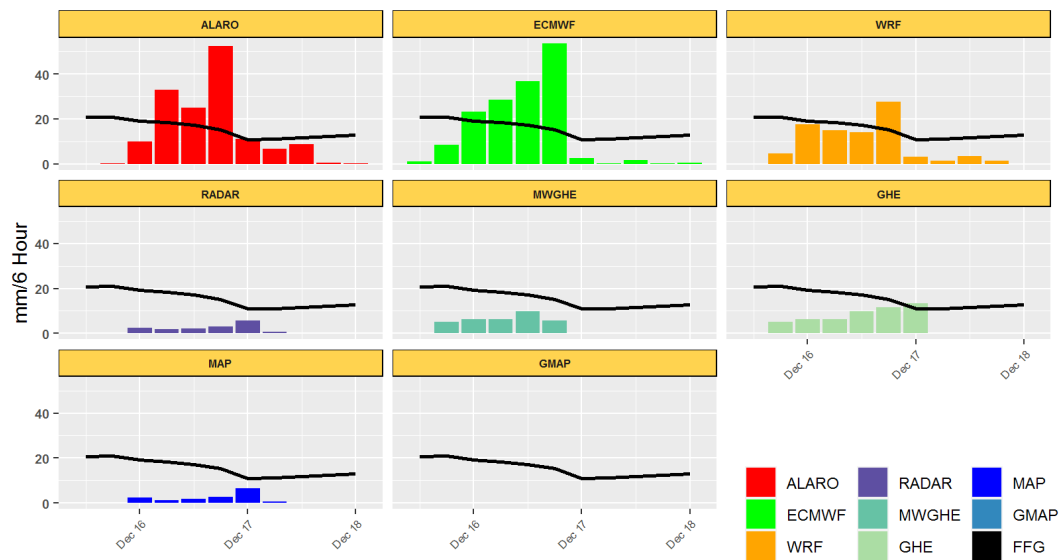


Figure 4.15 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021402929 (Kemer).

4.3.2 Flash Flood Events on 28 September 2019 in Arhavi and Borcka

Artvin province is located in the Black Sea coast and represented by mountainous topography hence orographic precipitation evolution is dominant. Convective instability is dominant at the end of the summer and beginning of fall over the Eastern Black Sea area and that phenomenon causes mostly intense precipitation and flooding over this region. The eastern Black Sea coastal region is one of the wettest areas in Turkey because of mountainous topography and its orographic effect. Thus, the flash flood events took place not only because of frontal depression or orography or convective activities but also realized coupling all of them together. On 28 September 2019, several devastating flash floods affected Artvin province. In particular, Arhavi and Borcka towns of Artvin have been affected by intense downpour. Heavy rain started early times of 28 September and ended at night of same day because of coupling frontal and orography activities.

Figure 4.16 indicates location of study area, selected sub-basins from BSMEFFGS and in-situ rainfall gauges in Artvin province.

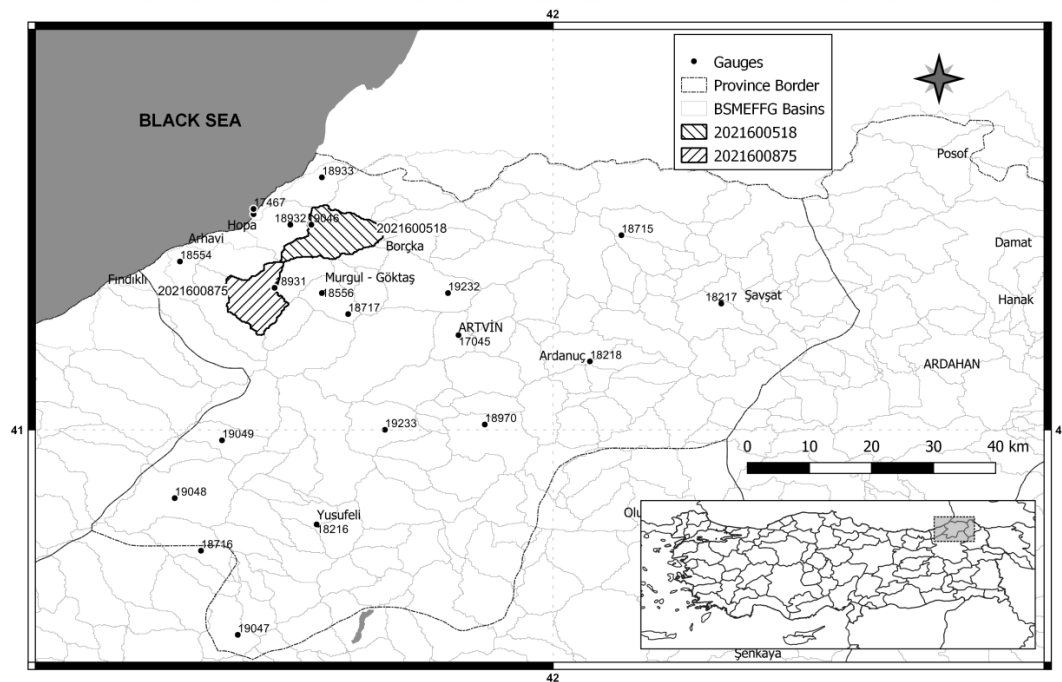


Figure 4.16 Location of Artvin province, rainfall gauges and selected watersheds.

The appropriate sub-basins are selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. Identification numbers 2021600875 and 2021600518 are used for these basins in the BSMEFFGS. These basins are located in Arhavi and Borcka districts borders respectively.

The surface and upper atmosphere charts are used to define rainfall signature for this case (see Figure C.3 and C.4 in Appendices). Flash flood events are verified by related severe weather report from TSMS and newspaper article (WEB3). Figure 4.17 shows images of flash flood events for Borcka and Arhavi. According to the TSMS severe weather report, there is no casualty due to flash flood but event caused landslide. The highway - which connects Borcka and Arhavi districts - was damaged with covering mud and huge amount of water; trucks were dragged from road to stream by water.

Figure 4.18 shows distribution of daily precipitation on 28 September at 06:00 UTC. The figure shows that more than 100 mm rainfall is observed at many stations in Artvin province.

Rainfall gauges in the region and observed daily amounts during the event are given in Table 4.2. The highest daily precipitation was observed at station Arhavi / Boyuncuk Koyu (18931) and Borcka / Cankurtaran Gecidi (19046). On morning 28 September, 89.4 mm and 134.2 mm daily rainfall amounts were observed at stations 18931 and 19046 respectively.

Figure 4.19 shows cumulative rainfall curves for these stations. Hourly rainfall data between 18:00 UTC 27 September and 18:00 UTC 28 September is used for the plots. Station number 18931 represents Arhavi and the other one is for Borcka. Slope of curves indicate that the highest intensity of precipitation is found between 00:00 and 06:00 UTC on 28 September for both station.



Figure 4.17 Flash flood event images for Borcka (a) and Arhavi (b) (WEB3).

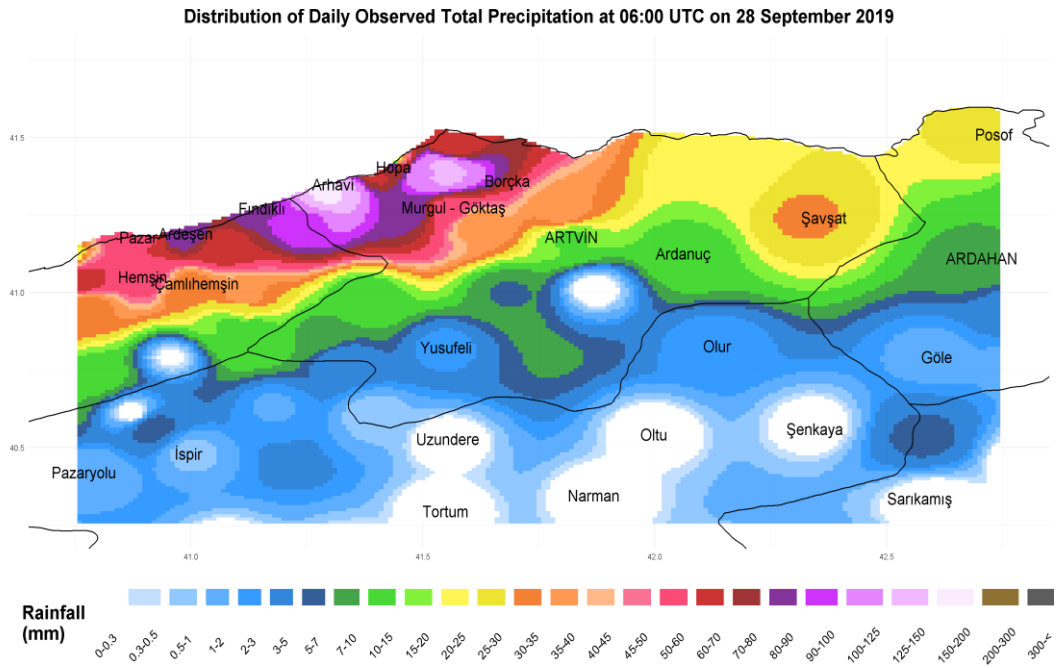


Figure 4.18 Distribution of daily total precipitation at 06:00 UTC on 28 September.

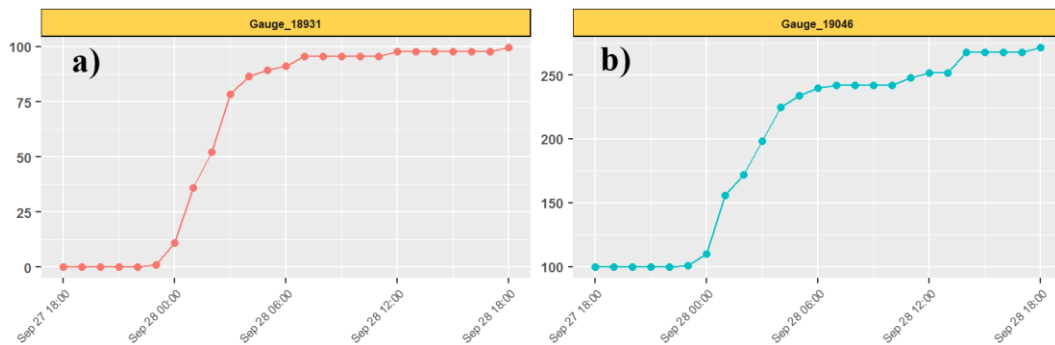


Figure 4.19 Cumulative hourly rainfall plots between 18:00 UTC 27 September 2019 and 18:00 UTC 28 September 2019 for station 18931 (a) and 19046 (b).

Table 4.2 Rain gauges in Artvin province and daily precipitation amounts throughout the event period.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>Sept28</i>	<i>Sept29</i>	<i>Total</i>
Hopa (17042)	41.41	41.43	33	86.00	24.90	110.90
Artvin (17045)	41.18	41.82	613	14.60	6.80	21.40
Hopa Ana Mendirek Fener (17467)	41.42	41.43	0	0.00	0.00	0.00
Yusufeli (18216)	40.82	41.55	601	2.60	0.00	2.60
Şavşat (18217)	41.24	42.32	1125	30.30	0.80	31.10
Ardanuç (18218)	41.13	42.07	577	12.40	1.00	13.40
Arhavi (18554)	41.32	41.29	290	152.10	15.60	167.70
Murgul (18556)	41.26	41.56	565	53.70	5.50	59.20
Şavşat/Çukur Yaylası (18715)	41.37	42.13	2257	20.30	15.90	36.20
Yusufeli/Dokumacılar Köyü (18716)	40.77	41.33	2057	3.50	0.00	3.50
Murgul Karagöl (18717)	41.22	41.61	2024	36.60	2.70	39.30
Arhavi/Boyuncuk Köyü (18931)	41.27	41.47	1345	89.40	10.40	99.80
Hopa/Çavuşlu Köyü (18932)	41.39	41.50	330	122.60	52.70	175.30
Hopa/Köprücü Köyü (18933)	41.48	41.56	425	60.60	23.00	83.60
Artvin/Yukarımaden Köyü (18970)	41.01	41.87	1503	0.00	0.10	0.10
Borçka/Cankurtaran Geçidi (19046)	41.39	41.54	659	134.20	44.50	178.70
Yusufeli/Yamaçüstü Köyü (19047)	40.61	41.40	1918	0.60	0.10	0.70
Yusufeli/Yaylalar Köyü (19048)	40.87	41.28	1784	9.20	2.10	11.30
Yusufeli/Altıparmak Köyü (19049)	40.98	41.37	1481	11.00	1.20	12.20
Artvin/Beşagıl Köyü (19232)	41.26	41.80	695	37.30	4.40	41.70
Yusufeli/Demirköy Köyü (19233)	41.00	41.68	988	6.90	0.00	6.90

The basins 2021600875 (Arhavi) and 2021600518 (Borcka) are not covered by any radar so that only satellite and on-site observations are used to produce MAP in the BSMEFFGS.

Figure 4.20 and Figure 4.21 indicate that comparing FFG threshold values with six-hour forecast and estimated precipitation amounts between 18:00 UTC 27 September and 18:00 UTC 28 September for catchments 2021600875 (Arhavi) and 2021600518 (Borcka) respectively.

For both basins the remotely sensed precipitation shows under-estimation. However, station 18931 is available in the BSMEFFGS and GMAP value exceed FFG threshold for catchment 2021600875 at 00:00 UTC on 28 September. Unfortunately, GMAP values don't exceed FFG threshold for watershed 2021600518 because station 19046 is not included within the BSMEFFGS where intense rainfall was observed.

Over both sub-basins FFG values are lower than values for ALARO, ECMWF and WRF rainfall predictions at 00:00 UTC on 28 September. It means that flash flood occurrence risk exist as per all NWP model, especially WRF. The analysis shows that these three NWP models are successful and can be assumed as convenient to prepare flash flood warnings for this case study.

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021600875 (2019-09-27 18:00 UTC - 2019-09-28 18:00 UTC)

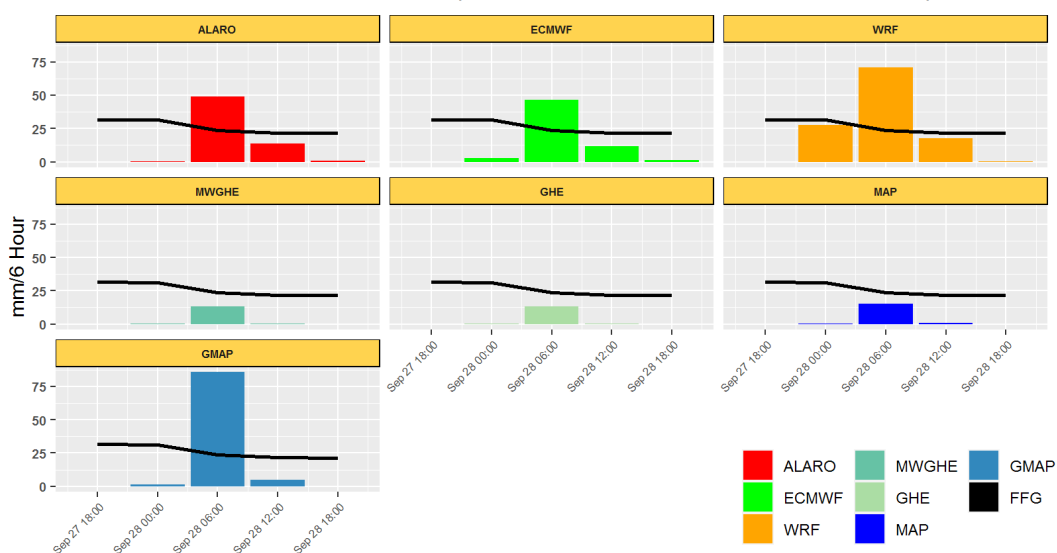


Figure 4.20 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021600875 (Arhavi).

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021600518 (2019-09-27 18:00 UTC - 2019-09-28 18:00 UTC)

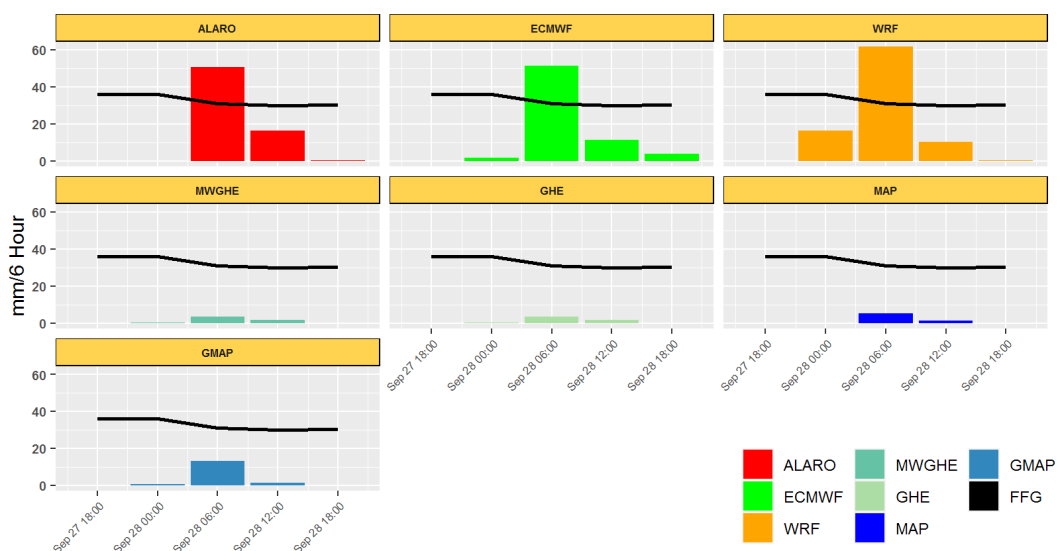


Figure 4.21 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021600518 (Borcka).

4.3.3 Flash Flood Event on 08 February 2017 in Bodrum

Aegean Sea is storage of moisture for the western coasts of Turkey, especially from the beginning of autumn to end of winter when frontal systems are effective related deep troughs. These synoptic formations may result with catastrophic flash flood events by generating large amounts of precipitation. The Mugla province affected by the flash floods frequently is one of the wettest area in Turkey with 805 mm long term average. It is noted that the normal of Turkey is 574 mm (TSMS, 2019[a]). On 8 February 2017, a deep low pressure system with heavy rainfall hit the southwestern coasts of Turkey and caused flash flood in Bodrum district of Mugla province. The flash flood caused destructive impacts in terms of social and economic losses.

Figure 4.22 indicates location of study area, selected watershed from BSMEFFGS for Bodrum to compare NWP model rainfall predictions with FFG thresholds and in-situ rainfall gauges in Mugla province.

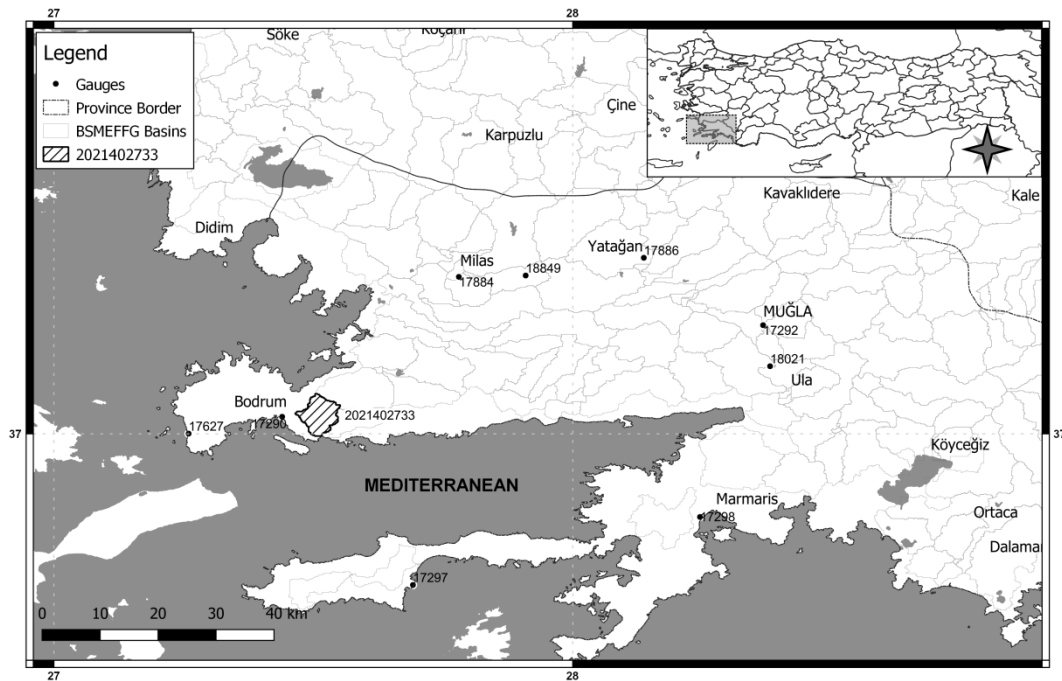


Figure 4.22 Location of Mugla province, rainfall gauges and selected watershed.

The appropriate watershed is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. Identification number 2021402733 is used for this basin in the BSMEFFGS. The basin is located inside of Bodrum district border.

The surface and upper level synoptic charts are used to define rainfall signature for this case (see Figure C.5, C.6 and C.7 in Appendices). In this case, the flash flood event was caused by a low pressure depression therefore the rainfall system is classified as frontal type precipitation. Flash flood events are verified by related severe weather report from TSMS and newspaper article (WEB4). The image of flash flood event for Bodrum can be examined in Figure 4.23.

Figure 4.24 indicates the spatial distribution of observed rainfall on 08 February at 06:00 UTC. The daily precipitation data from meteorological stations in the region were used to create the maps. On 8 February, heavy rainfall is observed over southwestern coast of Turkey with more than 40 mm rainfall amounts.

Rainfall gauges in the region and observed daily amounts during the event are given in Table 4.3. The highest daily rainfall amount was observed at station Bodrum (17290) with 56.8 mm.

Bodrum meteorological station with 17290 identification number is the closest one to flooded region so its data have been used to explain the event. Figure 4.25 shows cumulative rainfall curve for this station. Hourly rainfall data between 12:00 UTC 07 February and 12:00 UTC 08 February is used for the plot. It can be interpreted from the line that rainy period lasted just within six-hours interval between 00:00 UTC and 06:00 UTC on 08 February. Thus, observed daily rainfall with 56.8 mm at Bodrum station should be considered as six-hour rainfall which is considered as very heavy precipitation intensity.



Figure 4.23 Flash flood event image for Bodrum (WEB4).

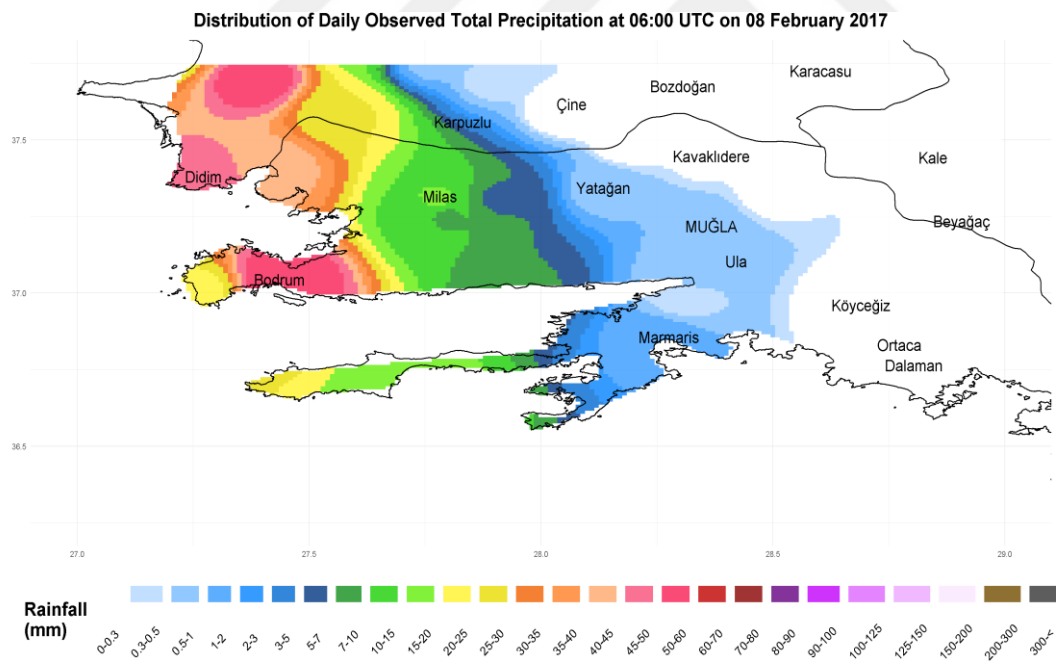


Figure 4.24 Distribution of daily total precipitation at 06:00 UTC on 08 February.

Table 4.3 On-site gauges in Mugla and daily rainfall amounts on 08 February.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>Feb08</i>
Bodrum (17290)	37.03	27.44	26	56.80
Bodrum/Turgutreis Marina (17627)	37.00	27.26	6	23.60
Dikili (17180)	39.07	26.89	3	19.00
Datça (17297)	36.71	27.69	28	18.60
Milas (17884)	37.30	27.78	57	15.40
Milas Orman Sahası (18849)	37.31	27.91	529	6.80
Bayındır (18049)	38.20	27.67	70	5.50
Marmaris (17298)	36.84	28.25	16	1.60
Muğla (17292)	37.21	28.37	646	0.80
Yatağan (17886)	37.34	28.14	365	0.60
Ula/Helikopter Pisti Orman Sahası (18021)	37.13	28.38	649	0.60

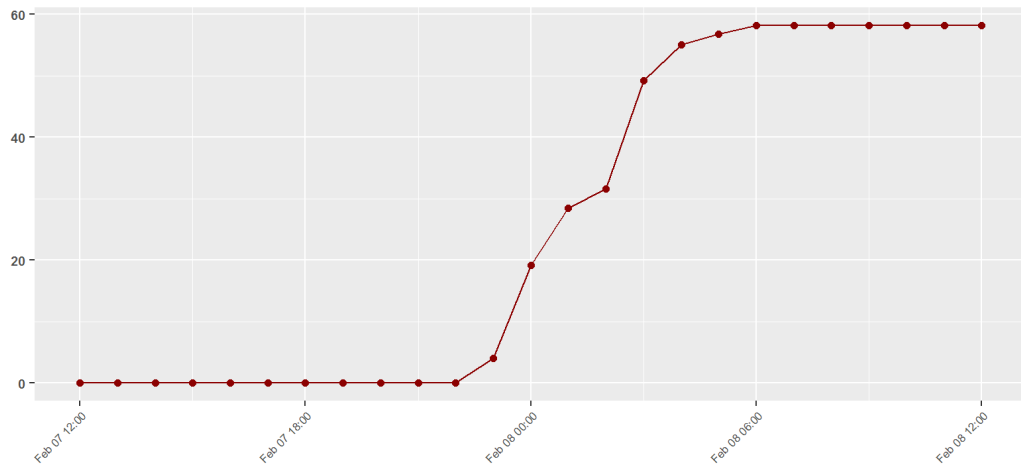


Figure 4.25 Cumulative hourly rainfall curve between 12:00 UTC 07 February 2017 and 12:00 UTC 08 February 2017 for station Bodrum (17290).

The selected basin (2021402733) is covered by Mugla Radar umbrella thence radar rainfall is used to estimate MAP product of BSMEFFGS. Figure 4.26 indicates the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 12:00 UTC 07 February and 12:00 UTC 08 February 2017 for catchment 2021402733 (Bodrum). Remotely sensed precipitation estimations such as radar, GHE and MWGHE exceed the FFG threshold value at 06:00 UTC on 08 February. Meteorological station 17290 is available within the BSMEFFGS so that GMAP value exceed threshold at 06:00 UTC on 08 February. As expected, MAP product is above the FFG for the same period. Only WRF model predictions are higher than FFG threshold for 00:00 UTC and 06:00 UTC on 08 February, particularly for six-hour prediction at 06:00 UTC. It can be assumed that WRF model is suitable in context of precipitation prediction and flash flood warning for this case study.

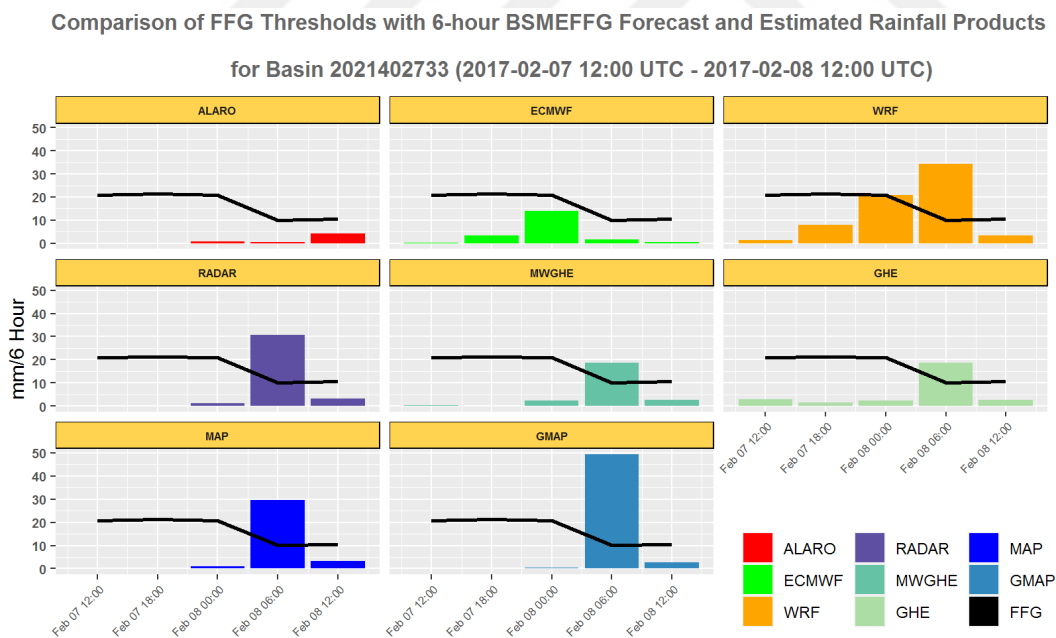


Figure 4.26 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021402733 (Bodrum).

4.3.4 Flash Flood Event of 11-12 January 2019 in Susurluk

Over the northwest Aegean coastal region, heavy precipitation may be result of either frontal or non-frontal processes as air mass lifted up by convective or orographic procedures- or a combination of both. Kaz Mountains are located near the Gulf of Edremit with more than 1700 meter altitude therefore heavy rainfall and snowfall is common during fall and winter terms respectively. These hydrometeorological and topographical conditions often cause flash flood events in Balıkesir by generating large amount of water volume. Balıkesir city was hit by a low pressure storm between 11 and 12 January 2019. The frontal system depending on that low depression caused intermittent heavy precipitation over northwestern Turkey. Susurluk district and Balıkesir center were affected by destructive flash floods due to this frontal system.

Figure 4.27 indicates location of study area, selected sub-basin from BSMEFFGS for Susurluk and on-site rainfall gauges in Balıkesir province.

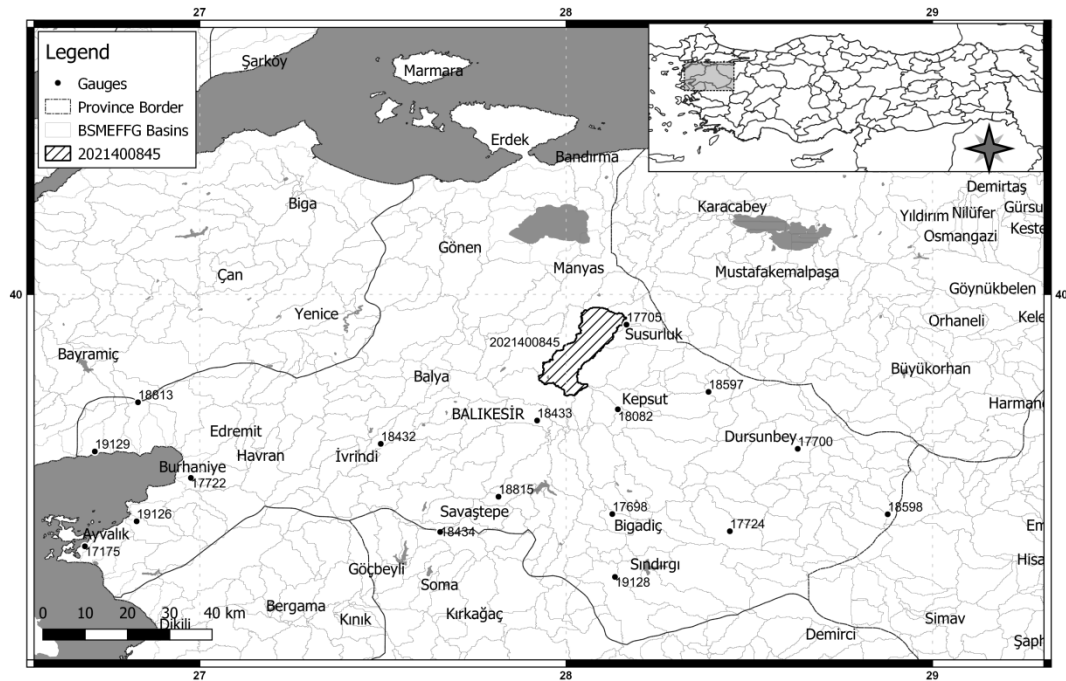


Figure 4.27 Location of Balıkesir province, rainfall gauges and selected watershed.

The appropriate watershed is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. Identification number 2021400845 is used for this basin in the BSMEFFGS. The watershed is located inside of Susurluk district border.

The synoptic analysis is done to define rainfall signature for this case by using surface and upper atmosphere charts (see Figure C.8, C.9 and C.10 in Appendices). Synoptic analysis shows that flash flood event was caused by frontal heavy rainfall with a deep low pressure depression in this case. Flash flood events are verified by related severe weather report from TSMS and newspaper article (WEB5). According to the TSMS report, snow melting contributed to flash flood occurrence in addition to frontal rainfall. In Susurluk, agricultural areas, roads and property were damaged by heavy rainfall. The image of flash flood event for Susurluk can be examined in Figure 4.28.

Figure 4.29 indicates that spatial distribution of observed rainfall at 06:00 UTC on 12 January; more than 40 mm amounts were observed in Balıkesir province and its surrounding.

On-site rainfall gauges in the region and observed daily amounts along the event period are given in Table 4.4. At the stations Balıkesir (18433), Susurluk (17705) and Kepsut (18082), considerable rainfall amounts were observed during the three-day period. On 12 January, 50.4 mm, 51.4 mm and 40.2 mm amount of rainfalls were observed at these stations respectively.

Gauge 17705 (Susurluk) is the closest one to the selected watershed and flooded area so that its data have been used to explain the event. Figure 4.30 indicates the cumulative rainfall curve for this station for the period 00:00 UTC 10 January and 23:00 UTC 12 January. It can be interpreted from the plot that rainfall signature is frontal because curve is rising gradually. Additionally, the highest intensity that refers the possible reason for flash flood was observed between 06:00 UTC and 12:00 UTC on 11 January 2019.

The rainfall duration is more than six hours, so it may lead to the interpretation that the event was not a flash flood. However, this event was considered as a flash flood because the highest rainfall intensity was observed in six hours.



Figure 4.28 Flash flood event image for Susurluk district (WEB5).

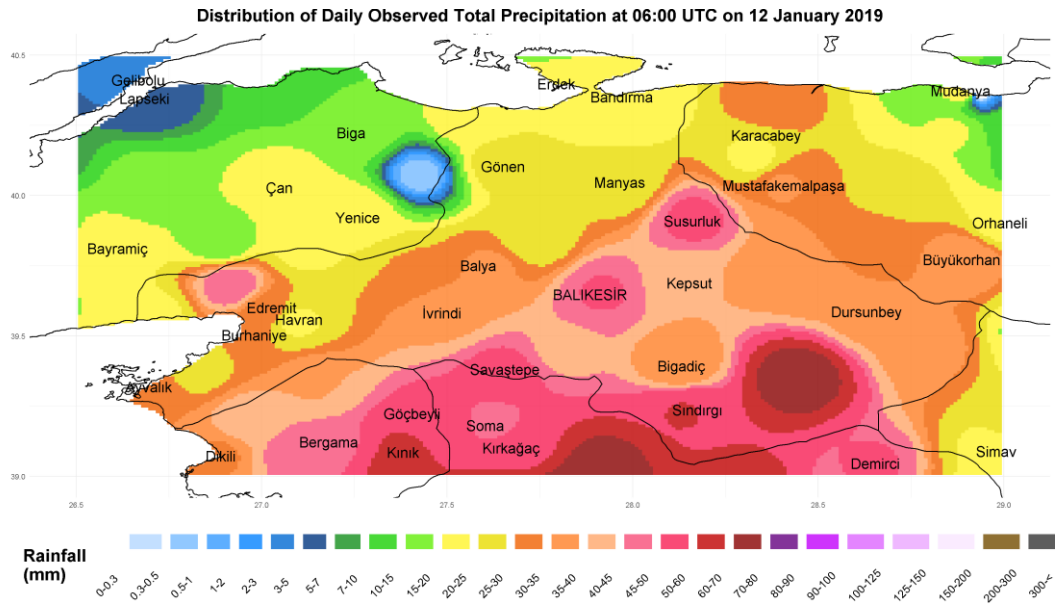


Figure 4.29 Distribution of daily total precipitation at 06:00 UTC on 12 January.

Table 4.4 Gauges in Balıkesir and rainfall amounts throughout the event period.

Station	Lat	Lon	Height	January10	January11	January12	Total
AYVALIK (17175)	39.31	26.69	4	30.60	10.70	34.40	75.70
BİGADİÇ (17698)	39.40	28.13	260	0.00	36.40	35.00	71.40
DURSUNBEY (17700)	39.58	28.63	637	0.00	2.20	38.20	40.40
SUSURLUK (17705)	39.92	28.16	47	1.80	7.40	51.40	60.60
BURHANİYE (17722)	39.50	26.98	20	11.60	18.60	30.40	60.60
BİGADİÇ/AŞAĞIÇAMLI KÖYÜ (17724)	39.35	28.45	844	19.40	32.20	75.60	127.20
KEPSUT (18082)	39.69	28.14	97	0.00	16.30	40.20	56.50
İVRİNDİ (18432)	39.59	27.49	240	12.40	22.90	38.80	74.10
BALIKESİR (18433)	39.66	27.92	110	5.70	25.10	50.40	81.20
SAVAŞTEPE (18434)	39.35	27.66	293	13.00	57.10	53.10	123.20
KEPSUT/DALKÖY (18597)	39.73	28.39	865	0.50	28.60	37.60	66.70
DURSUNBEY/REŞADİYE MEVKİ (18598)	39.40	28.88	1360	37.90	6.60	28.80	73.30
EDREMİT/KAZ DAĞI MİLLİ PARKI (18813)	39.70	26.83	1733	50.80	96.90	49.10	196.80
ALTIEYLÜL/KİRAZPINAR KÖYÜ (18815)	39.45	27.82	425	9.00	55.60	44.00	108.60
GÖMEÇ (19126)	39.38	26.83	15	25.60	18.00	28.30	71.90
SINDIRGI (19128)	39.23	28.13	237	4.00	80.50	60.20	144.70
EDREMİT/ALTINOLUK (19129)	39.57	26.71	33	16.70	34.30	23.50	74.50

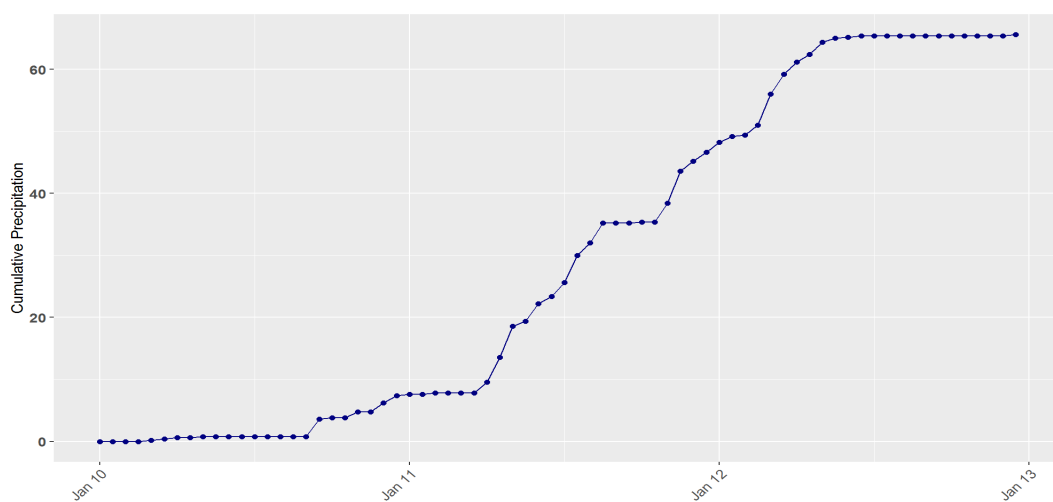


Figure 4.30 Cumulative hourly rainfall curve between 00:00 UTC 10 January 2019 and 23:00 UTC 12 January 2019 for station 17705.

The flash flood event in Susurluk was caused by not only frontal heavy rainfall but also snow melting when winter weather conditions were effective. Figure 4.31 shows daily snow cover area and four-day accumulated snow melt at 00:00 UTC on 10 January and at 00:00 UTC on 12 January respectively. The data for these products are derived from BSMEFFGS server (via Snow 17 Model) and visualized by using QGIS application. As indicated on the image each basin is fully covered by snow before the event and approximately 30 mm snow melted in the catchment located in Susurluk district. Thus, some contribution from snowmelt can be expected during the flash flood event and it should be taken into account while evaluating the event.

The selected watershed (2021400845) is covered by Balikesir Radar so that radar rainfall estimation is used while MAP calculation.

Figure 4.32 indicates the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 06:00 UTC on 10 January and 18:00 UTC on 12 January for catchment 2021400845 (Susurluk). Rainfall estimation products are lower than FFG threshold values during the event except radar. The rainfall estimation which is derived from radar exceeds the FFG value at 12:00 UTC on 11 January. Additionally, none of the NWP rainfall predictions are higher than threshold values. There is no satisfactory NWP model to forecast the flash flood process for this case. However, snow melt is a key element for flash flood occurrence beside intense rainfall in this case.

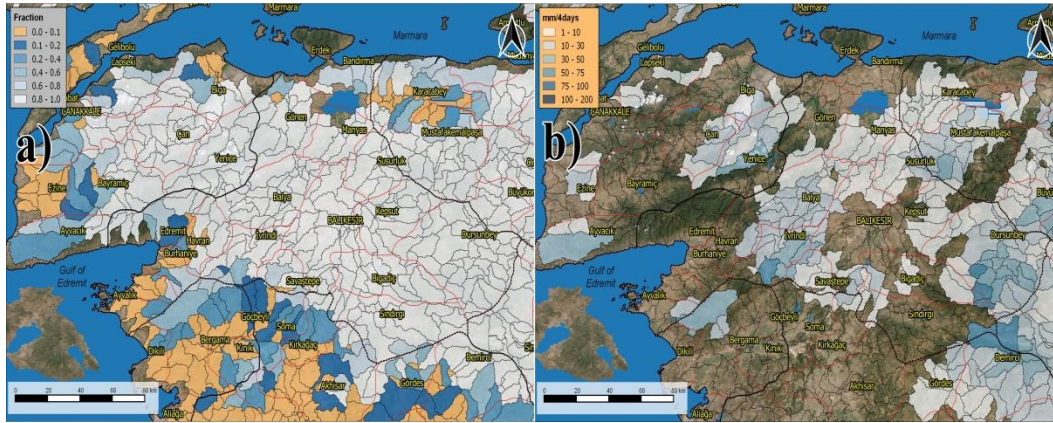


Figure 4.31 Snow cover area at 00:00 UTC on 10 January 2019 (a) and 4-Day snow melt accumulation at 00:00 UTC on 12 January 2019 (b).

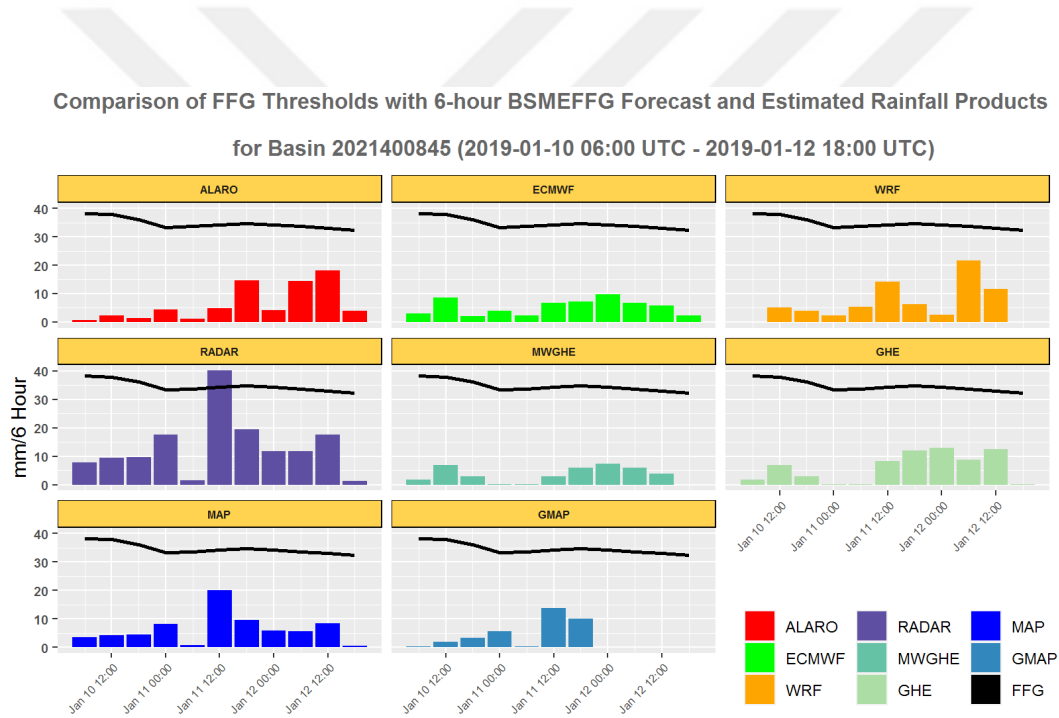


Figure 4.32 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021400845 (Susurluk).

4.3.5 Flash Flood Events on 29 March 2018 in Tarsus and Camliyayla

Mediterranean acts as storage of energy and moisture for the coastal surface of southeastern Turkey, especially from the beginning of autumn to end of winter when frontal systems are effective. Frontal systems bring severe weather conditions with warm and humid air at ground level along the Mediterranean coastal region while passing over the sea. The low pressure depressions cause destructive flash flood events frequently in southeastern Mediterranean coast of Turkey. Mersin province and its surroundings were hit by a low depression storm between 28 and 29 March 2018. Tarsus and Camliyayla districts of Mersin were affected by flash flood events because of the frontal system. Tarsus is one of the most crowded and economically important residential places in terms of industrial and agricultural affairs for southeast of Turkey. Camliyayla district is near to Tarsus and has a high altitude with respect to its surrounding.

Figure 4.33 indicates location of study area, selected basins from BSMEFFGS for Tarsus and Camliyayla districts and on-site rainfall gauges in Balikesir province.

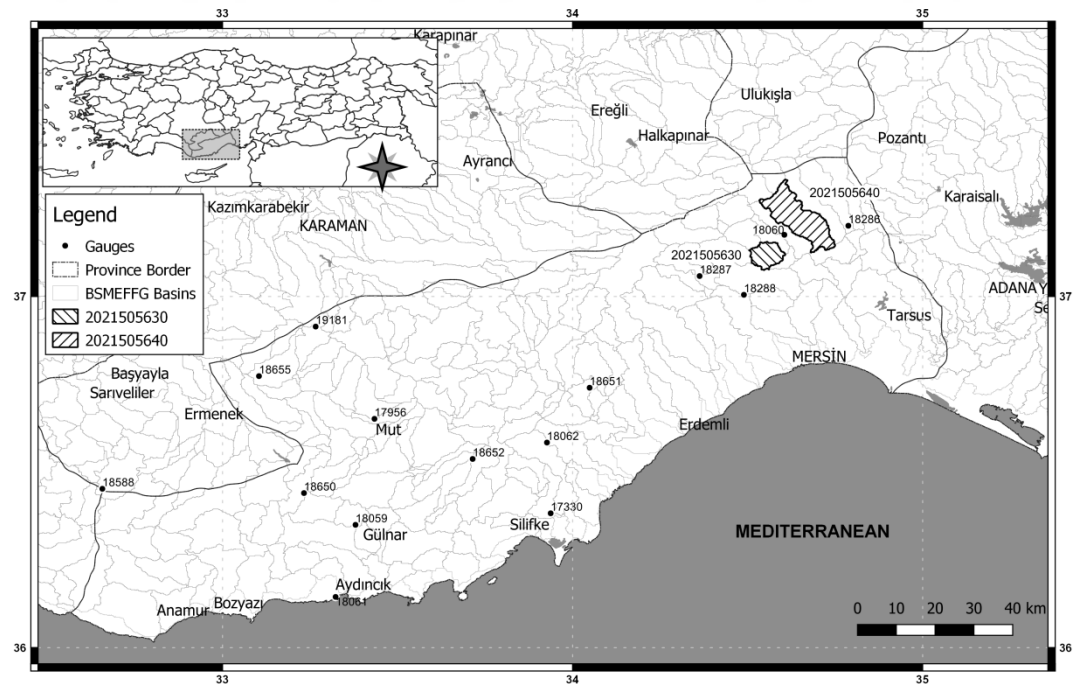


Figure 4.33 Location of Mersin province, rainfall gauges and selected watersheds.

The appropriate sub-basins are selected within the BSMEFFGS to perform individual analysis for this case. Identification numbers 202150630 and 202150640 are used for these basins in the BSMEFFGS. The basins are located in Camliyayla and Tarsus district borders respectively.

The surface and upper atmosphere charts are used to define rainfall signature for this case (see Figure C.11 and C.12 in Appendices). Flash flood events are verified by related severe weather report from TSMS and newspaper articles (WEB6). Agricultural lands, roads and settlements were damaged by heavy rainfall in Mersin, the results of flash floods in Tarsus and Camliyayla can be seen in the Figure 4.34.

Figure 4.35 indicates the distribution of daily precipitation at 06:00 UTC on 29 March 2019. At 06:00 UTC on 29 March 2018, observed rainfall values are around 60 mm over inland part of Mersin. Rainfall amounts are higher over the inland part of Mersin than coastal region since orographic effect of Taurus Mountains.

Rainfall gauges with their geographical positions and altitudes in Mersin and their daily rainfall amounts on 29 March 2018 are given in Table 4.5. The highest daily amounts were observed at stations 18060 and 18286 on 29 March with 75.4 and 60.1 mm respectively. Gauges 18060 and 18286 are closest ones to Camliyayla and Tarsus districts, elevation of stations are 1115 and 775 meters respectively.

Cumulative rainfall curves are given in Figure 4.36 for gauges 18060 (Camliyayla) and 18286 (Tarsus). Hourly rainfall data between 12:00 UTC on 28 March and 12:00 UTC on 29 March is used for the plots. It can be interpreted that rainfall signature for both stations is frontal system because lines are rising gradually. The highest intensity of precipitation is found between 21:00 UTC 28 March and 03:00 UTC 29 March for both stations.

The basins 202150630 (Camliyayla) and 202150640 (Tarsus) are not covered by any radar so that radar rainfall estimation is not used while MAP calculation within the BSMEFFGS.



Figure 4.34 Flash flood event images for Tarsus (a) and Camliyayla (b) (WEB6).

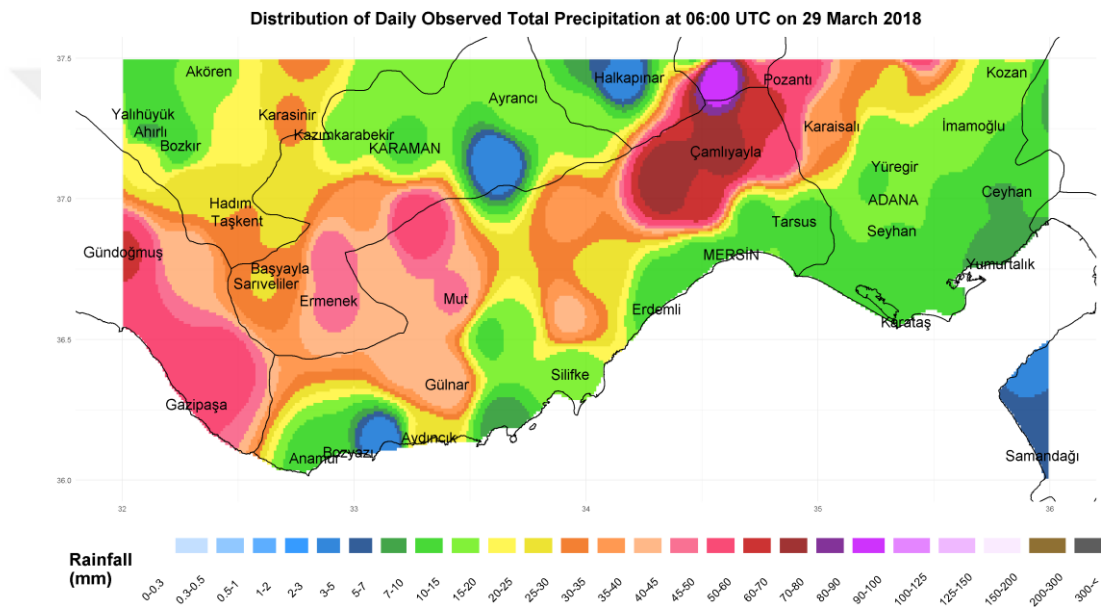


Figure 4.35 Distribution of daily rainfall at 06:00 UTC on 29 March 2018.

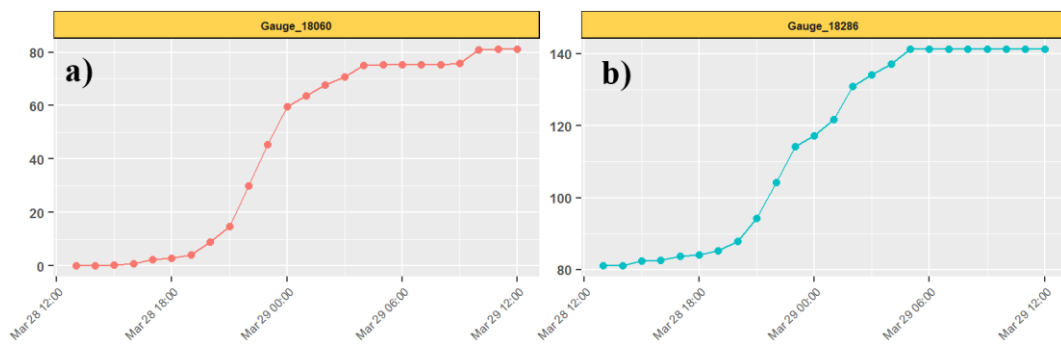


Figure 4.36 Cumulative hourly rainfall curves between 12:00 UTC 28 March and 12:00 UTC 29 March for station 18060 (a) and 18286 (b).

Table 4.5 On-site gauges in Mersin and daily rainfall amounts on 29 March 2018.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>Rainfall</i>
Silifke (17330)	36.38	33.94	10	16.40
Mut (17956)	36.65	33.43	340	45.50
Gülnar (18059)	36.35	33.38	1013	44.60
Çamlıyayla/Meyvecilik Arş. (Tagem) (18060)	37.18	34.60	1115	75.40
Mersin/Aydıncık (18061)	36.14	33.32	2	25.60
Silifke/Uzuncaburç (18062)	36.58	33.93	1204	41.10
Tarsus/Çamalan (18286)	37.20	34.79	775	60.10
Toroslar/Arslanköy (18287)	37.06	34.36	1440	80.30
Toroslar/Kızılbag (18288)	37.00	34.49	1070	68.90
Anamur/Elbalak Yaylası (18588)	36.45	32.66	1905	33.70
Gülnar/Kuskan Mevki (18650)	36.44	33.23	1355	43.40
Erdemli/Yağda Köyü (18651)	36.74	34.05	1362	28.30
Silifke/Gündüzler Köyü (18652)	36.54	33.71	1426	19.20
Mut/Kızıllalan Mevki (18655)	36.77	33.10	1659	43.70
Mut/Sertavul Geçidi (19181)	36.91	33.27	1660	55.50

Figure 4.37 and Figure 4.38 indicate the comparison of FFG threshold values with six-hour forecasted and estimated rainfall amounts between 12:00 UTC on 28 March and 00:00 UTC on 30 March for catchments 202150630 (Camliyayla) and 202150640 (Tarsus) respectively. Satellite rainfall and MAP products are lower but GMAP product is higher than FFG threshold at 00:00 and 06:00 UTC on 29 March 2018 for both the basins 202150630 and 202150640. Nevertheless, each NWP model predictions exceed threshold value at 00:00 and 06:00 UTC on 29 March. It is noted that the highest rainfall occurred between 21:00 UTC on 28 March and 03:00 UTC on 29 March when the event probably was effective. The analysis shows that these three NWP models are successful and can be assumed as convenient to prepare flash flood warnings for this case study. However, ECMWF model has higher rainfall predictions for this case study that provides higher performance for flash flood warning issuance.

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021505630 (2018-03-28 12:00 UTC - 2018-03-30 00:00 UTC)

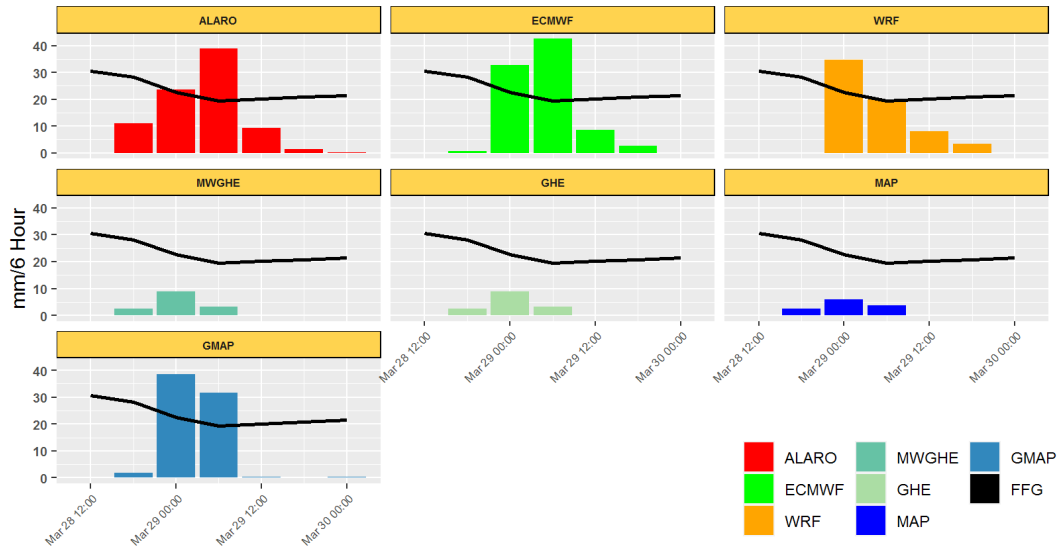


Figure 4.37 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 202150630 (Camliyayla).

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021505640 (2018-03-28 12:00 UTC - 2018-03-30 00:00 UTC)

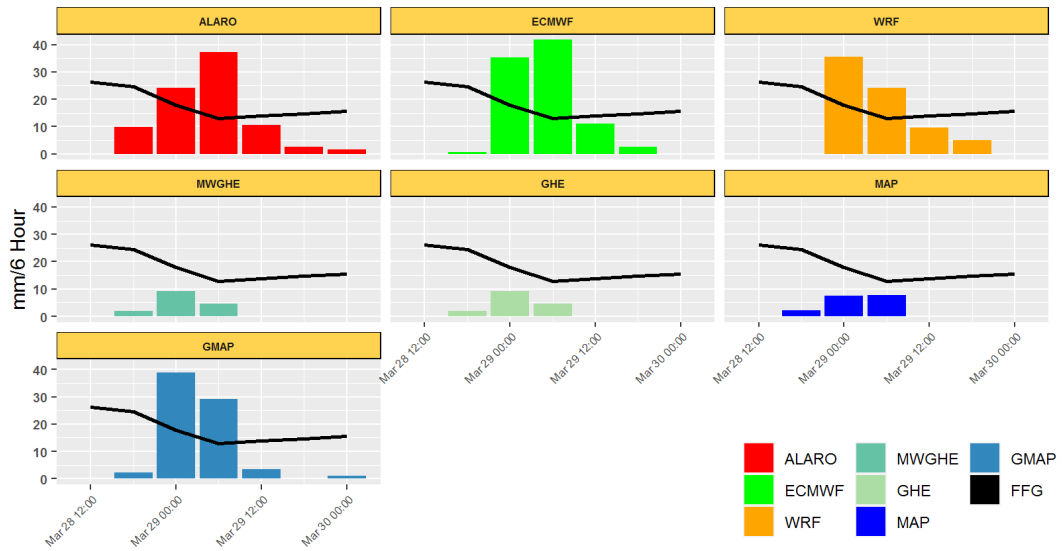


Figure 4.38 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 202150640 (Tarsus).

4.4 Convective-Induced Flash Flood Case Studies

4.4.1 Flash Flood Events of 23-24 August 2019 in Salipazari and Terme

Mesoscale convective systems cause heavy rainfall over Black Sea coast and mostly resulted with flash floods during beginning of summer and end of autumn seasons. The circumstances of Black Sea region are very efficient for developing of thunderstorms and heavy rainfall while Black Sea is a source of energy-moisture and mountainous topography supports orography. A mesoscale convective system developed over central Black Sea coastal region during the late evening and early morning of 23-24 August 2019 and produced intense rainfall. The convective system caused flash floods and landslides in Salipazari and Terme districts of Samsun province. Flash floods caused property damage and loss of life in these districts.

Figure 4.39 indicates location of study area, selected basins from BSMEFFGS for Salipazari and Terme districts and on-site rainfall gauges in Samsun province.

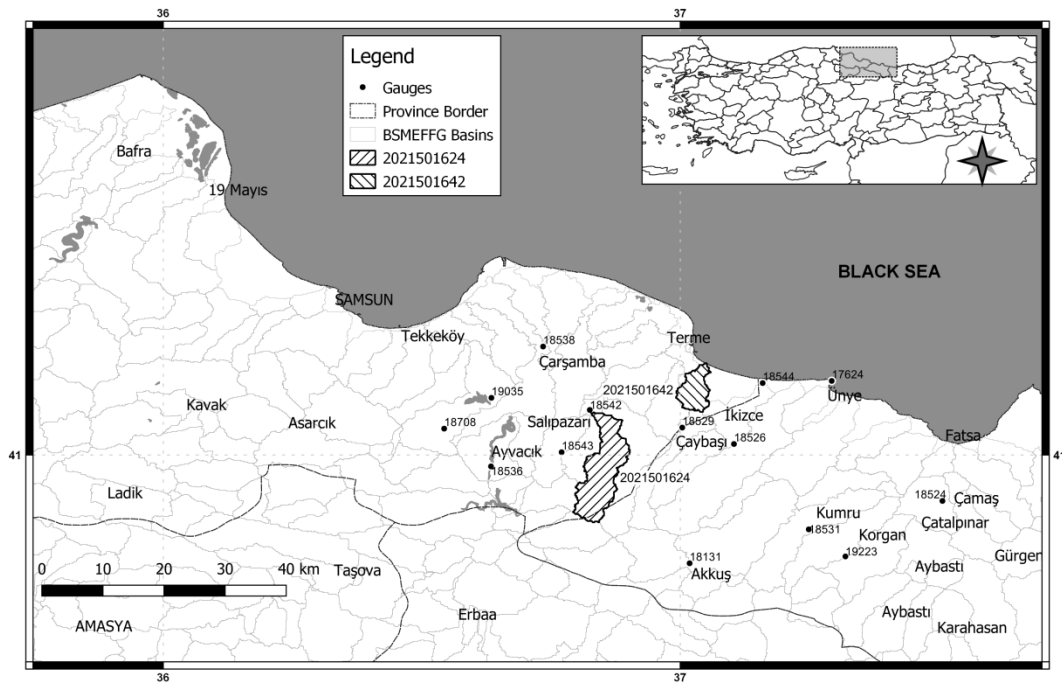


Figure 4.39 Location of Samsun province, rainfall gauges and selected watersheds.

The appropriate watersheds are selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. Identification numbers 2021501624 and 2021501642 are used for these basins in the BSMEFFGS. The catchments are located in Salipazari and Terme district boundaries respectively.

The meteorological analysis is done to define rainfall signature for this case by using appropriate synoptic charts, radiosonde observation and sounding indices (see Figure C.13, C.14, C.15 and C.16 in Appendices). Synoptic analysis shows that flash flood events were caused by a mesoscale convective storm in this case.

Flash flood events are verified by related TSMS severe weather reports and newspaper article (WEB7). According to TSMS report and newspaper article, two people were swept away by flood waters and killed due to flash flood in Salipazari. In both districts, flash floods caused economic and social losses such as resulting in damage to buildings, agricultural lands, bridges, power poles and trees. The images of flash flood events for Salipazari and Terme can be examined in Figure 4.40. The image for Salipazari was taken from coastal side and high mountains are viewed clearly, damaged bridges on the creek and buildings are shown in the figure.



Figure 4.40 Flash flood event images for Salipazari (a) and Terme (b) (WEB7).

Considerable daily amount of rainfall values across the event region between 22 and 25 August 2019 are given in Table 4.6. One of the highest daily rainfall amounts were observed at stations Salipazari (18542) and Terme/Kozluk (18544) on 24 August with 201.1 and 86.3 mm respectively.

Figure 4.41 indicates the cumulative rainfall curves for the period 00:00 UTC and 23:00 UTC on 23 August 2019 for 18542 and 18544 stations. Slopes of curves are raised abruptly which proves convective instability. Additionally, there are two different intense rainfall periods available between 06:00-12:00 UTC and 18:00-21:00 UTC.

Figure 4.42 shows distribution of daily precipitation at 06:00 UTC on 24 August 2019. Interpolated rainfall amounts are more than 150 mm and 200 mm over Salipazari and Terme districts respectively.

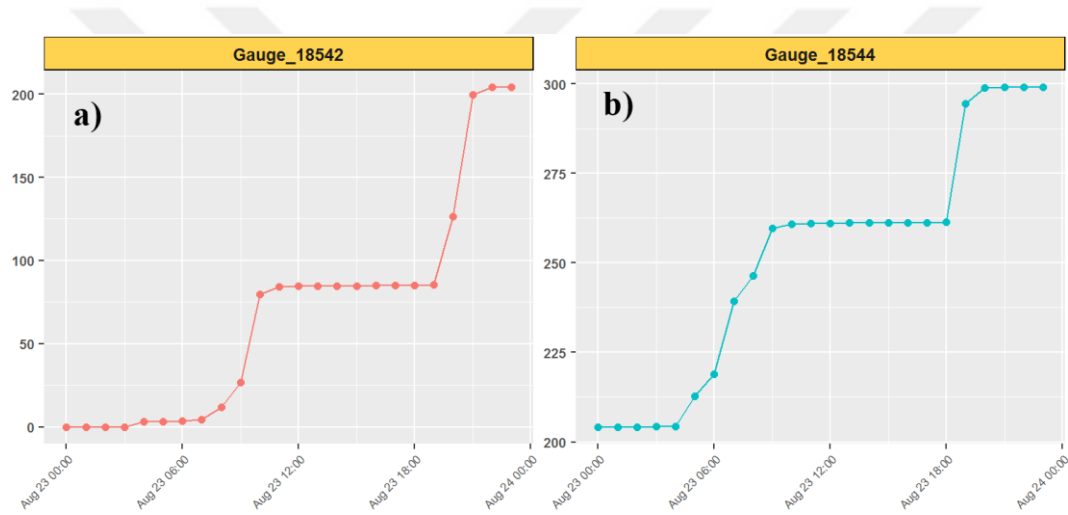


Figure 4.41 Cumulative hourly rainfall curves between 00:00 UTC and 23:00 UTC 23 August 2019 for gauges 18542 (a) and 18544 (b).

Distribution of lightning strikes between 00:00 and 23:59 UTC on 23 August 2019 over Samsun are shown in Figure 4.43. The vast majority of lightning records were observed between 06:00 UTC and 21:00 UTC over Salipazari and Terme districts. This period was the most severe in terms of rainfall intensity. Heavy rainfall and dense lightning flashes areas look like very similar. These circumstances indicate that lightning data should be considered for flash flood warning issuance in this case.

Table 4.6 Gauges in Samsun and daily rainfall amounts along the event period.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>August22</i>	<i>August23</i>	<i>August24</i>	<i>August25</i>	<i>Total</i>
Ünye (17624)	41.14	37.29	16	5.00	6.80	129.80	0.00	141.60
Akkuş (18131)	40.79	37.02	1285	13.00	16.60	58.30	0.00	87.90
Çamaş (18524)	40.91	37.51	510	10.10	7.90	16.80	0.00	34.80
Çaybaşı (18526)	41.02	37.10	553	11.80	25.30	58.70	0.00	95.80
İkizce/Şenbolluk (18529)	41.05	37.00	735	15.50	13.30	124.10	0.00	152.90
Kumru (18531)	40.86	37.25	790	7.00	3.90	26.90	0.00	37.80
Ordu/Ulubey (18534)	40.87	37.75	610	1.50	40.60	22.30	0.00	64.40
Samsun/Ayvacak (18536)	40.98	36.63	72	1.10	0.00	59.50	0.00	60.60
Çarşamba (18538)	41.21	36.73	20	3.70	0.00	53.60	0.00	57.30
Salıpazarı (18542)	41.09	36.83	75	5.00	3.10	201.10	0.00	209.20
Salıpazarı/Düzdağ Yaylaköy (18543)	41.01	36.77	921	2.40	5.40	198.30	0.00	206.10
Terme/Kozluk Beldesi (18544)	41.14	37.16	8	5.40	8.60	86.30	0.10	100.40
Çarşamba/Eğridere Köyü (18708)	41.05	36.54	663	1.30	0.00	64.10	0.00	65.40
Çarşamba/Çakmak Barajı (19035)	41.11	36.63	135	2.10	1.50	118.30	0.00	121.90
Korgan (19223)	40.80	37.32	1109	4.00	25.10	23.50	0.00	52.60

Figure 4.44 shows the observed hourly temperature, dew point temperature and precipitation values between 00:00 UTC on 22 August and 23:00 UTC on 24 August for stations 18542 and 18544. In the Figure 4.44a, surface temperature is higher prior to the rainfall events which support convective instability and developing severe weather conditions. Surface temperature decreases during the events and get closer with dew point temperature due to condensation. It can be interpreted from the graphs that rainy weather conditions were available in two periods for both gauges. The highest hourly rainfall intensity values are 73.2 and 32.9 mm/hour at 21:00 UTC and 19:00 UTC on 23 August for stations 18542 and 18544 respectively.

The basins 2021501624 (Salıpazarı) and 2021501642 (Terme) are covered by Samsun Radar so that radar rainfall estimations are used to produce MAP in the BSMEFFGS.

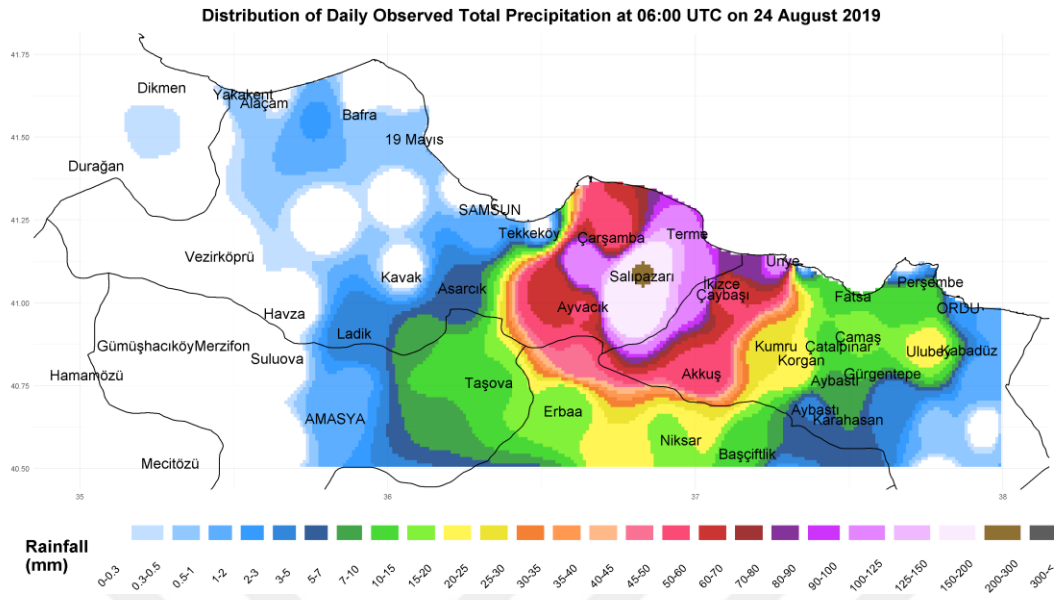


Figure 4.42 Distribution of daily rainfall at 06:00 UTC on 24 August 2019.

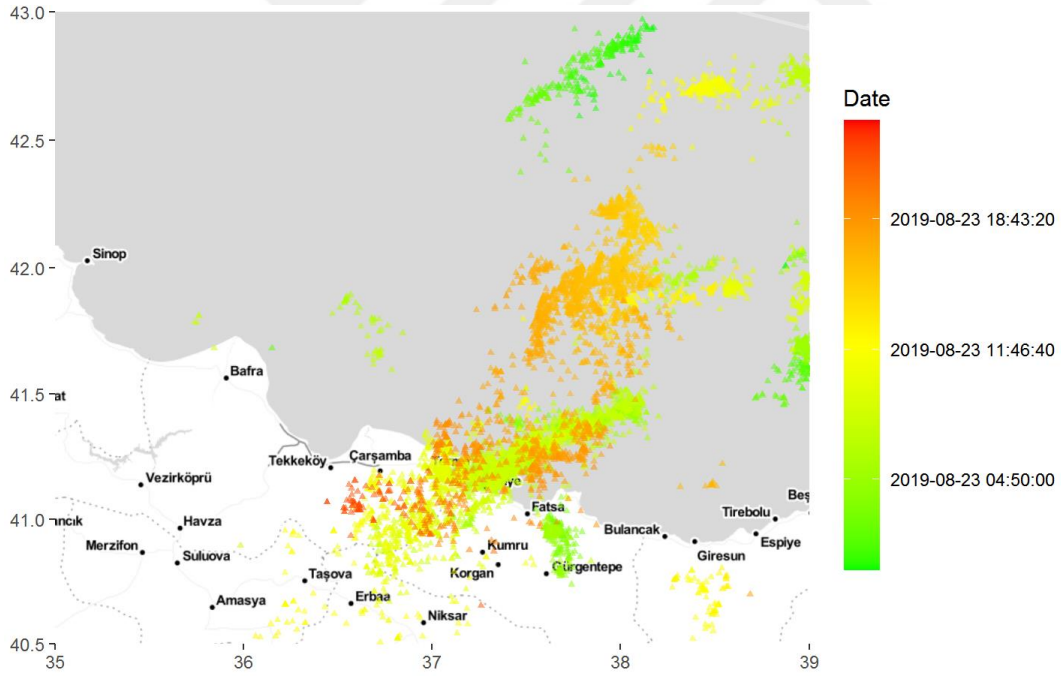


Figure 4.43 Lightning flashes over Samsun on 23 August 2019.

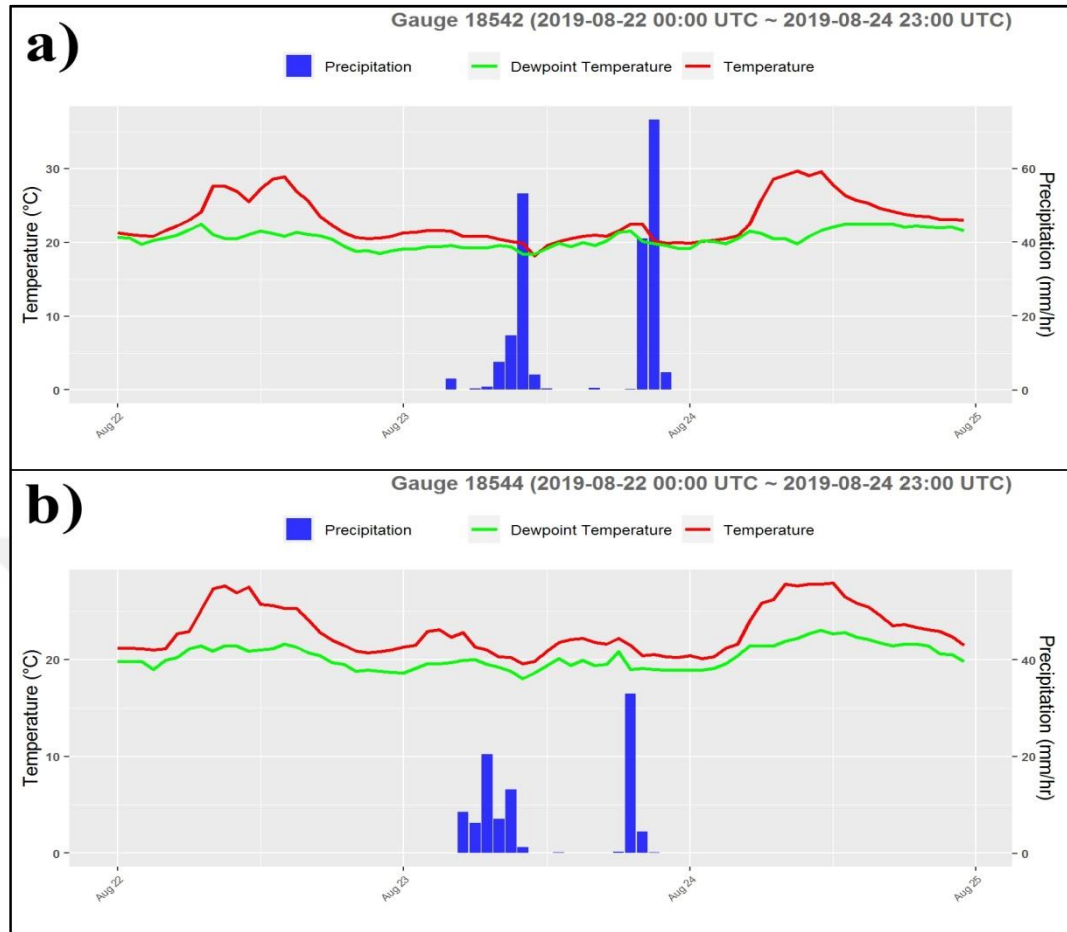


Figure 4.44 Hourly time series of air temperature, dew-point temperature and precipitation as recorded at stations 18542 (a) and 18544 (b) for the period 00:00 UTC 22 August and 23:00 UTC 24 August.

Figure 4.45 and Figure 4.46 indicate the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 18:00 UTC on 22 August and 00:00 UTC on 24 August 2019 for basins 2021501624 and 2021501642 respectively. Rainfall estimation products are below the FFG values for basin 2021501624. Satellite rainfall estimations are above the threshold values at 12:00 UTC on 23 August and 00:00 UTC on 24 August for basin 2021501642. However, GMAP values exceed FFG thresholds for both catchments at 12:00 UTC on 23 August and 00:00 UTC on 24 August. None of NWP model prediction exceed FFG threshold before and during the event in both watersheds. Consequently, there is no satisfactory NWP model to forecast the flash flood process for this case.

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021501624 (2019-08-22 18:00 UTC - 2019-08-24 00:00 UTC)

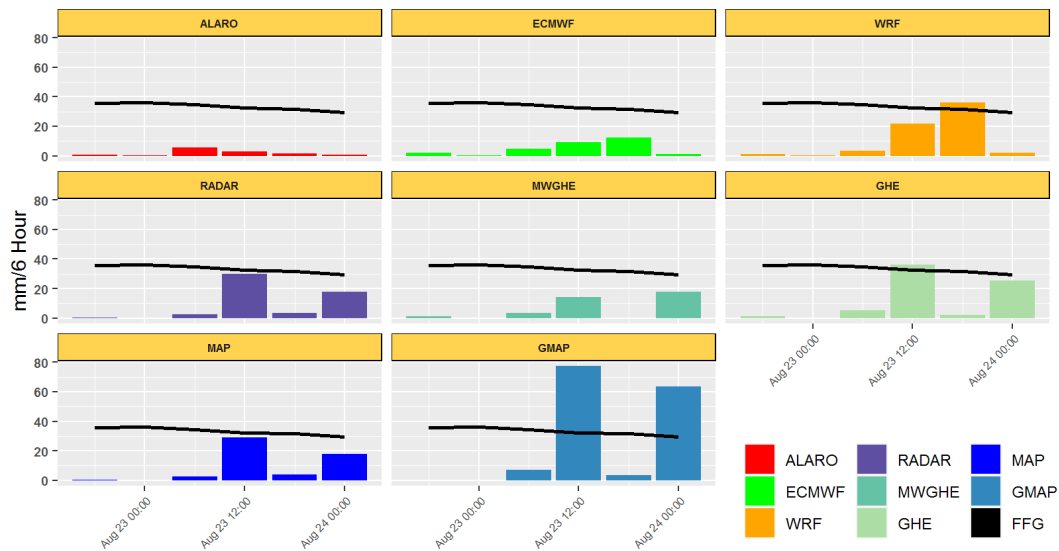


Figure 4.45 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021501624 (Salipazari).

Comparison of FFG Thresholds with 6-hour BSMEFFG Forecast and Estimated Rainfall Products
for Basin 2021501642 (2019-08-22 18:00 UTC - 2019-08-24 00:00 UTC)

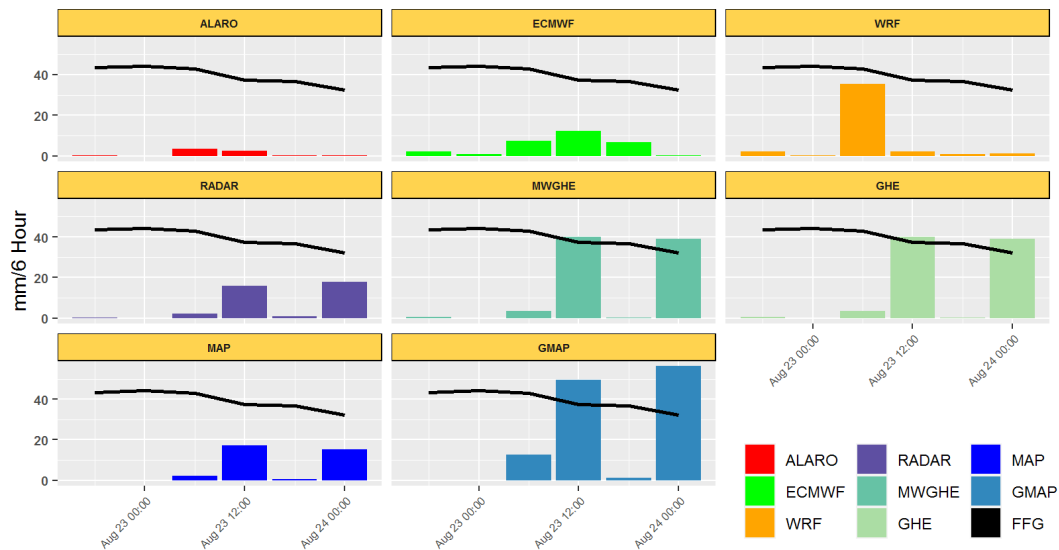


Figure 4.46 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021501642 (Terme).

4.4.2 Flash Flood Event on 17 June 2018 in Cal

Convection conditions are mostly favorable for developing thunderstorms for early summer months over inner Aegean region of Anatolia due to climatological conditions and topography. Severe thunderstorms often cause local heavy rainfall and flash flood occurrences in the region. Denizli province is located inner Aegean region of Turkey and Cal district is situated north of Denizli. Viticulture is vital for farmers of Cal district and its villages where is very famous with endemic grape species in ancient Greek mythology. Therefore, flash floods mostly damage grape cultivation and other agricultural activities in Cal.

A mesoscale convective system developed over inner region of Aegean of Turkey on June 17 2018 and contributed developing short-term downpour which lasted just two hours. The convective storm that led to flash flood in Cal resulted in the loss of the property and damages in agricultural areas.

Figure 4.47 indicates location of study area, selected basins from BSMEFFGS for Cal districts and on-site rainfall gauges in Denizli province.

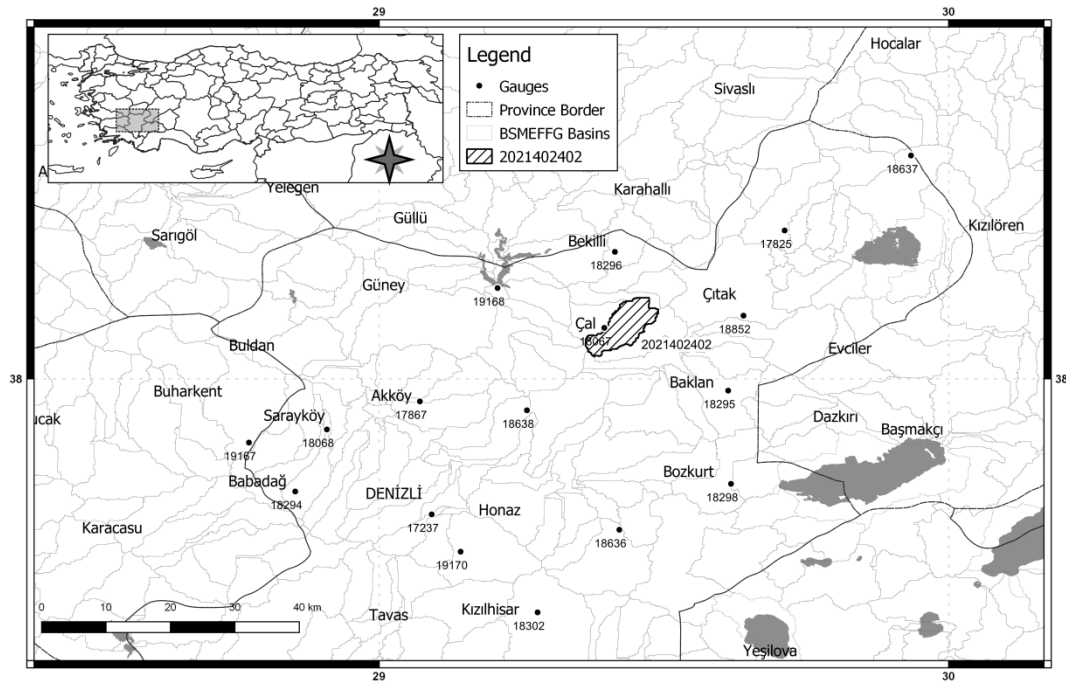


Figure 4.47 Location of Denizli province, rainfall gauges and selected watershed.

The appropriate watershed is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. In the BSMEFFGS, identification number 2021402402 is used for selected basin which is located in Cal district boundary.

The meteorological analysis is done to define rainfall signature for this case by using appropriate synoptic charts, radiosonde observation and sounding indices (see Figure C.17, C.18 and C.19 in Appendices). Synoptic analysis shows that flash flood event was caused by a mesoscale convective storm in this case.

Flash flood event is verified by related TSMS severe weather report and newspaper articles. Figure 4.48 shows image of flash flood for Cal (WEB9). According to severe report and newspaper articles, social and economic losses are listed as damages in buildings, agricultural lands, roads and infrastructure due to covered by mud and flood waters. Agricultural damage is estimated by local authorities approximately 35-40 million liras in total because of the flash flood (WEB10).



Figure 4.48 Flash flood event image for Cal (WEB9).

Remarkable daily rainfall amounts across the event region for the period of 16 June and 18 June 2018 are given in Table 4.7. The highest daily rainfall amount was observed at stations Cal (18067) on 17 June with 49.7 mm.

Figure 4.49 indicates that cumulative rainfall curve for station 18067 for the period 00:00 UTC 16 June and 23:00 UTC 18 June 2018. Slope of curve is rising gradually in first but it reached to peak in just two hours, between 12:00 UTC and 14:00 UTC 17 June, which proves that intensity precipitation induced by convective instability conditions.

Figure 4.50 indicates spatial distribution of daily precipitation at 06:00 UTC on 18 June 2018. Interpolated rainfall amounts are more than 40 mm over Cal and its surrounding.

Spatial and temporal distribution of lightning from 12 UTC to 15 UTC 17 June 2018 is shown in Figure 4.51. The lightning flashes are intense over Cal district with respect to the figure. The lightning period is similar with intensity rainfall period. Thus, the lightning data should be considered for flash flood warning issuance in this case.

Figure 4.52 show that observed hourly temperature, dew point temperature and precipitation values between 00:00 UTC 16 June and 23:00 UTC 18 June 2018 for gauge 18067. Relatively high surface temperature enhances convective activity which contributes air mass upward rising. However, surface temperature decreases because of condensation and get close to dew point temperature. This mechanism is valid for gauge 18067 in Figure 4.52. The blue bars symbolizes hourly rainfall accumulations, 15.9 mm and 29.5 mm amounts were measured at 13:00 and 14:00 UTC on 17 June respectively, total amount is 45.4 mm in just two hours. Hourly rainfall peaks are triggered by high surface temperature and low dew point temperature values relatively. In short, there is no doubt that intensity precipitation caused by convective weather conditions in this case.

Table 4.7 On-site gauges in Denizli and daily rainfall amounts along the event period.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>June16</i>	<i>June17</i>	<i>June18</i>	<i>Total</i>
Babadag (18294)	37.80	28.85	903	0.20	10.40	1.10	11.70
Baklan (18295)	37.98	29.61	1032	3.40	15.00	11.50	29.90
Bekilli (18296)	38.22	29.41	845	7.90	7.30	0.00	15.20
Çal (18067)	38.09	29.40	817	16.40	4.20	49.70	70.30
Çameli (18066)	37.08	29.35	1294	0.40	9.50	2.20	12.10
Çivril (17825)	38.26	29.71	824	15.00	11.90	0.80	27.70
Çivril/Kavakalanı Köyü (18637)	38.39	29.93	1205	30.20	21.10	1.80	53.10
Çivril/Kıralan Beldesi (18852)	38.11	29.64	825	5.30	10.90	2.60	18.80
Denizli (17237)	37.76	29.09	425	8.40	44.60	13.80	66.80
Denizli/Bozkurt (18298)	37.82	29.62	885	0.00	12.00	0.10	12.10
Güney/Adıgüzeller Köyü (19168)	38.16	29.21	473	2.00	6.20	0.00	8.20
Honaz/Akbaş Köyü (18636)	37.73	29.42	1160	1.50	6.60	2.10	10.20
Pamukkale/Akköy (17867)	37.96	29.07	198	4.60	6.60	6.40	17.60
Pamukkale/Bağbaşı (19170)	37.70	29.14	1365	1.30	18.90	2.90	23.10
Pamukkale/Güzelpınar Köyü (18638)	37.94	29.26	1195	5.50	11.40	2.80	19.70
Sarayköy (18068)	37.91	28.91	194	4.80	10.70	9.00	24.50
Sarayköy/Tırkaz (19167)	37.89	28.77	682	0.80	35.90	1.40	38.10
Serinhisar (18302)	37.59	29.28	923	4.60	0.20	2.70	7.50

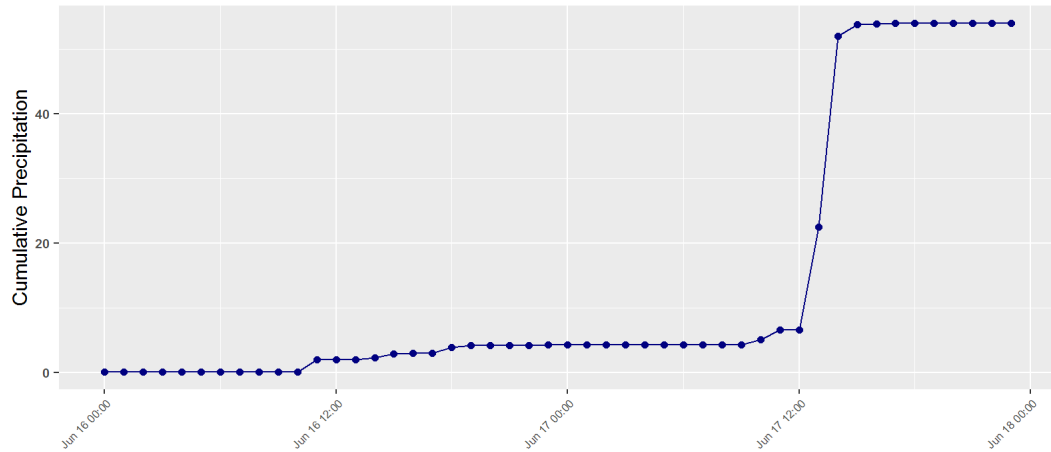


Figure 4.49 Cumulative hourly rainfall curve between 00:00 UTC 16 June and 23:00 UTC 18 June 2018 for station 18067.

The selected watershed (2021402402) is not covered by any radar so that radar rainfall estimation is not used for MAP calculation. Figure 4.53 indicates the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 06:00 UTC on 17 June and 06:00 UTC on 18 June 2018 for catchment 2021402402 (Cal). FFG threshold values are not exceeded by satellite based rainfall estimations or MAP values during the event. However, GMAP product is above threshold value at 18:00 UTC on 17 June while the product represents occurred rainfall between 12:00 UTC and 18:00 UTC. FFG values are far higher than values of ALARO, ECMWF and WRF model rainfall predictions during the event period. NWP models are under-estimated with respect to occurred amount of rainfall for the event period. The analysis shows that these three NWP model predictions are not skillful in terms of capturing threshold values. Thus, these models are not convenient to prepare flash flood warnings for this case study.

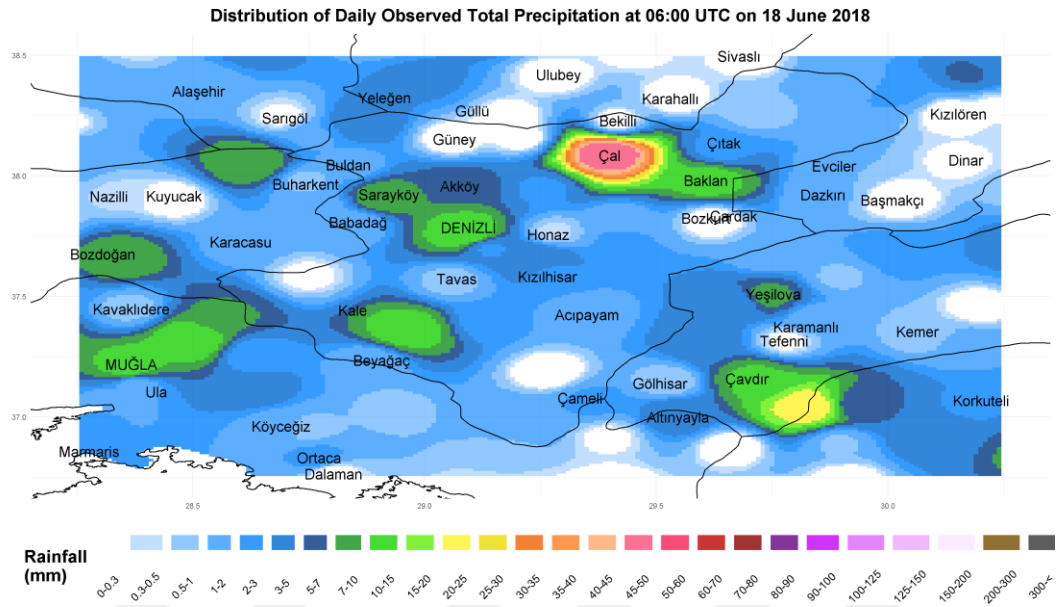


Figure 4.50 Distribution of daily rainfall at 06:00 UTC on 18 June 2018.

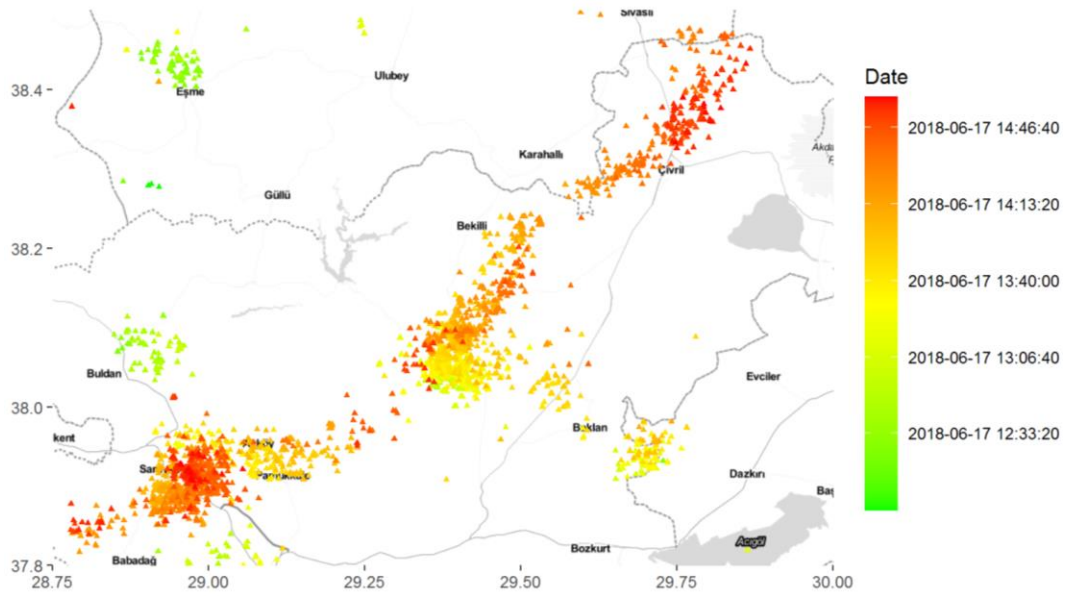


Figure 4.51 Lightning flashes over Denizli for the period 12:00 UTC and 15:00 UTC 17 June 2018.

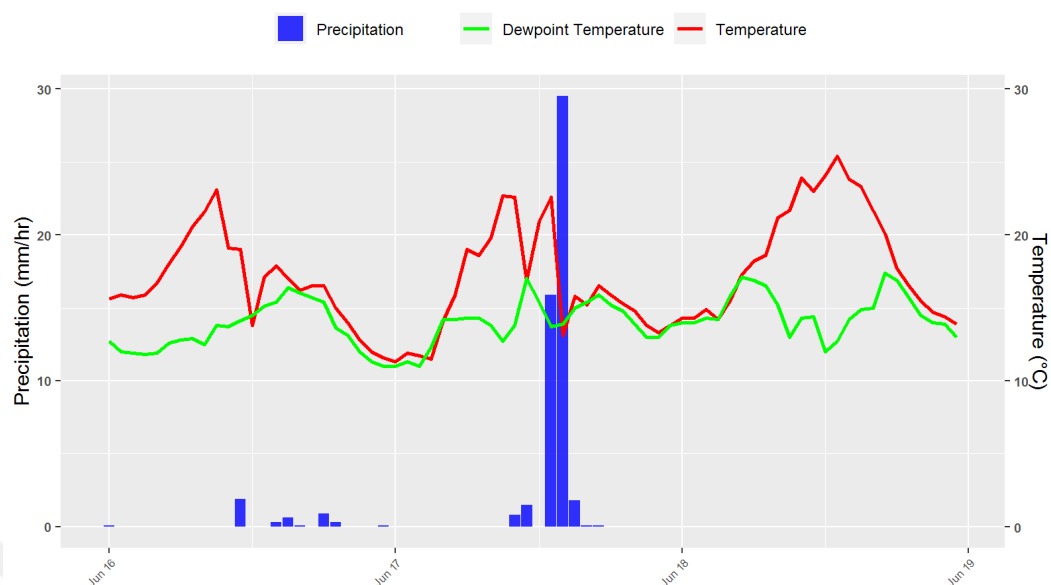


Figure 4.52 Hourly time series of air temperature, dew-point temperature and precipitation as recorded at station 18067 for the period 00:00 UTC 16 June and 23:00 UTC 18 June 2018.

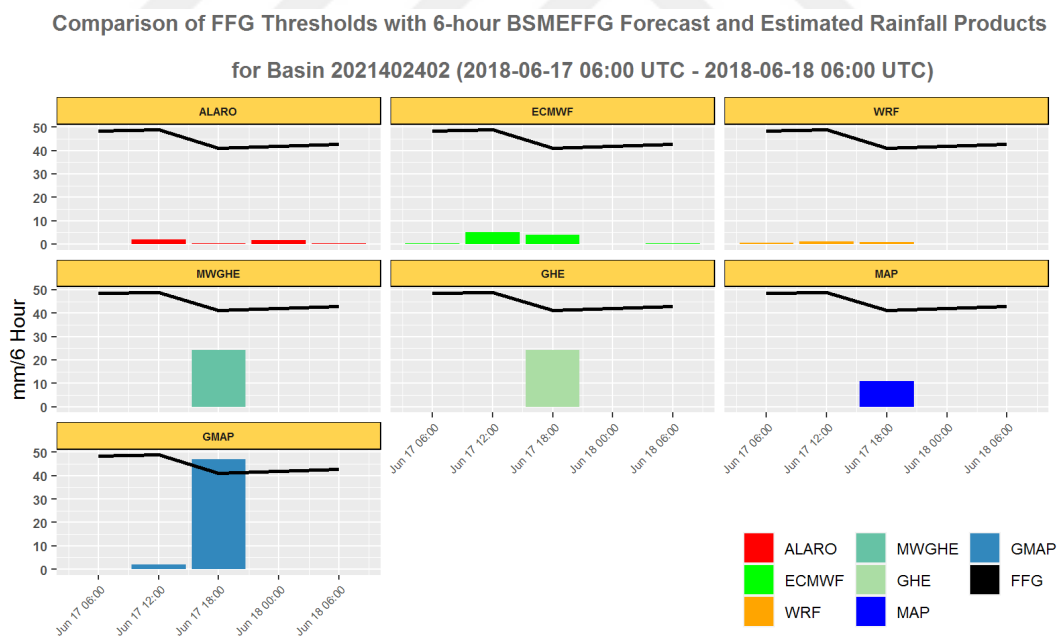


Figure 4.53 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021402402 (Cal).

4.4.3 Flash Flood Event on 27 May 2018 in Selendi

Convective instability conditions are mostly favorable for developing severe weather during spring and summer seasons over inner Aegean region of Anatolia because of meteorological, climatological and topographic factors. Thunderstorms cause local intense rainfall and flash flood occurrences in this region frequently. Manisa province is located in western inner part of Turkey.

On 27 May 2018, a localized strong convective storm developed over Selendi district of Manisa province and lead to short-term downpour which lasted just one hour. The short-term convective rainfall caused a flash flood event with devastating impacts in terms of social and economic losses.

Figure 4.54 indicates location of study area, selected catchment from BSMEFFGS for Selendi district and in-situ rainfall gauges in Manisa province.

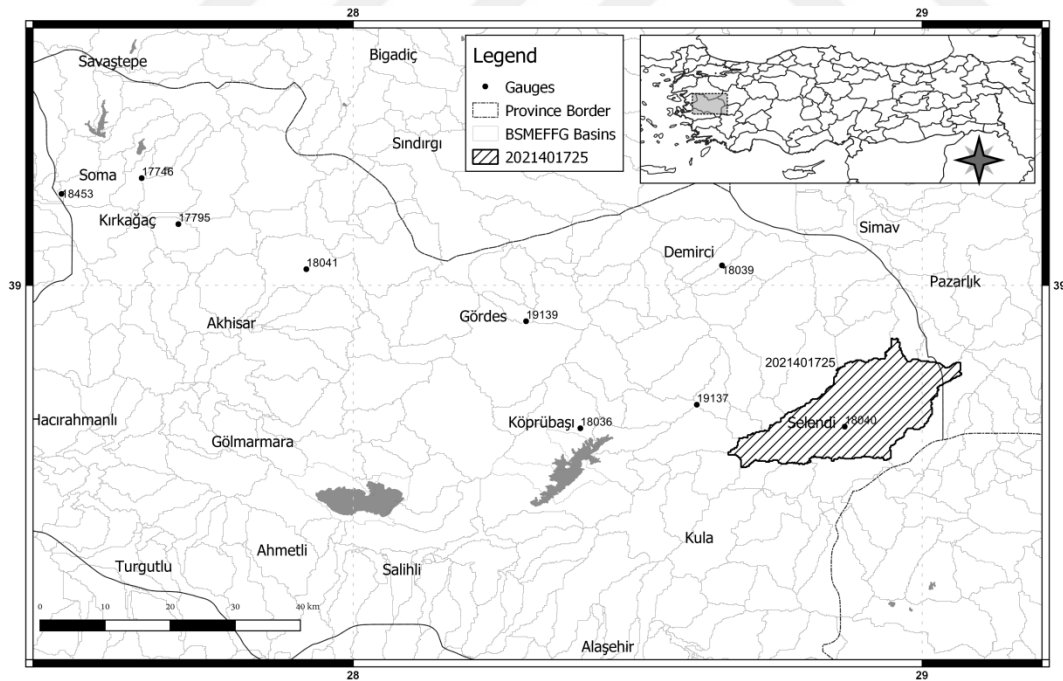


Figure 4.54 Location of Manisa province, rainfall gauges and selected watershed.

The appropriate watershed is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. In the BSMEFFGS, identification number 2021401725 is used for selected basin which is located in Selendi district boundary.

The meteorological analysis is done to define rainfall signature for this case by using appropriate synoptic charts, radiosonde observation and sounding indices (see Figure C.20 and C.21 in Appendices). Synoptic analysis shows that flash flood event was caused by a mesoscale convective storm in this case.

Flash flood event is verified by related TSMS severe weather report and newspaper articles. Figure 4.55 is shown for image of flash flood for Selendi (WEB11). According to severe report and newspaper articles, social and economic losses are listed as damages in buildings, agricultural lands, roads and infrastructure.



Figure.4.55 Flash flood event image for Selendi (WEB11).

The daily precipitation totals across the event region between the days before and after the event are given in Table 4.8. The highest daily amount is observed at station Selendi (18453) on 28 May with 29.6 mm and there is no significant rainfall in other days.

Table 4.8 On-site gauges around Selendi and daily rainfall amounts between 27 and 29 May 2018.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>May_27</i>	<i>May_28</i>	<i>May_29</i>	<i>Total</i>
Soma/Cenkleri Orman Sahası (18039)	39.16	27.49	134	0.00	1.70	0.00	1.70
Soma (18040)	39.19	27.63	166	0.00	4.50	0.00	4.50
Selendi (18453)	38.75	28.86	475	0.80	29.60	0.80	31.20
Köprübaşı (17795)	38.75	28.40	250	5.20	2.00	0.20	7.40
Kırkağaç (19137)	39.11	27.69	158	0.00	1.80	0.00	1.80
Gördes (18041)	38.94	28.30	622	0.60	0.50	0.00	1.10
Demirci/İcikler (19139)	38.79	28.60	722	0.90	2.00	0.00	2.90
Demirci (17746)	39.03	28.65	855	0.80	7.40	0.00	8.20
Akhisar/Karaköy Orman Deposu (18036)	39.03	27.92	209	0.50	3.20	0.00	3.70

Figure 4.56 indicates that cumulative rainfall curve for station 18453 for the period 00:00 UTC and 23:00 UTC on 27 May 2018. Slope of curve is rising abruptly in just one hour, between 11:00 UTC and 12:00 UTC 27 May, which proves that intense rainfall induced by convective instability conditions.

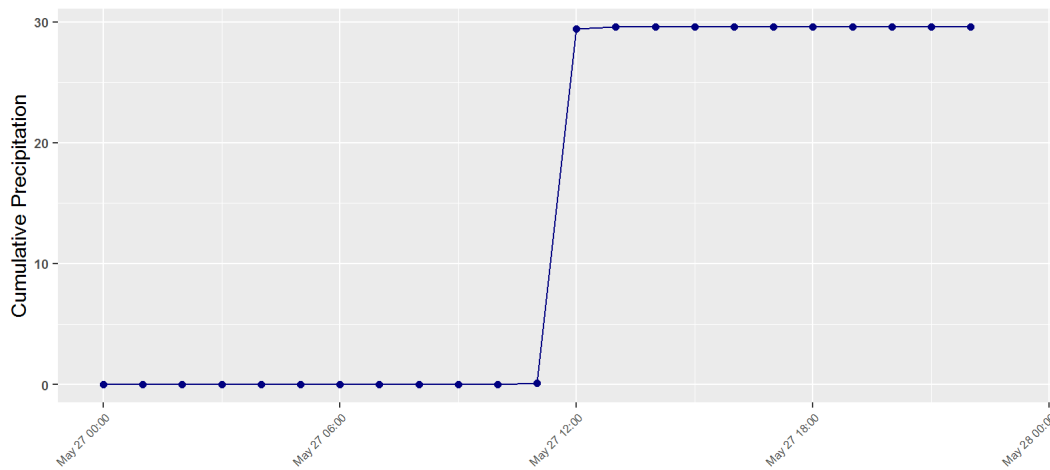


Figure 4.56 Cumulative hourly rainfall curve between 00:00 UTC and 23:00 UTC 27 May 2018 for station 18453.

Figure 4.57 shows the spatial distribution of daily rainfall amounts at 06:00 UTC on 28 May 2018. On the rainfall interpolation map, approximately 25 mm rainfall amounts are available over Selendi district.

Spatial and temporal distribution of lightning over Manisa from 11 UTC to 13 UTC on 27 May 2018 is shown in Figure 4.58. The lightning flashes are intense over Selendi district with respect to the figure. The lightning period is similar with intense rainfall period. Thus, the lightning data should be considered for flash flood warning issuance in this case.

Figure 4.59 show the observed hourly temperature, dew point temperature and precipitation values between 00:00 UTC on 26 May and 23:00 UTC on 28 May 2018 for station 18453. Surface temperature increases prior to the beginning of a convective storm that contributes convective activity. As usual, it decreases after the storm terminates due to precipitation. This mechanism is valid for station 8453 according to analysis plot. At 12 UTC on May 27, 29.6 mm hourly rainfall is recorded when surface temperature reached to peak. Thus, the localized intense rainfall must be triggered by a strong convective storm.

The selected watershed (2021401725) is not covered by any radar so that radar rainfall estimation is not used for MAP calculation. Figure 4.60 indicates the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 06:00 UTC on 27 May and 06:00 UTC on 28 May 2018 for catchment 2021401725 (Selendi). It can be interpreted from figure that neither rainfall prediction of NWP models nor remote sensed rainfall exceed FFG threshold. However, GMAP product is above threshold value at 18:00 UTC on 27 May while it represents occurred rainfall between 12:00 UTC and 18:00 UTC. Eventually, there is not any capable NWP model in terms of rainfall prediction and flash flood warning issuance for this case.

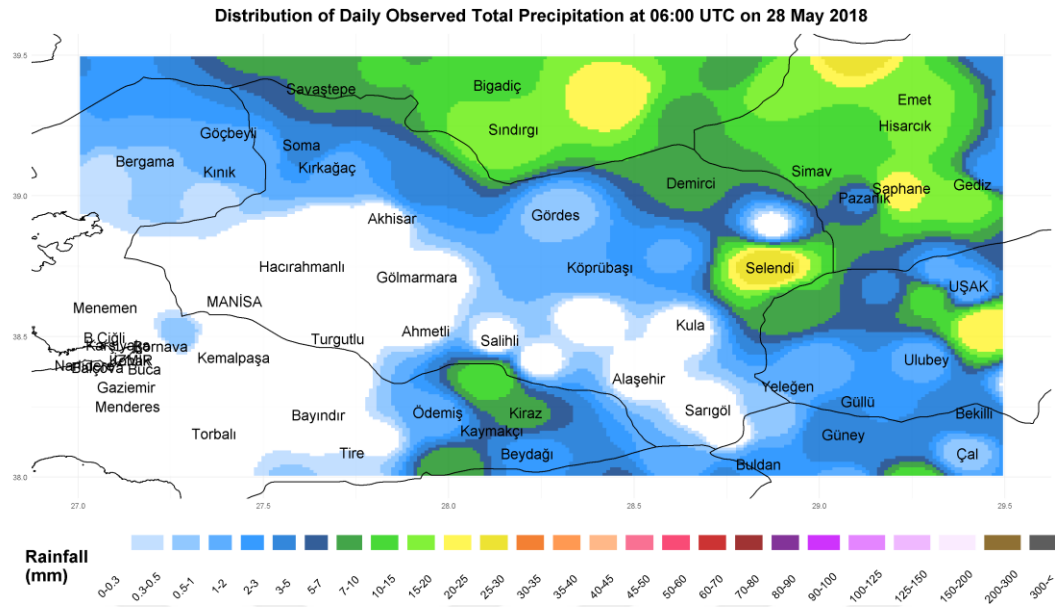


Figure 4.57 Distribution of daily rainfall at 06:00 UTC on 28 May 2018.

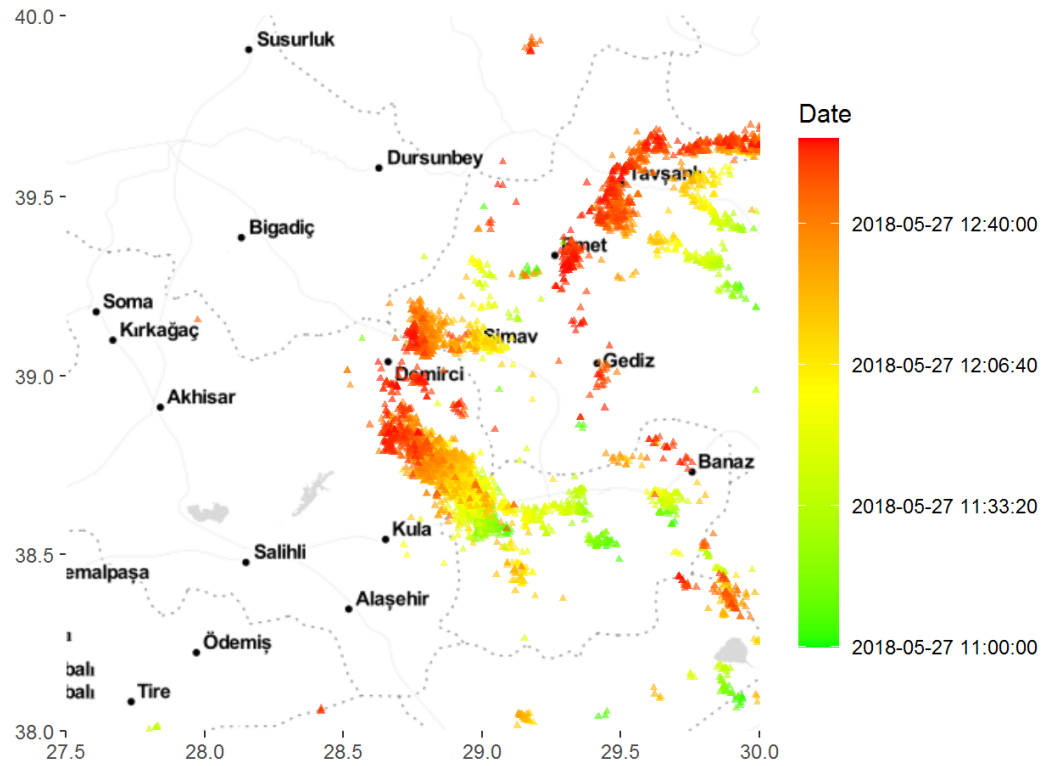


Figure 4.58 Lightning flashes over Manisa for the period 11:00 UTC and 13:00 UTC 27 May 2018.

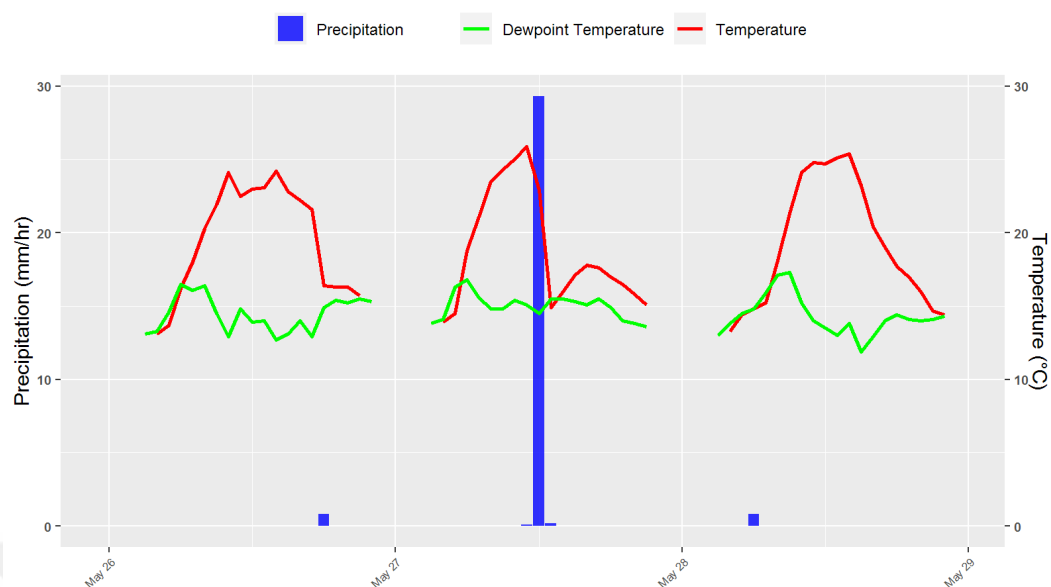


Figure 4.59 Hourly time series of air temperature, dew-point temperature and precipitation as recorded at station 18453 for the period 00:00 UTC 26 May and 23:00 UTC 28 May 2018.

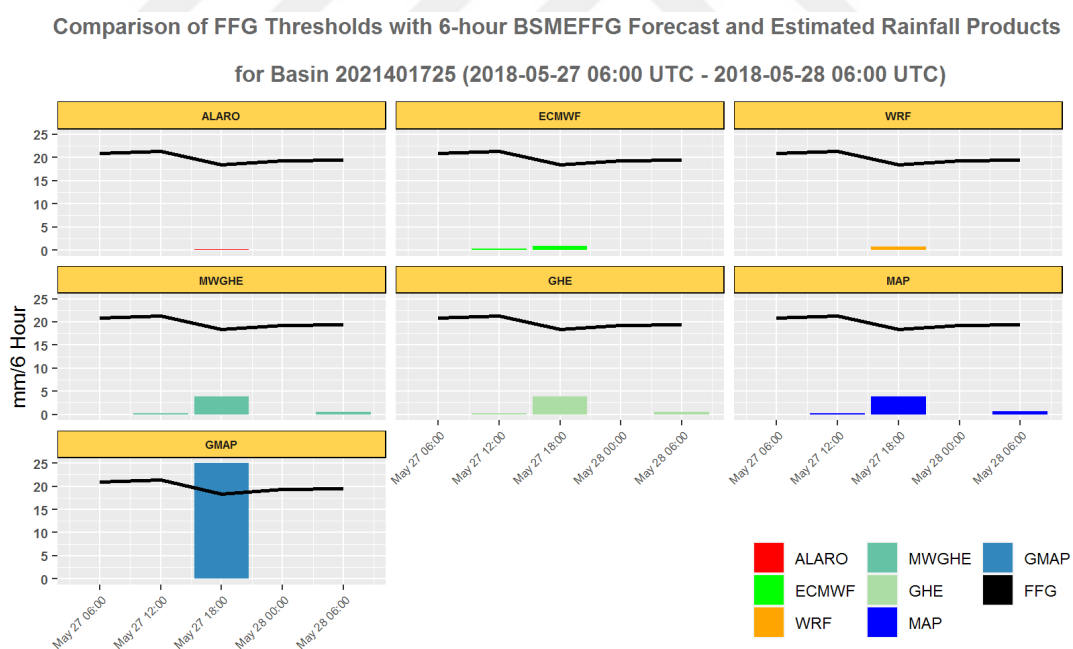
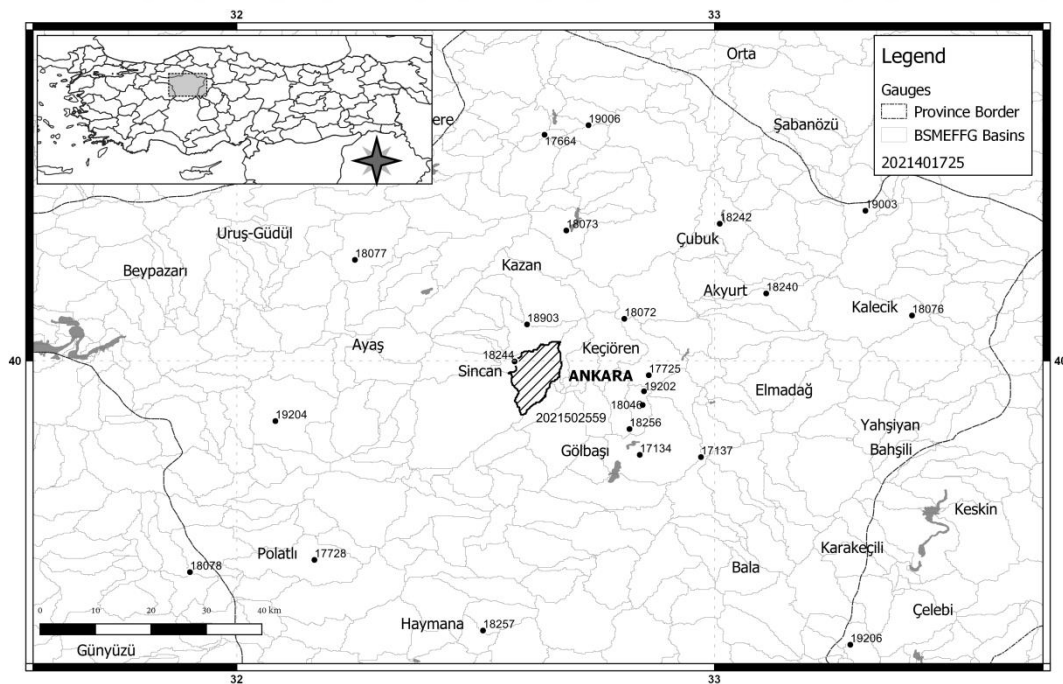


Figure 4.60 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021401725 (Selendi).

4.4.4 Flash Flood Event on 09 June 2019 in Ankara

Convective instability conditions are mostly favorable for developing severe weather during spring and summer seasons over inland parts of Anatolia because of meteorological, climatological and topographic factors. Convective instability conditions often trigger thunderstorms, local heavy rainfall and flash flood occurrences in the region. On afternoon 09 June 2019, a major convective system hit central Anatolia which led to severe storm with intensity rainfall and hail. The downtown of Ankara and its surrounding rural counties were affected by a devastating flash flood on 09 June 2019. The flash flood caused loss of life, economic and social damages in Ankara, especially in Etimesgut and Sincan districts.

Figure 4.61 indicates location of study area, selected watershed (around Etimesgut and Sincan districts) from BSMEFFGS for Ankara province and on-site stations. The appropriate watershed (2021502559) is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case.



Synoptic analysis is done to define rainfall signature for this case by using appropriate synoptic charts, radiosonde observation and sounding indices (see Figure C.22 and C.23 in Appendices). Synoptic (large-scale) analysis ensured minor insight into the causes of severe weather events during summer or spring over Central Anatolia. However, sounding indices release that flash flood event was caused by a mesoscale convective storm in this case.

Flash flood event is verified by related TSMS severe weather report and newspaper articles. Figure 4.62 shows image of flash flood for Ankara (WEB12). According to severe report and newspaper article, flash flood lasted for just a few-hour period but damaged buildings, roads and infrastructure. However, the most distressing result of the flash flood disaster was that three people were killed in Sincan and Etimesgut districts (WEB12).



Figure 4.62 Flash flood event images for Ankara (WEB12).

On-site gauges in Ankara and daily rainfall amounts between 09 June and 11 June 2019 are given in Table 4.9. In station Sincan (18244) located in downtown of Ankara, 33.3 mm amount of rainfall was recorded on 10 June. . Station 18244 is the closest station to selected watershed within BSMEFFGS.

Table 4.9 On-site gauges in Ankara and daily rainfall amounts during the event.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>June9</i>	<i>June10</i>	<i>June11</i>	<i>Total</i>
Gölbaşı/Ufuk Danışment (17134)	39.80	32.84	1115	0.00	27.40	1.20	28.60
Elmadağ Radar Sahası (17137)	39.80	32.97	1807	0.20	19.40	17.20	36.80
Kızılcahamam (17664)	40.47	32.64	1033	0.20	23.80	1.00	25.00
Keçiören/Mgm (17725)	39.97	32.86	885	0.00	10.30	3.30	13.60
Polatlı (17728)	39.58	32.16	886	0.00	10.00	5.20	15.20
Çankaya/Tbmm (18046)	39.91	32.85	927	0.00	15.30	0.40	15.70
Keçiören/Bağlum (18072)	40.09	32.81	1456	0.00	14.10	8.30	22.40
Kazan/Kurtboğazi Barajı (18073)	40.27	32.69	1036	0.00	11.00	0.00	11.00
Kalecik (18076)	40.09	33.41	702	0.00	26.20	0.90	27.10
Güdül (18077)	40.21	32.25	731	0.00	17.10	2.10	19.20
Polatlı/Acıkır (18078)	39.56	31.90	839	0.00	10.10	2.40	12.50
Akyurt (18240)	40.14	33.11	1114	0.00	18.30	0.00	18.30
Çubuk (18242)	40.29	33.01	1174	0.00	16.30	0.00	16.30
Sincan (18244)	40.00	32.58	886	0.00	33.30	0.00	33.30
Çankaya/Çaldağ (18256)	39.86	32.82	1295	0.00	19.60	0.10	19.70
Haymana (18257)	39.44	32.52	1280	6.20	20.70	4.60	31.50
Kazan/Sarayköy Toprak (18903)	40.08	32.61	833	0.00	16.00	0.00	16.00
Kalecik/Koyunbaba Köyü (19003)	40.31	33.32	894	0.00	12.30	0.00	12.30
Kızılcahamam/Yıldırım Orman Sahası (19006)	40.49	32.74	1560	0.00	58.50	1.40	59.90
Altındağ/Gençlik Parkı (19202)	39.94	32.85	0	0.20	13.10	0.40	13.70
Polatlı/Sarıoba Köyü (19204)	39.87	32.08	703	0.00	10.70	0.00	10.70
Bala/Aşağıhacıbekir Köyü (19206)	39.41	33.28	867	1.20	44.90	0.20	46.30

Figure 4.63 indicates the cumulative rainfall curve for station 18244 for the period 00:00 UTC and 23:00 UTC on 09 June 2019. Slope of curve is rising abruptly in just one hour, between 13:00 UTC and 14:00 UTC on 09 June, which proves rainfall intensity induced by convective instability conditions.

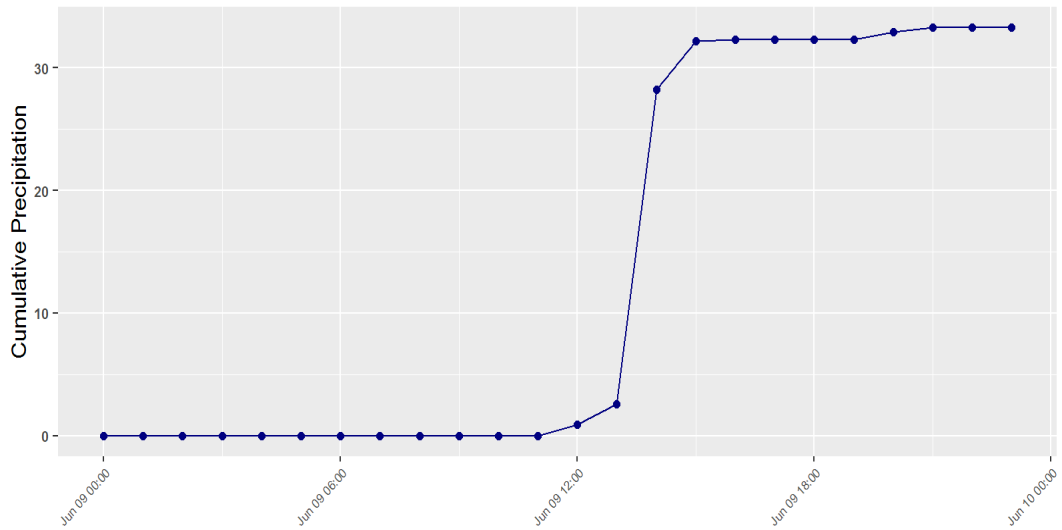


Figure 4.63 Cumulative hourly rainfall curve between 00:00 UTC and 23:00 UTC 09 June 2019 for station 18244.

Figure 4.64 displays the spatial distribution of observed total daily rainfall over Ankara, for the 24-hr period from 06:00 UTC on 09 June to 06:00 UTC on 10 June 2019. It can be interpreted from the interpolation map that around 40 mm rainfall amounts were observed in several points over Ankara.

Spatial and temporal distribution of cloud-to-cloud and cloud-to-ground lightning for the period 11 UTC and 17 UTC on 09 June 2019 is shown in Figure 4.65. The lightning flashes are dense between 13:00 UTC and 14:00 UTC over downtown of Ankara province with respect to the figure. The lightning period is very similar with intensity rainfall period. Eventually, the lightning data should be considered for flash flood warning issuance in this case.

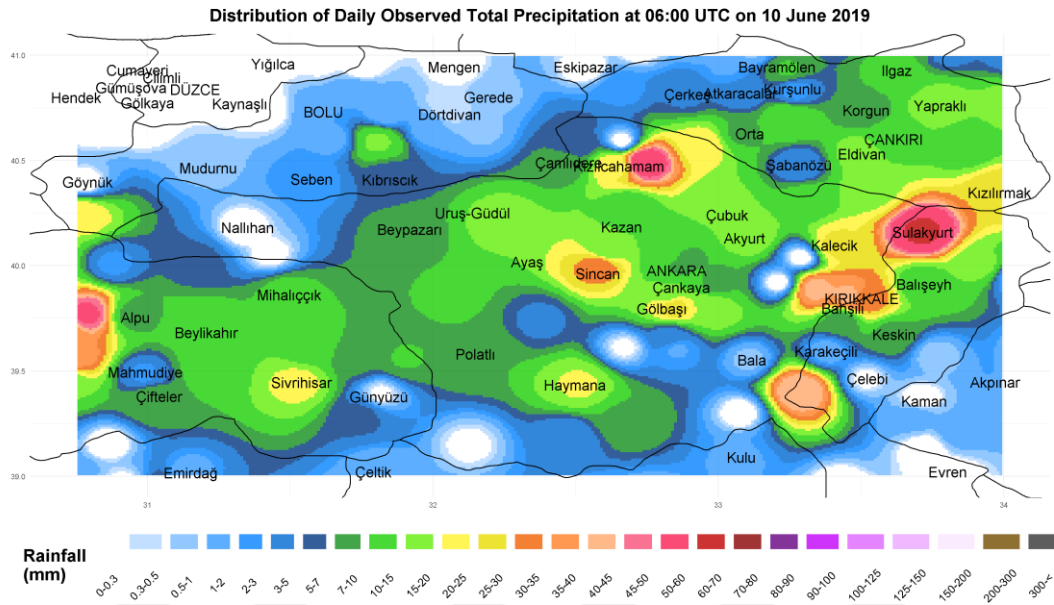


Figure 4.64 Distribution of daily rainfall at 06:00 UTC on 10 June 2019.

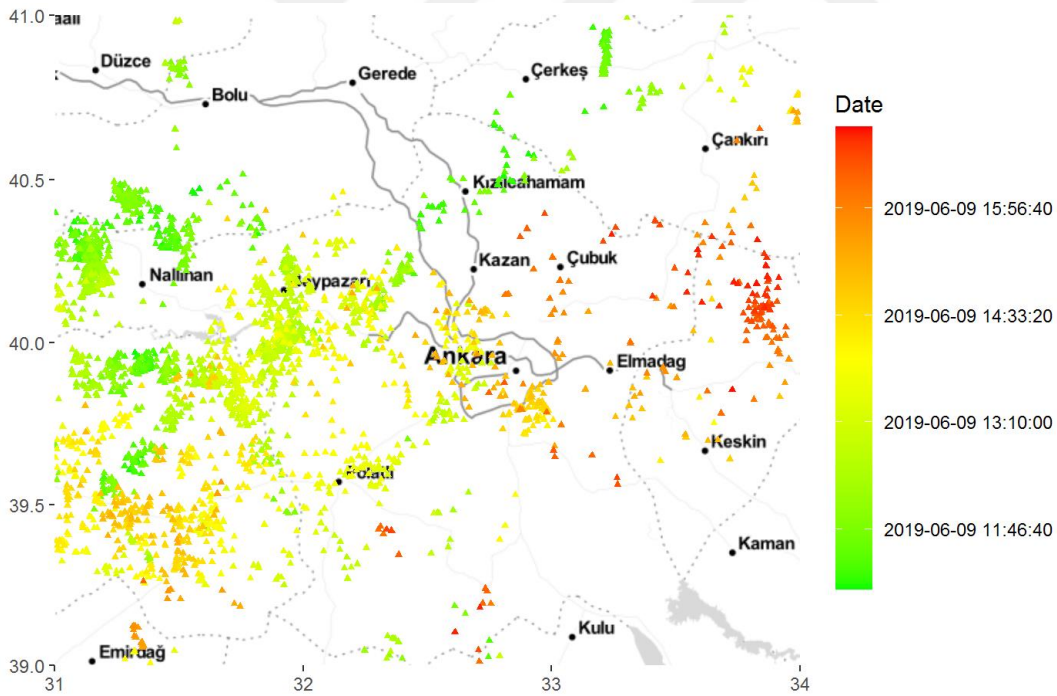


Figure 4.65 Lightning flashes over Ankara for the period 11:00 UTC and 17:00 UTC 09 June 2019.

Figure 4.66 represents time-series of temperature, dew point temperature and rainfall in hour for station 18244 for the period from 00:00 UTC on 08 June to 23:00 UTC on 10 June 2019. Convective instability conditions develop more once surface temperature is relatively high and cooling is high enough (dew point temperature approaches to air temperature) while rainfall is occurring. . This mechanism is valid for station 18244 with respect to the plot. It can be appraised from the plot that temperature decreased dramatically at 13 UTC and duration of precipitation was very short, from 12 UTC to 15 UTC. 25.6 mm rainfall was observed only in one hour at 14:00 UTC on 09 June. Thus, the localized intense rainfall must be triggered by a strong convective storm.

The selected watershed (2021502559) is inside of Ankara Radar coverage so that radar rainfall estimation is used for MAP calculation within BSMEFFGS. Figure 4.67 indicates the comparison of FFG threshold values with six-hour forecasted and estimated precipitation amounts between 06:00 UTC on 09 June and 06:00 UTC 28 on 10 June 2019 for catchment 2021502559 (Ankara). It can be interpreted from the plot that neither rainfall prediction of NWP models nor satellite based rainfall exceed FFG threshold during the event. On the other hand, radar, MAP and GMAP rainfall estimations are above threshold value at 18 UTC on 09 June. The occurred rainfall is represented between 12:00 UTC and 18:00 UTC. In short, none of the NWP models were accomplished in terms of rainfall amount prediction and flash flood warning issuance for this case.

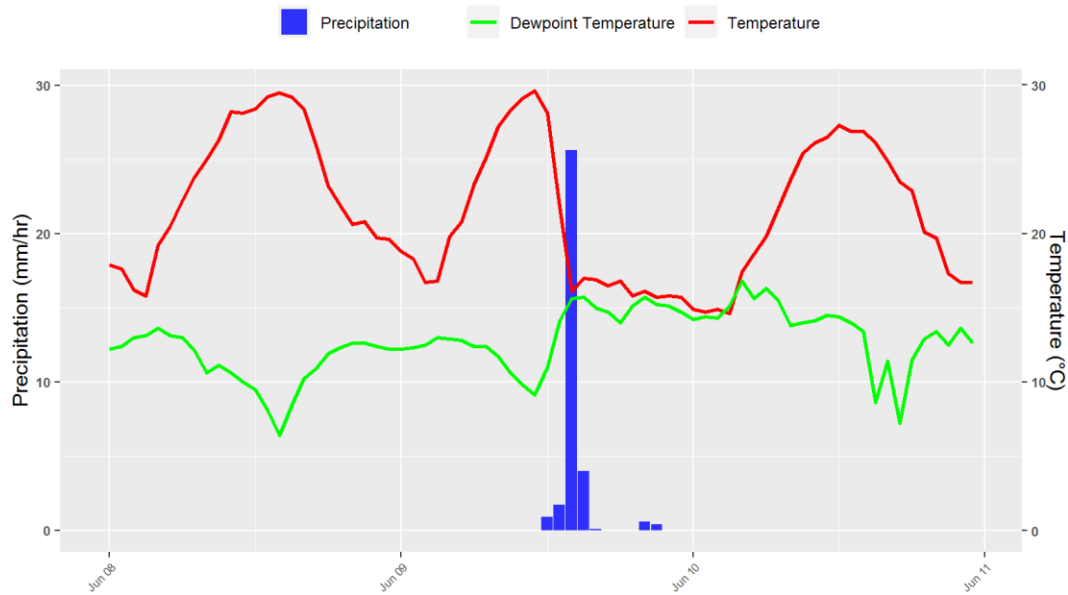


Figure 4.66 Hourly time series of air temperature, dew-point temperature and precipitation as recorded at station 18244 for the period 00:00 UTC 08 June and 23:00 UTC 08 June 2019.

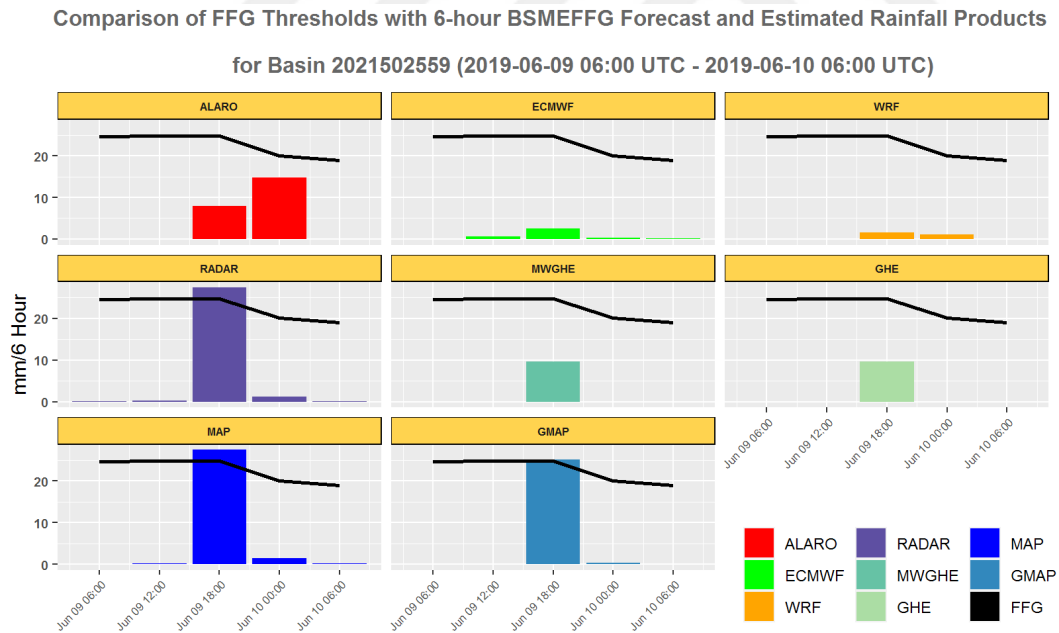


Figure 4.67 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021502559 (Ankara).

4.5 Snowmelt-Induced Flash Flood Case Study

4.5.1 Flash Flood Event on 02 May 2019 in Karlioiva

The region of eastern Anatolia is quite different from other regions of Turkey in terms of altitude ($>$ mean elevation 1500 meter) and continental climate. Severe weather conditions influence the eastern part of Turkey during winter months in which the region receives heavy snowfall. Indeed, snowfall in this region is very significant for Turkey since it feeds Euphrates and Tigris rivers which are vital in terms of energy producing and agricultural activities. Snow melting is beneficial during early spring months for Euphrates and Tigris which are the longest two rivers of Turkey. However, spring rain showers over snowpack or heat waves cause snow melting and may produce flash flooding in eastern part of Turkey during early spring days.

On 02 May 2019, Bingol province and its districts located in eastern part of Anatolia were affected by flash floods. . Genc and Karlioiva districts were exposed to flash floods triggered by combination of rainfall and snowmelt. In this case study, only Karlioiva flash flood is studied due to data availability.

The goal of this case study is showing importance of snow melting for flash flood occurrence unlike other case studies in this thesis. However, rainfall prediction of NWP models data are also used and compared with each other since moderate amount of rainfall contributed the flash flood event.

Figure 4.68 shows location of study area, watershed from BSMEFFGS for Karlioiva district and on-site stations in Bingol province. The appropriate catchment is selected within the BSMEFFGS to compare NWP model rainfall predictions with FFG thresholds for this case. In the BSMEFFGS, identification number 2021603322 is used for selected basin which is located in Karlioiva district.

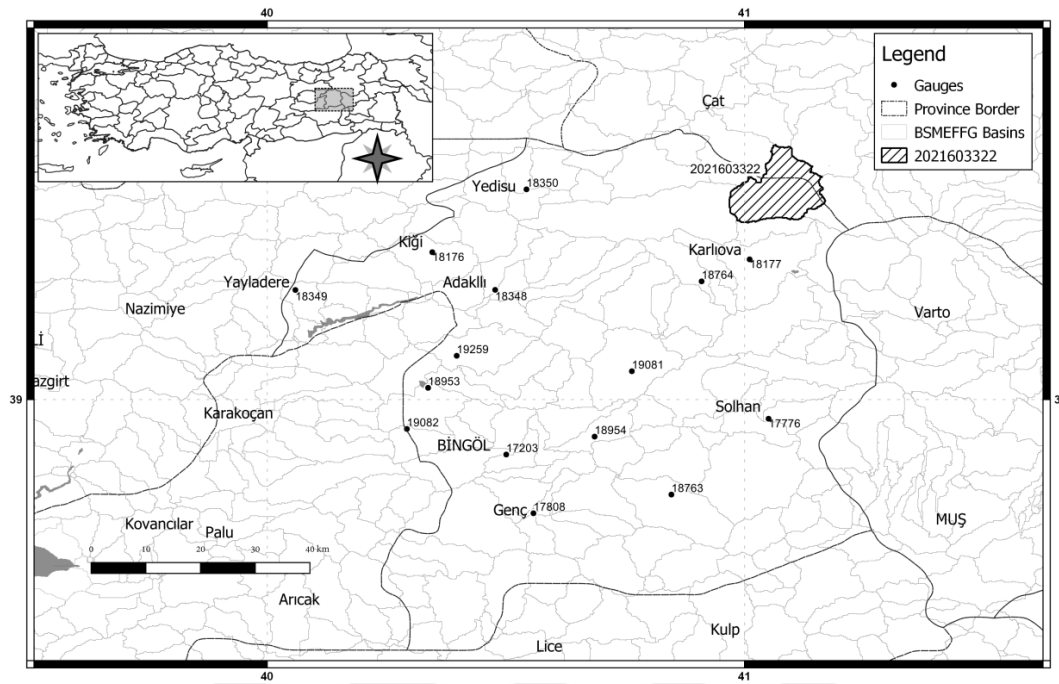


Figure 4.68 Location of Bingöl province, rainfall gauges and selected watershed.

The synoptic conditions have been evaluated to explain moderate rainfall over eastern Turkey by using synoptic charts for 00:00 UTC on 02 May 2019 (see Figure C.24 in Appendices). On the upper atmosphere charts, a weak trough extended from southwest to northeast of Turkey that brought humid-warm air over eastern Anatolia. In this case, it can be assumed that flash flood event was caused by a synoptic scale system which increased the surface temperature and led to moderate rainfall.

Flash flood event is verified by related TSMS severe weather report and newspaper articles. Figure 4.69 shows image of flash flood for Karlıova (WEB13). According to severe report and newspaper article, a little kid was killed because of flooding in Genç and the flash flood caused economic and social damages in Karlıova district.



Figure 4.69 Flash flood event image for Karlioia (WEB13).

On-site gauges in Bingol and daily rainfall amounts between 01 May and 04 May 2019 are given in Table 4.10. In Karlioia (18177) and Karlioia/Kaynak (18764) gauges 19.8 mm and 28.7 mm amount of rainfall was recorded on 03 May respectively. Station 18764 is used for further analysis in this case since it is close to selected watershed within BSMEFFGS.

Figure 4.70 indicates the cumulative rainfall curve for station 18764 for the period 00:00 UTC on 01 May and 23:00 UTC on 02 May 2019. Slope of curve is rising between 12:00 UTC and 14:00 UTC on 02 May and total rainfall is 23.1 mm between these hours. Spatial distribution of observed daily rainfall totals over Bingol is shown on the Figure 4.71. It can be interpreted from the rainfall interpolation map that around 20 mm rainfall amounts were observed in several points across Bingol province.

Figure 4.72 shows the observed hourly temperature, dew point temperature and precipitation values from 00:00 UTC on 01 May to 23:00 UTC on 03 May 2019 for station 18764. It can be appraised from the graph that surface temperature values are higher on 01 May than following two days which might cause snow melting. Thus, combination of rainfall and snowmelt initiated flash flood on 02 May.

Table 4.10 On-site gauges in Bingöl and rainfall amounts along the event period.

<i>Station</i>	<i>Lat</i>	<i>Lon</i>	<i>Height</i>	<i>May_1</i>	<i>May_2</i>	<i>May_3</i>	<i>May_4</i>	<i>Total</i>
Bingöl (17203)	38.88	40.50	1139	1.80	1.00	25.00	38.80	66.60
Solhan (17776)	38.96	41.05	1366	1.20	3.80	13.40	32.00	50.40
Genç (17808)	38.76	40.56	993	0.40	3.40	20.00	35.80	59.60
Kığı (18176)	39.31	40.35	1495	3.50	2.50	22.80	16.90	45.70
Karlıova (18177)	39.29	41.01	1828	1.10	0.40	19.80	13.50	34.80
Adaklı (18348)	39.23	40.48	1488	0.00	0.00	29.20	21.00	50.20
Yayladere (18349)	39.23	40.06	1710	0.20	0.10	23.50	18.20	42.00
Yedisu (18350)	39.44	40.54	1598	2.70	1.90	29.60	20.10	54.30
Genç/Bayırlı Köyü (18763)	38.80	40.85	1788	1.80	3.20	23.20	35.50	63.70
Karlıova/Kaynak Köyü (18764)	39.25	40.91	1979	0.60	0.50	28.70	18.80	48.60
Bingöl/Gayt Barajı (18953)	39.02	40.34	1529	2.60	0.00	21.70	24.60	48.90
Bingöl/Gülbahar Barajı (18954)	38.92	40.69	1270	4.30	1.70	16.30	31.20	53.50
Bingöl/Alatepe Köyü (19081)	39.06	40.76	1535	2.40	0.80	14.80	26.50	44.50
Bingöl/Yolçatı Köyü (19082)	38.94	40.29	1639	1.70	0.00	27.60	30.20	59.50
Bingöl/Sancak Köyü (19259)	39.09	40.40	1642	0.10	0.20	23.90	22.10	46.30

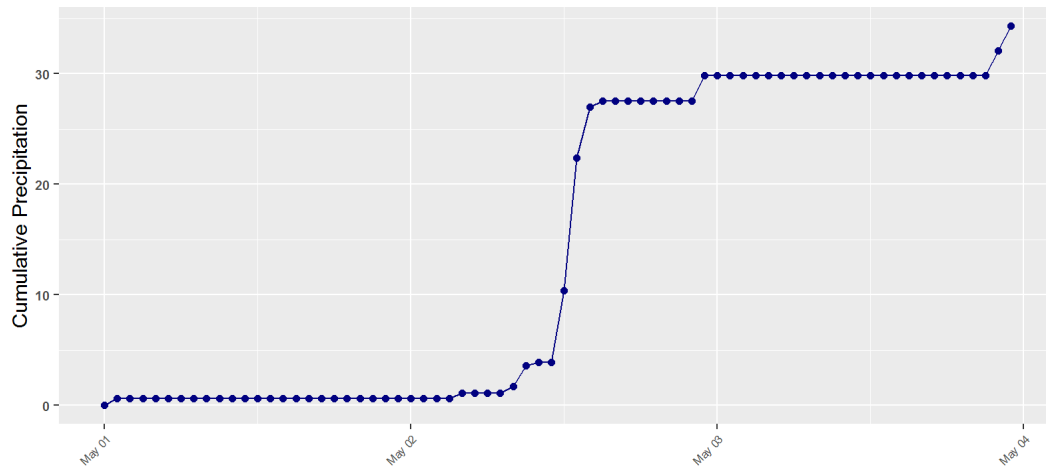


Figure 4.70 Cumulative hourly rainfall curve between 00:00 UTC 01 May and 23:00 UTC 02 May 2019 for station 18764.

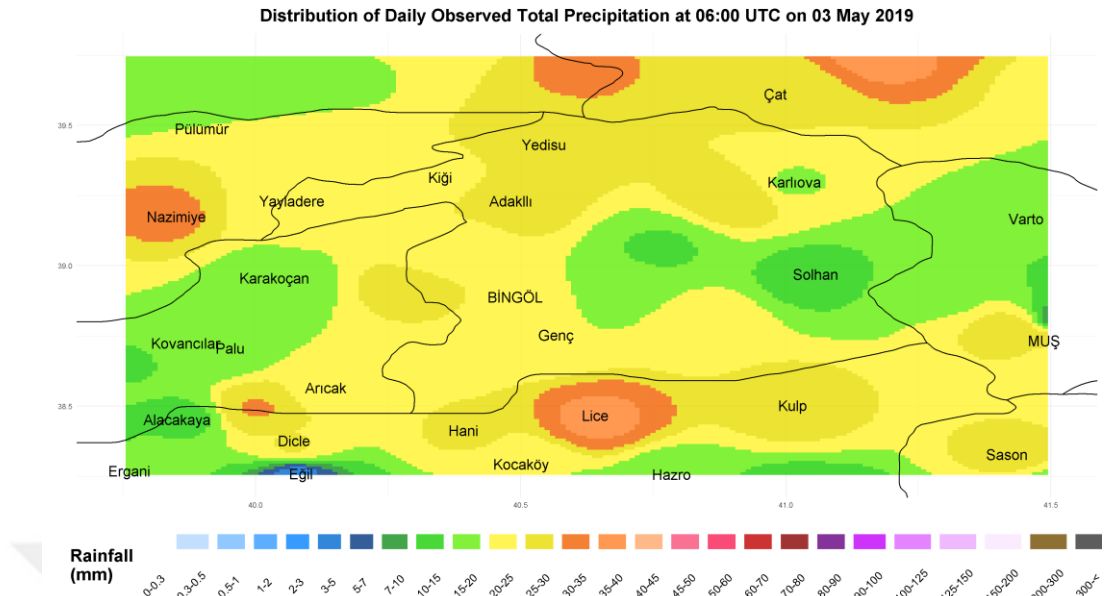


Figure 4.71 Distribution of daily rainfall at 06:00 UTC on 03 May 2019.

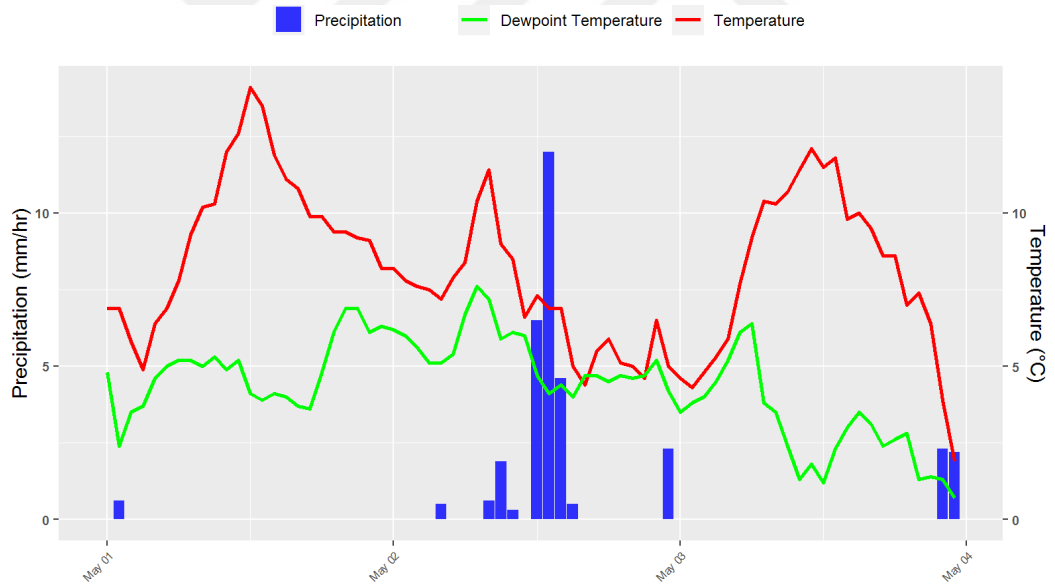


Figure 4.72 Hourly time series of air temperature, dew-point temperature and precipitation as recorded at station 18764 for the period 00:00 UTC 01 May and 23:00 UTC 03 May 2019.

Figure 4.73 shows snow cover area (SCA) product of BSMEFFGS at 00:00 UTC on 01 May 2019. Karlioiva district is covered by snow with approximately % 50. The product proves that the catchments in Karlioiva were covered by snow on 01 May. Figure 4.74 indicates the four-day snow melt product of BSMEFFGS for sub-basins in Bingöl on 02 May. Snow melt amounts were more than 50 mm during last four days in several watersheds of Karlioiva.

The selected watershed is not covered by any radar so radar rainfall estimation is not used for MAP calculation within BSMEFFGS. Figure 4.75 indicates the comparison of FFG threshold values with six-hour forecasted and estimated rainfall amounts between 06:00 UTC on 01 May and 06:00 UTC on 03 May 2019 for catchment 2021603322 (Karlioiva). It can be interpreted from the plot that neither rainfall prediction of NWP models nor satellite based rainfall exceed FFG threshold during the event. However, only MAP rainfall estimation is above threshold value at 18 UTC on 02 May. In short, none of the NWP models were able to issue a warning for this snow-dominated flash flood event.

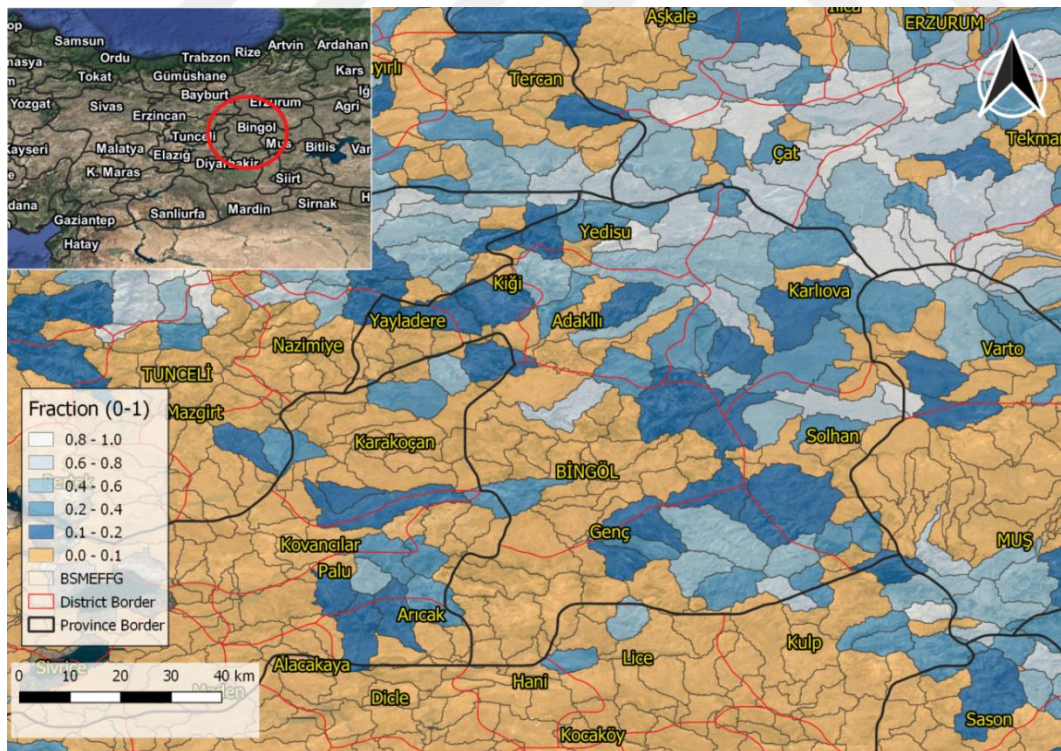


Figure 4.73 Snow cover area at 00:0 UTC on 01 May 2019.

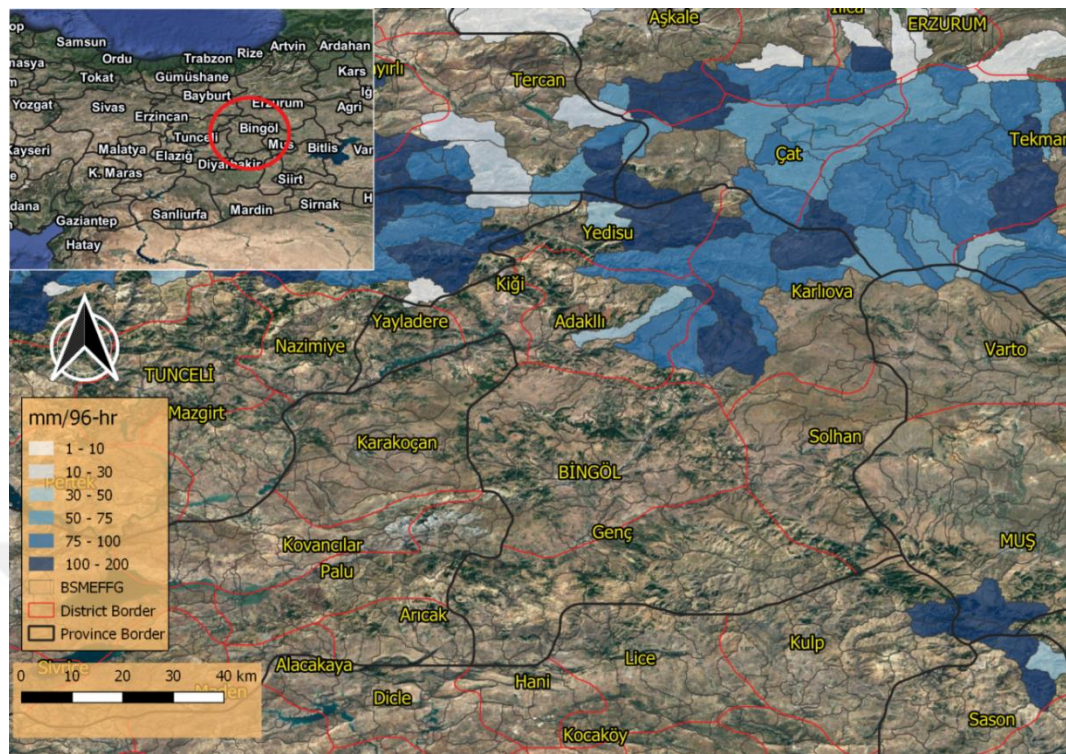


Figure 4.74 4-Day snow melt accumulation at 00:00 UTC on 02 May 2019.

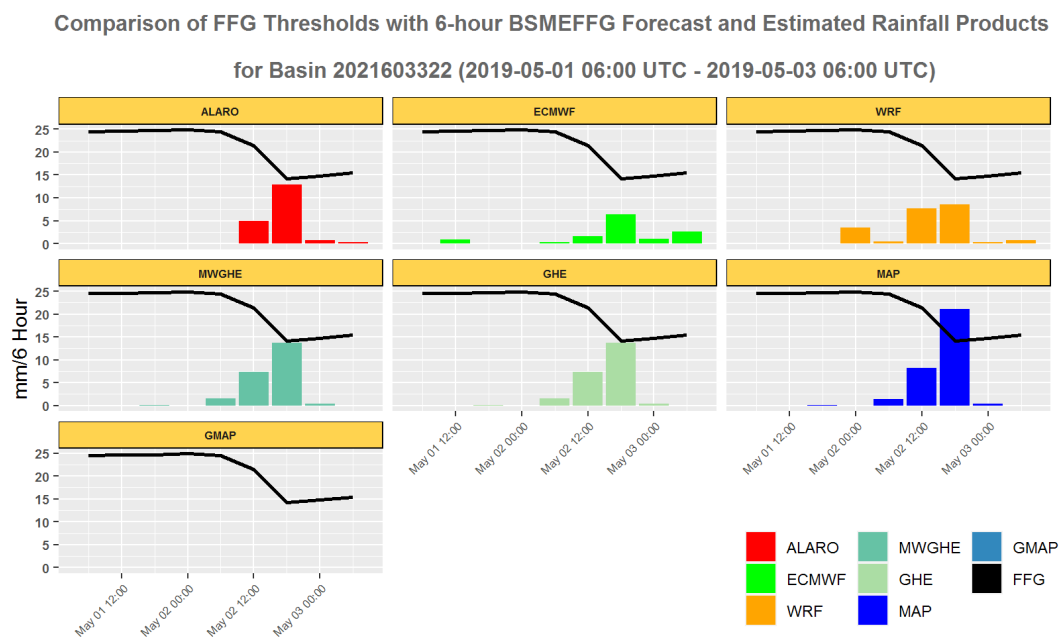


Figure 4.75 Comparison of FFG thresholds with six-hour estimation and forecast rainfall products within BSMEFFGS for sub-basin 2021603322 (Karlıova).

4.6 Summary of Flash Flood Case Studies

A summary table for examined flash flood case studies is presented in Table 4.11. It includes date and location information for each flash flood event. The system signature(s) of the events reported as non-convective, convective and snowmelt are also presented in the table. NWP models are listed if a forecast model exceeded the FFG threshold value in a flash flood event for a selected basin during an event period. It is used as a measure of being considered successful a NWP model in terms of flash flood warning. Additionally, the selected basin areas in km² are given in the table.

There are five flash flood case studies triggered by frontal or orographic activities or combination of both. These flash floods occurred in Kemer (Antalya), Arhavi-Borcka (Artvin), Bodrum (Mugla), Susurluk (Balikesir) and Tarsus-Camliyayla (Mersin) are located mostly on coastal regions of Turkey. ALARO and ECMWF models were convenient for Kemer and Antalya events. All models were considered as successful for the Arhavi-Borcka and Tarsus-Camliyayla flash floods. Only WRF model captured the FFG threshold value for Bodrum flash flood event. However, there was no convenient model for Susurluk flash flood that was caused by combination of precipitation resulted from frontal weather system and snowmelt runoff. In addition, satellite-derived rainfall estimates (GHE, MWGHE) were not able to exceed the FFG threshold for non-convective events occurred in Tarsus and Borcka while forecasted precipitation amounts from three NWPs captured the threshold.

There are four flash flood case studies triggered by convection. These flash floods occurred in Salipazari-Terme (Samsun), Cal (Denizli), Selendi (Manisa) and Ankara. None of the NWP model was successful for any event caused by convectively intense rainfall. The six hourly forecasted rainfall amounts along the event period from each NWP model were lower than the corresponding FFG threshold values for each of these four convective-induced flash flood events. Even though all NWP models predict less precipitation than threshold amount for these

four cases their performances are different in temporal changes and event total. Similarly, satellite and radar rainfall products also show weakness in reaching the FFG threshold values for flash floods originated from convective systems. It should be noted that the calculated FFG threshold value is dynamic changing with time within the event as it is updated by soil moisture accounting model in the system. It may also contain errors from these sources. Hence, the success of NWP model in capturing the FFG value may depend on these factors. Like the difficulty in solving convective precipitation, the calculation of soil moisture due to precipitation involves a lot of uncertainty. However, precipitation resulted from frontal systems contributes less uncertainty in soil moisture processes within a hydrological model.

There is no significant relationship was found between catchment area and NWP models success. For example, area of the basins is 39.66 and 408.61 km² for Bodrum and Selendi districts respectively. However, WRF model was considered convenient for Bodrum flash flood case but not for Selendi.

There is only one snowmelt-induced event that occurred in Karlioiva district to evaluate the NWP models. There was no convenient NWP model for this case in terms of flash flood warning. However, ALARO model shows a better performance than WRF and ECMWF as the discrepancy between ALARO-forecasted precipitation and the FFG threshold is much smaller than the other two models. ECMWF model released the worst performance for this event.

Among these total 10 cases WRF, ALARO and ECMWF exceeded the FFG threshold values that are assigned to three non-convective induced precipitation events. There are also cases for which estimated rainfall products from radar, satellite-based algorithms (GHE, MWGHE) are not able to capture the FFG threshold value.

Table 4.11 Summary table of flash flood case studies.

<i>Date</i>	<i>Location</i>	<i>Reason</i>	<i>Exceedance_FFG</i>	<i>Basin_Area_sq.km</i>
16-17 December 2018	Kemer and Antalya	Non-Convective (Frontal)	ALARO + ECMWF	146.34 & 168.93
28 September 2019	Arhavi and Borçka	Non-Convective (Frontal + Orographic)	ALARO + ECMWF + WRF	92.69 & 111.61
08 February 2017	Bodrum	Non-Convective (Frontal)	WRF	39.66
11-12 January 2019	Susurluk	Non-Convective (Frontal + Snowmelt)	None	218.32
29 March 2018	Tarsus and Çamlıyayla	Non-Convective (Frontal)	ALARO + ECMWF + WRF	167.42 & 53.15
23-24 August 2019	Salıpazarı and Terme	Convective	None	110.19 & 36.48
17 June 2018	Çal	Convective	None	62.54
27 May 18	Selendi	Convective	None	408.61
09 June 2019	Ankara	Convective	None	94.43
02 May 19	Karlıova	Snowmelt	None	189.44

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

In this study, spatiotemporal distribution of extreme rainfall events and lightning flashes over Turkey for the period of 2015 and 2019 are examined. Additionally, the ten different flash flood events categorized as convective, non-convective and snow-dominated are selected throughout Turkey to provide spatial representativeness for each of these events. Among these ten events five, four and one events are from non-convective, convective and snow-dominated respectively. In order to evaluate the performance of numerical weather prediction models (ALARO, WRF, and ECMWF) in capturing the FFG threshold values for issuing flash flood warnings, event-based flash flood cases are analyzed with BSMEFFGS products and supportive meteorological observations.

The following main conclusions are derived from this study based on ten selected events:

- The flood-based extreme rainfall event distribution shows strong seasonality and spatiality in Turkey. Interior parts particularly for western Anatolia and northwestern Anatolia show the highest extreme events from May to August. Black Sea coastal region had the highest number of events in August and September while Mediterranean coastal parts showed higher events from autumn to winter.
- The convective instability of warm season is the main factor for forming flash flood events over inland parts of Turkey while frontal systems of cyclonic depressions were the dominant factor for occurrence of flash flood events over Mediterranean coastal parts of Turkey. On the other hand, combination of frontal, convective and orographic conditions were effective

over Black Sea coastal region for developing intense rainfall and flash flood.

- Lightning flashes showed low frequency over coastal regions in autumn while they released homogeneous distribution over Turkey during warm season with high frequency over northwestern of Anatolia. May and June were the top months in terms of frequency of lightning flashes.
- The spatiotemporal distribution of lightning flashes helps verify the occurrence of flash floods. The distributions from lightning and extreme rainfall event showed strong similarity during warm season. May and June were the top months for both frequency of heavy rainfall events and lightning flashes.
- NWP models were successful in four non-convective cases in terms of flash flood warnings during cold season when non-convective conditions are effective. Nevertheless, each NWP model was considered as unsatisfactory based on four convective cases during warm season when convective instability conditions are effective. Even, rainfall products derived from satellite and radar mostly missed the FFG threshold for these events.
- There is no significant relationship was found from selected ten case studies between catchment area and NWP models success in releasing a warning.
- Performances of NWP models show variability in approaching and exceeding the FFG threshold to issue a warning depending on location and time feature. For some events, radar and satellite rainfall products act as efficient supplementary data.

The following future recommendations can be drawn from this study:

- In this study, extreme rainfall event records of TSMS have been used instead of flash flood events due to lack of such data availability. Thus, a flash flood database should be created in Turkey for future studies and applications.
- In the success of issuing a warning from the system, errors in FFG threshold value calculation are important as much as errors in forecasted

rainfalls from NWP models. Thus, FFG threshold values within BSMEFFGS should be reviewed for Turkey. Furthermore, sensitivity of FFG values should be analyzed for Turkey in future research.

- NWP models were failed for both Karliova and Susurluk flash flood events where snow melt was the main and supportive reason respectively. Snow products within BSMEFFGS provided some important insights for these cases but it wasn't enough to generate flash flood warning. Thus, available snow observations should be added into the BSMEFFG.
- In the convective-induced case studies, GMAP and MAP products were mostly successful to capture the FFG threshold values with respect to the NWP models. It shows the importance of using gauge observations and utilization of radar rainfall estimations. Therefore, rainfall gauge and radar networks should be improved in the BSMEFFGS.
- The assessment of lightning flashes and convective-induced cases in this study showed the importance of lightning data for heavy rainfall events during warm season. There are several studies in the literature that investigate on determination of rainfall amount and location by using lightning as given in section 4.2. Thus, lightning flashes should be used for nowcasting flash flood warnings in Turkey by estimating rainfall amount. In order to achieve this, utilization a proven method, which is previously used in the literature for different regions, or developing a new one for Turkey may be beneficial.



REFERENCES

- Ahrens, C. D., (2007). *Meteorology today: an introduction to weather, climate, and the environment*. Belmont, CA :Thomson/Brooks/Cole.
- Ajami, N. K., Gupta, H., Wagener, T., & Sorooshian, S. (2004). Calibration of a semi-distributed hydrologic model for streamflow estimation along a river system. *Journal of hydrology*, 298(1-4), 112-135.
- Anderson, E. A. (2006). *Snow accumulation and ablation model–SNOW-17*. US National Weather Service, Silver Spring, MD.
- Baltaci, H. (2017). Meteorological analysis of flash floods in Artvin (NE Turkey) on 24 August 2015. *Natural Hazards and Earth System Sciences*, 17(7), 1221.
- Barredo, J. I. (2007). Major flood disasters in Europe: 1950–2005. *Natural Hazards*, 42(1), 125-148.
- Barthold, F. E., Workoff, T. E., Cosgrove, B. A., Gourley, J. J., Novak, D. R., & Mahoney, K. M. (2015). Improving flash flood forecasts: The HMT-WPC flash flood and intense rainfall experiment. *Bulletin of the American Meteorological Society*, 96(11), 1859-1866.
- Bechtold, P., Köhler, M., Jung, T., Doblas- Reyes, F., Leutbecher, M., Rodwell, M. J., ... & Balsamo, G. (2008). Advances in simulating atmospheric variability with the ECMWF model: From synoptic to decadal time- scales. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 134(634), 1337-1351.
- Beniston, M., Stephenson, D. B., Christensen, O. B., Ferro, C. A., Frei, C., Goyette, S., ... & Palutikof, J. (2007). Future extreme events in European climate: an exploration of regional climate model projections. *Climatic change*, 81(1), 71-95.
- Bergeron, T. (1935). On the physics of cloud and precipitation. *Proc. 5th Assembly U.G.G.I. Lisbon*. Vol. 2, . p. 156.
- Borga, M., Anagnostou, E. N., Blöschl, G., & Creutin, J. D. (2011). Flash flood forecasting, warning and risk management: the HYDRATE project. *Environmental Science & Policy*, 14(7), 834-844.

- Burnash, R. J. C. (1995). The NWS river forecast system-catchment modeling. Computer models of watershed hydrology. Water Resources Publication, Highlands Ranch, Colorado, pp. 311–366.
- Carpenter, T. M., Sperflage, J. A., Georgakakos, K. P., Sweeney, T., & Fread, D. L. (1999). National threshold runoff estimation utilizing GIS in support of operational flash flood warning systems. *Journal of hydrology*, 224(1-2).
- Cho, J. Y., & Kurdzo, J. M. (2020). Weather radar network benefit model for flash flood casualty reduction. *Journal of Applied Meteorology and Climatology*, 59(4), 589-604.
- Cuo, L., Pagano, T. C., & Wang, Q. J. (2011). A review of quantitative precipitation forecasts and their use in short-to medium-range streamflow forecasting. *Journal of hydrometeorology*, 12(5), 713-728.
- Damrath, U., Doms, G., Frühwald, D., Heise, E., Richter, B., & Steppeler, J. (2000). Operational quantitative precipitation forecasting at the German Weather Service. *Journal of Hydrology*, 239(1-4), 260-285.
- Davies, H. (1976). A lateral boundary formulation for multi- level prediction models. *Quarterly Journal of the Royal Meteorological Society*, 102(432), 405-418.
- Demircan, M., Gürkan, H., Eskioglu, O., Arabacı, H., & Coşkun, M. (2017). Climate change projections for Turkey: three models and two scenarios. *Turkish Journal of Water Science & Management*, 1(1), 22-43.
- Dudhia, J. (1989). Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of the atmospheric sciences*, 46(20), 3077-3107.
- Dudhia, J. (1996). A multi-layer soil temperature model for MM5. In *Preprints, The Sixth PSU/NCAR mesoscale model users' workshop* (pp. 22-24).
- Đurán, I. B., Geleyn, J. F., & Váňa, F. (2014). A compact model for the stability dependency of TKE production–destruction–conversion terms valid for the whole range of Richardson numbers. *Journal of the Atmospheric Sciences*, 71(8), 3004-3026.
- ECMWF. (2020). Atmospheric physics. Retrieved March 29, 2020, from <https://www.ecmwf.int/en/research/modelling-and-prediction/atmospheric-physics>. European Centre for Medium-Range Weather Forecasts.
- Erickson, M. J., Kastman, J. S., Albright, B., Perfater, S., Nelson, J. A., Schumacher, R. S., & Herman, G. R. (2019). Verification Results from the 2017 HMT–WPC Flash Flood and Intense Rainfall Experiment. *Journal of Applied Meteorology and Climatology*, 58(12), 2591-2604.

- Erkal, T., & Topgül, İ. (2015). The last 15-year floods of the Meriç River and protection projects. *TUCAUM VIII. Geography Symposium*, 165-174.
- Farda, A., Déu, M., Somot, S., Horányi, A., Spiridonov, V., & Tóth, H. (2010). Model ALADIN as regional climate model for Central and Eastern Europe. *Studia Geophysica et geodaetica*, 54(2), 313-332.
- Findeisen, W. (1938). Die kolloidmeteorologischen Vorgänge bei der Niederschlagsbildung (Colloidal meteorological processes in the formation of precipitation). *Met. Z.* 55. p. 121.
- Flocas, H. A., Simmonds, I., Kouroutzoglou, J., Keay, K., Hatzaki, M., Bricolas, V., & Asimakopoulos, D. (2010). On cyclonic tracks over the eastern Mediterranean. *Journal of Climate*, 23(19), 5243-5257.
- Forbes, R. M., Tompkins, A. M., & Untch, A. (2011). A new prognostic bulk microphysics scheme for the IFS. Reading, UK: ECMWF.
- Gaume, E., Bain, V., Bernardara, P., Newinger, O., Barbuc, M., Bateman, A., ... & Daliakopoulos, I. (2009). A compilation of data on European flash floods. *Journal of Hydrology*, 367(1-2), 70-78, doi:10.1016/j.jhydrol.2008.12.028.
- Georgakakos, K. P. (2006). Analytical results for operational flash flood guidance. *Journal of Hydrology*, 317(1-2), 81-103.
- Georgakakos, K., Graham, R., Jubach, R., Modrick, T., Shamir, E., Spencer, C., & Sperflage, J. (2013). Global flash flood guidance system, phase I. HRC Technical Rep, 9. Hydrologic Research Center, San Diego.
- Gerard, L., Piriou, J. M., Brožková, R., Geleyn, J. F., & Banciu, D. (2009). Cloud and precipitation parameterization in a meso-gamma-scale operational weather prediction model. *Monthly Weather Review*, 137(11), 3960-3977.
- Gourley, J. J., Erlingis, J. M., Hong, Y., & Wells, E. B. (2012). Evaluation of tools used for monitoring and forecasting flash floods in the United States. *Weather and forecasting*, 27(1), 158-173.
- Gungle, B., & Krider, E. P. (2006). Cloud- to- ground lightning and surface rainfall in warm- season Florida thunderstorms. *Journal of Geophysical Research: Atmospheres*, 111(D19).
- Herman, G. R., & Schumacher, R. S. (2018). Flash flood verification: Pondering precipitation proxies. *Journal of Hydrometeorology*, 19(11), 1753-1776.
- Hong, S. Y., Dudhia, J., & Chen, S. H. (2004). A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly weather review*, 132(1), 103-120.

- Hong, S. Y., Noh, Y., & Dudhia, J. (2006). A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly weather review*, 134(9), 2318-2341.
- Hossain, F., & Katiyar, N. (2006). Improving flood forecasting in international river basins. *Eos, Transactions American Geophysical Union*, 87(5), 49-54.
- HRC. (2013). Global Flash Flood Guidance System, Phase I. HRC Technical Rep. No. 9, Hydrologic Research Center, San Diego [a].
- HRC. (2013). Development of Two-Year Return Period Relationships with Upstream Drainage Area for Bias Regions in Turkey. HRC Technical Note 50, Hydrologic Research Center, San Diego [b].
- HRC. (2019). Verification guidelines for the flash flood guidance system component products and derivative warnings. HRC Technical Rep. No. 102, Hydrologic Research Center, San Diego.
- Jonkman, S. N. (2005). Global perspectives on loss of human life caused by floods. *Natural hazards*, 34(2), 151-175.
- Joyce, R. J., Janowiak, J. E., Arkin, P. A., & Xie, P. (2004). CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *Journal of hydrometeorology*, 5(3), 487-503.
- Kadioğlu, M. (2000). Regional variability of seasonal precipitation over Turkey. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 20(14), 1743-1760.
- Kahle, D., & Wickham, H. (2013). ggmap: Spatial Visualization with ggplot2. *The R journal*, 5(1), 144-161.
- Kahraman, A., Kadioğlu, M., & Markowski, P. M. (2017). Severe convective storm environments in Turkey. *Monthly Weather Review*, 145(12), 4711-4725.
- Karadavut, C. (2015). Comparison of Verification Results for WRF and ALARO Numerical Weather Prediction Models (Doctoral dissertation, ITU Institute of Science).
- Koren, V., Smith, M., Wang, D., & Zhang, Z. (2000). 2.16 Use of soil property data in the derivation of conceptual rainfall-runoff model parameters. In *Proceedings of the 15th Conference on Hydrology*, American Meteorological Society, Long Beach, California (pp. 103-106).
- Kömüßcü, A. Ü., & Çelik, S. (2013). Analysis of the Marmara flood in Turkey, 7–10 September 2009: an assessment from hydrometeorological perspective. *Natural hazards*, 66(2), 781-808.
- Lopez, P. (2002). Implementation and validation of a new prognostic large- scale cloud and precipitation scheme for climate and data- assimilation

- purposes. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 128(579), 229-257.
- Mašek, J., Geleyn, J. F., Brožková, R., Giot, O., Achom, H. O., & Kuma, P. (2016). Single interval shortwave radiation scheme with parameterized optical saturation and spectral overlaps. *Quarterly Journal of the Royal Meteorological Society*, 142(694), 304-326.
- Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., & Clough, S. A. (1997). Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated- k model for the longwave. *Journal of Geophysical Research: Atmospheres*, 102(D14), 16663-16682.
- Modrick, T. M., Georgakakos, K. P., Shamir, E., Spencer, C. R. (2017). Operational Quality Control and Enhancement of Radar Data to Support Regional Flash Flood Warning Systems. *Journal of Hydrologic Engineering*, 22(5), E4016001.
- Nikolopoulos, E. I., Anagnostou, E. N., & Borga, M. (2013). Using high-resolution satellite rainfall products to simulate a major flash flood event in northern Italy. *Journal of Hydrometeorology*, 14(1), 171-185.
- NOAA. (2019). Hydrologic Services Program, Definitions and General Terminology. National Weather Service Manual 10-950 (p. 4). Retrieved May 14, 2020, from <https://www.nws.noaa.gov/directives/sym/pd01009050curr.pdf>. National Oceanic and Atmospheric Administration.
- Noilhan, J., & Planton, S. (1989). A simple parameterization of land surface processes for meteorological models. *Monthly weather review*, 117(3), 536-549.
- Ntelekos, A. A., Georgakakos, K. P., & Krajewski, W. F. (2006). On the uncertainties of flash flood guidance: Toward probabilistic forecasting of flash floods. *Journal of Hydrometeorology*, 7(5), 896-915.
- Ozkaya, A., & Akyurek, Z. (2019). Evaluating the use of bias-corrected radar rainfall data in three flood events in Samsun, Turkey. *Natural Hazards*, 98(2), 643-674.
- Oztopal, A. (2017). Türkiye'nin Yıldırım ve Şimşek Gözlemlerinin İncelenmesi. Investigation of Turkey's Lightning Observation. *Journal of Science and Engineering*, 19(56).
- Persson, A. (2001). User guide to ECMWF forecast products.
- Pineda, N., Rigo, T., Bech, J., & Soler, X. (2007). Lightning and precipitation relationship in summer thunderstorms: Case studies in the North Western Mediterranean region. *Atmospheric research*, 85(2), 159-170.

- Rigo, T., Pineda, N., & Bech, J. (2010). Analysis of warm season thunderstorms using an object-oriented tracking method based on radar and total lightning data. *Natural Hazards and Earth System Sciences*, 2010, Vol. 10, p. 1881-1893.
- Sariş, F., Hannah, D. M., & Eastwood, W. J. (2010). Spatial variability of precipitation regimes over Turkey. *Hydrological Sciences Journal–Journal des Sciences Hydrologiques*, 55(2), 234-249.
- Schmidt, J. A., Anderson, A. J., & Paul, J. H. (2007). Spatially-variable, physically-derived flash flood guidance. In *Preprints, 21st Conf. on Hydrology*, San Antonio, TX, Amer. Meteor. Soc. B (Vol. 6).
- Scofield, R. A., & Kuligowski, R. J. (2003). Status and outlook of operational satellite precipitation algorithms for extreme-precipitation events. *Weather and Forecasting*, 18(6), 1037-1051.
- Sen, O., L. Retrieved October 14, 2019, from ITU webpage, <http://climatechangeinturkey.com/climate-change-basics-how-does-the-climate-of-turkey-change.html>.
- Shamir, E., & Georgakakos, K. P. (2006). Distributed snow accumulation and ablation modeling in the American River basin. *Advances in Water Resources*, 29(4), 558-570.
- Shamir, E., Carpenter, T. M., Spencer, C. R., Georgakakos, K. P., (2012). Snow Assessments for Southeastern Europe and Black Sea and Middle East Region for the spring of 2012. HRC Limited Distribution Report No. 39, Hydrologic Research Center, San Diego.
- Shamir, E., Georgakakos, K. P., Spencer, C., Modrick, T. M., Murphy, M. J., & Jubach, R. (2013). Evaluation of real-time flash flood forecasts for Haiti during the passage of Hurricane Tomas, November 4–6, 2010. *Natural hazards*, 67(2), 459-482.
- Shrestha, D. L., Robertson, D. E., Wang, Q. J., Pagano, T. C., & Hapuarachchi, H. A. P. (2013). Evaluation of numerical weather prediction model precipitation forecasts for short-term streamflow forecasting purpose. *Hydrology and Earth System Sciences*, 17(5), 1913.
- Silvestro, F., Rossi, L., Campo, L., Parodi, A., Fiori, E., Rudari, R., & Ferraris, L. (2019). Impact-based flash-flood forecasting system: Sensitivity to high resolution numerical weather prediction systems and soil moisture. *Journal of Hydrology*, 572, 388-402.
- Sweeney, T. L. (1992). Modernized areal flash flood guidance. NOAA Technical Memorandum NWS Hydro 44.
- Tapia, A., Smith, J. A., & Dixon, M. (1998). Estimation of convective rainfall from lightning observations. *Journal of Applied Meteorology*, 37(11), 1497-1509.

- Termonia, P., Fischer, C., Bazile, E., Bouyssel, F., Brožková, R., Bénard, P., ... & Hamdi, R. (2018). The ALADIN System and its canonical model configurations AROME CY41T1 and ALARO CY40T1. *Geoscientific Model Development*, 11, 257-281.
- Tiedtke, M. (1993). Representation of clouds in large-scale models. *Monthly Weather Review*, 121(11), 3040-3061.
- Tiedtke, M. I. C. H. A. E. L. (1989). A comprehensive mass flux scheme for cumulus parameterization in large-scale models. *Monthly weather review*, 117(8), 1779-1800.
- TSMS. (2015). Black Sea and Middle East Flash Flood Guidance System User Guide. Turkish State Meteorological Service. Ankara, Turkey.
- TSMS. (2016). Lightning Detection Network System. Turkish State Meteorological Service. Ankara, Turkey.
- TSMS. (2019). Climate Assessment for 2019. Retrieved July 22, 2020, from <https://www.mgm.gov.tr/FILES/iklim/yillikiklim/2019-iklim-raporu.pdf>. Turkish State Meteorological Service (Turkish) [a].
- TSMS. (2019). Meteorological Disasters in 2019. Retrieved July 22, 2020, from <https://www.mgm.gov.tr/FILES/genel/kitaplar/2019MeteorolojikAfetlerDeg erlendirmesi.pdf>. Turkish State Meteorological Service (Turkish) [b].
- Türkeş, M., Koç, T., & Sariş, F. (2009). Spatiotemporal variability of precipitation total series over Turkey. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, 29(8), 1056-1074.
- USGS. Retrieved February 14, 2020, from https://www.usgs.gov/faqs/what-are-two-types-floods?qt-news_science_products=0#qt-news_science_products. U.S. Geological Survey.
- Van den Hurk, B., & Viterbo, P. (2003). The Torne-Kalix PILPS 2 (e) experiment as a test bed for modifications to the ECMWF land surface scheme. *Global and Planetary Change*, 38(1-2), 165-173.
- Vincendon, B., Ducrocq, V., Nuissier, O., & Vié, B. (2011). Perturbation of convection-permitting NWP forecasts for flash-flood ensemble forecasting. *Natural Hazards and Earth System Sciences*, 11(5), 1529.
- Ward, P. J., Jongman, B., Weiland, F. S., Bouwman, A., van Beek, R., Bierkens, M. F., ... & Winsemius, H. C. (2013). Assessing flood risk at the global scale: model setup, results, and sensitivity. *Environmental Research Letters*, 8(4), 044019.
- WEB1: <https://www.hurriyet.com.tr/galeri-kuvvetli-saganak-kemeri-vurdu-41054562/8>, retrieved November 17, 2019.

- WEB2: <https://www.haberturk.com/antalya-haberleri/65455591-antalyada-kuvvetli-yagis>, retrieved December 12, 2019.
- WEB3: <https://www.milliyet.com.tr/galeri/artvini-sel-vurdu-dereleler-tasti-yollar-kapandi-6042283/7>, retrieved September 30, 2019.
- WEB4: <https://www.trthaber.com/haber/turkiye/bodrumda-sokaklar-gole-dondu-297869.html>, retrieved January 30, 2020.
- WEB5: <https://www.iha.com.tr/haber-sel-sulari-yukseldi-mahsur-kaldi-759943/>, retrieved January 02, 2020.
- WEB6: <https://www.haberturk.com/yerel-haberler/59714386-tarsusta-sel-zarara-yol-acti>, retrieved March 02, 2020.
- WEB7: <http://www.gazetevatan.com/samsun-u-sel-vurdu-1-kisi-hayatini-kaybetti-1271917-gundem/>, retrieved June 14, 2020.
- WEB8: <https://www.kamupersoneli.net/gundem/samsun-un-terme-ilcesinde-sel-nedeniyle-mahsur-kalan-17-kisi-kurtarildi-h78639.html>, retrieved June 14, 2020.
- WEB9: <http://www.denizliguncel.com/cal/calda-sel-felaketi-h6613.html>, retrieved June 25, 2020.
- WEB10: <https://www.sondakika.com/haber/haber-denizli-nin-cal-ilcesinde-tarima-sel-darbesi-10967376/>, retrieved June 25, 2020.
- WEB11: <https://www.aksam.com.tr/guncel/selendide-siddetli-yagis-hayati-olumsuz-etkiledi-haber-739587>, retrieved June 18, 2020.
- WEB12: <https://www.evrensel.net/haber/380936/ankarada-saganak-sele-neden-oldu-3-kisi-hayatini-kaybetti>, retrieved April 01, 2020.
- WEB13: <https://www.dha.com.tr/yurt/karliovada-eriyen-kar-sele-yol-acti-haber-1640265/video/>, retrieved April 13, 2020.
- WMO. (2007). Fifteenth World Meteorological Congress. Retrieved November 09, 2019, from https://library.wmo.int/doc_num.php?explnum_id=5225). World Meteorological Organization.
- WMO. (2017). Flash Flood Guidance System (FFGS) with Global Coverage. Retrieved November 09, 2019, from http://www.wmo.int/pages/prog/hwrf/flood/ffgs/index_en.php. World Meteorological Organization.
- WRF. Retrieved March 21, 2020, from <https://www.mmm.ucar.edu/weather-research-and-forecasting-model>. The Weather Research and Forecasting (WRF) Model.
- Wu, F., Cui, X., & Zhang, D. L. (2018). A lightning-based nowcast-warning approach for short-duration rainfall events: Development and testing over

Beijing during the warm seasons of 2006–2007. *Atmospheric Research*, 205, 2-17.

- Xu, W., Adler, R. F., & Wang, N. Y. (2013). Improving geostationary satellite rainfall estimates using lightning observations: Underlying lightning–rainfall–cloud relationships. *Journal of applied meteorology and climatology*, 52(1), 213-229.
- Yücel, I., Kuligowski, R. J., & Gochis, D. J. (2011). Evaluating the hydro-estimator satellite rainfall algorithm over a mountainous region. *International journal of remote sensing*, 32(22), 7315-7342.
- Yücel, I. (2015). Assessment of a flash flood event using different precipitation datasets. *Natural Hazards*, 79(3), 1889-1911.
- Yücel, I., Onen, A., Yilmaz, K. K., & Gochis, D. J. (2015). Calibration and evaluation of a flood forecasting system: Utility of numerical weather prediction model, data assimilation and satellite-based rainfall. *Journal of Hydrology*, 523, 49-66 [a].
- Yücel, I., Güventürk, A., & Sen, O. L. (2015). Climate change impacts on snowmelt runoff for mountainous transboundary basins in eastern Turkey. *International Journal of Climatology*, 35(2), 215-228 [b].



APPENDICES

A. Additional Information From Literature

Table A. 1 Parameters of the SAC-SMA model (Ajami et al., 2004).

Parameters	Description
UZWWM	Upper zone tension-water capacity (mm)
UZFWM	Upper zone free-water capacity (mm)
UZK	Upper zone recession coefficient
PCTIM	Percent of impervious area
ADIMP	Percent additional impervious area
RIVA	Percent additional impervious area
ZPERC	Minimum percolation rate coefficient
REXP	Percolation equation exponent
LZWWM	Lower zone tension water capacity (mm)
LZFSM	Lower zone supplementary free-water capacity (mm)
LZFPM	Lower zone primary free-water capacity (mm)
LZSK	Lower zone supplementary recession coefficient (mm)
LZPK	Lower zone primary recession coefficient (mm)
PFREE	Percentage percolating directly lower zone free water
RSERV	Percentage of lower zone free water not transferable to lower zone tension water
SIDE	Ratio of deep recharge water going to channel baseflow
<i>State variables</i>	
UZWTC	Upper zone tension-water content (mm)
UZFWC	Upper zone free-water content (mm)
LZWTC	Lower zone tension-water content (mm)
LZFSC	Lower zone supplementary free-water content (mm)
LZFPC	Lower zone primary free-water content (mm)
ADIMC	Tension-water content of additional impervious area (mm)

$$Q_i - Q_r + Q_a - Q_s + Q_h + Q_e + Q_m + Q_g = \Delta Q$$

where: Q_i = incident solar radiation,
 Q_r = reflected solar radiation,
 Q_a = incoming atmospheric and terrestrial longwave radiation,
 Q_s = longwave radiation emitted by the snow cover,
 Q_h = sensible heat transfer,
 Q_e = latent heat transfer,
 Q_m = heat transfer due to mass changes,
 Q_g = heat transfer at the snow-soil interface, and
 ΔQ = change in the heat storage of the snow cover.

Figure A. 1 Energy balance equation (Anderson, 2006).

B. Spatiotemporal Analyses of NWP Models within BSMEFFG System

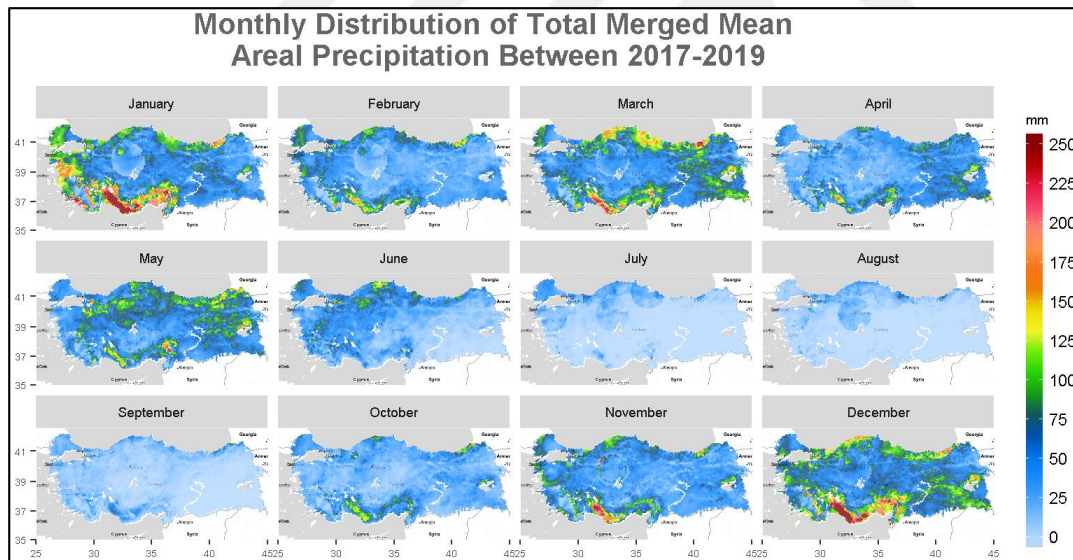


Figure B. 1 Monthly distribution of MAP between 2017 and 2019.

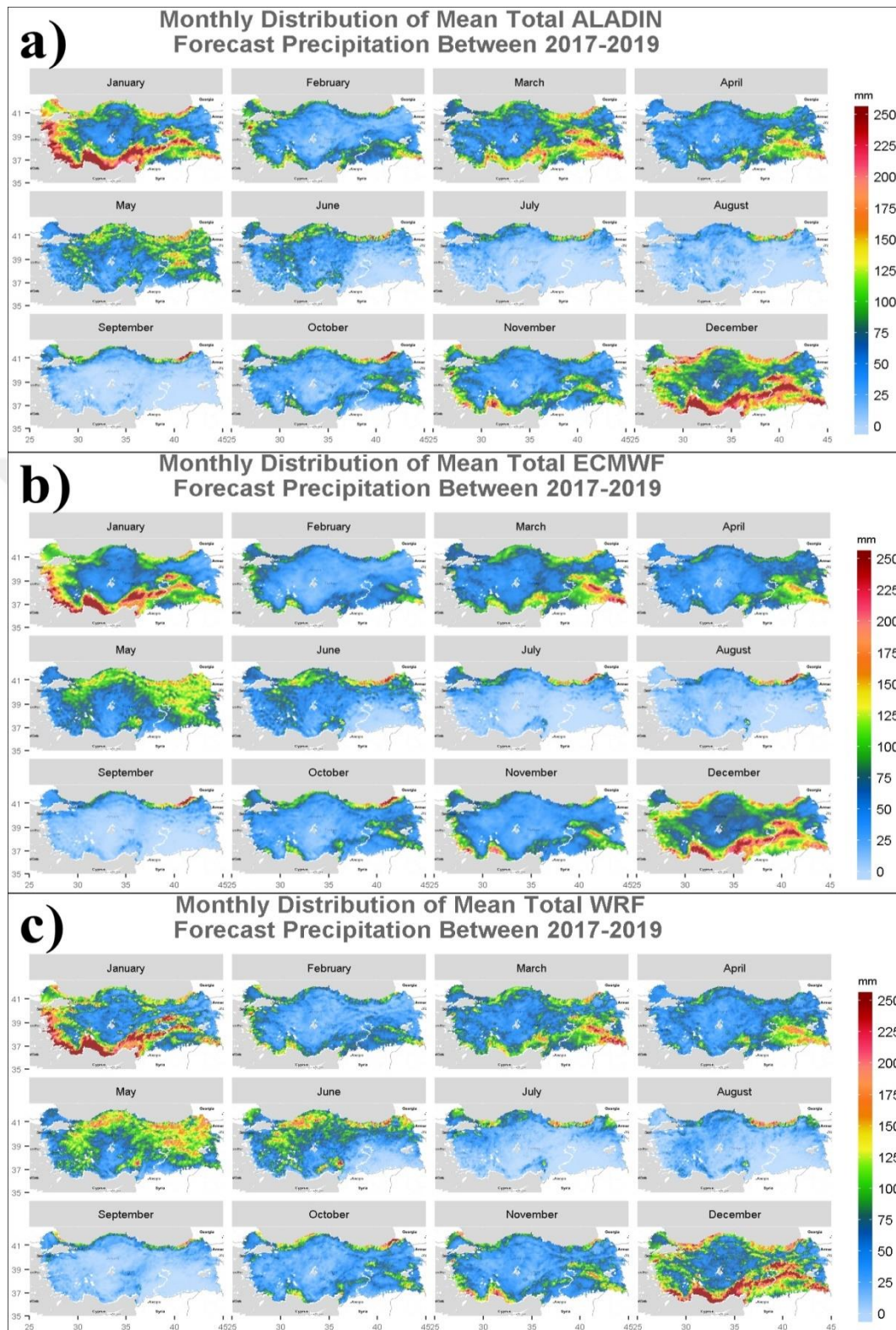


Figure B. 2 Monthly distribution of ALARO (a), ECMWF (b) and WRF (c) rainfall predictions between 2017 and 2019.

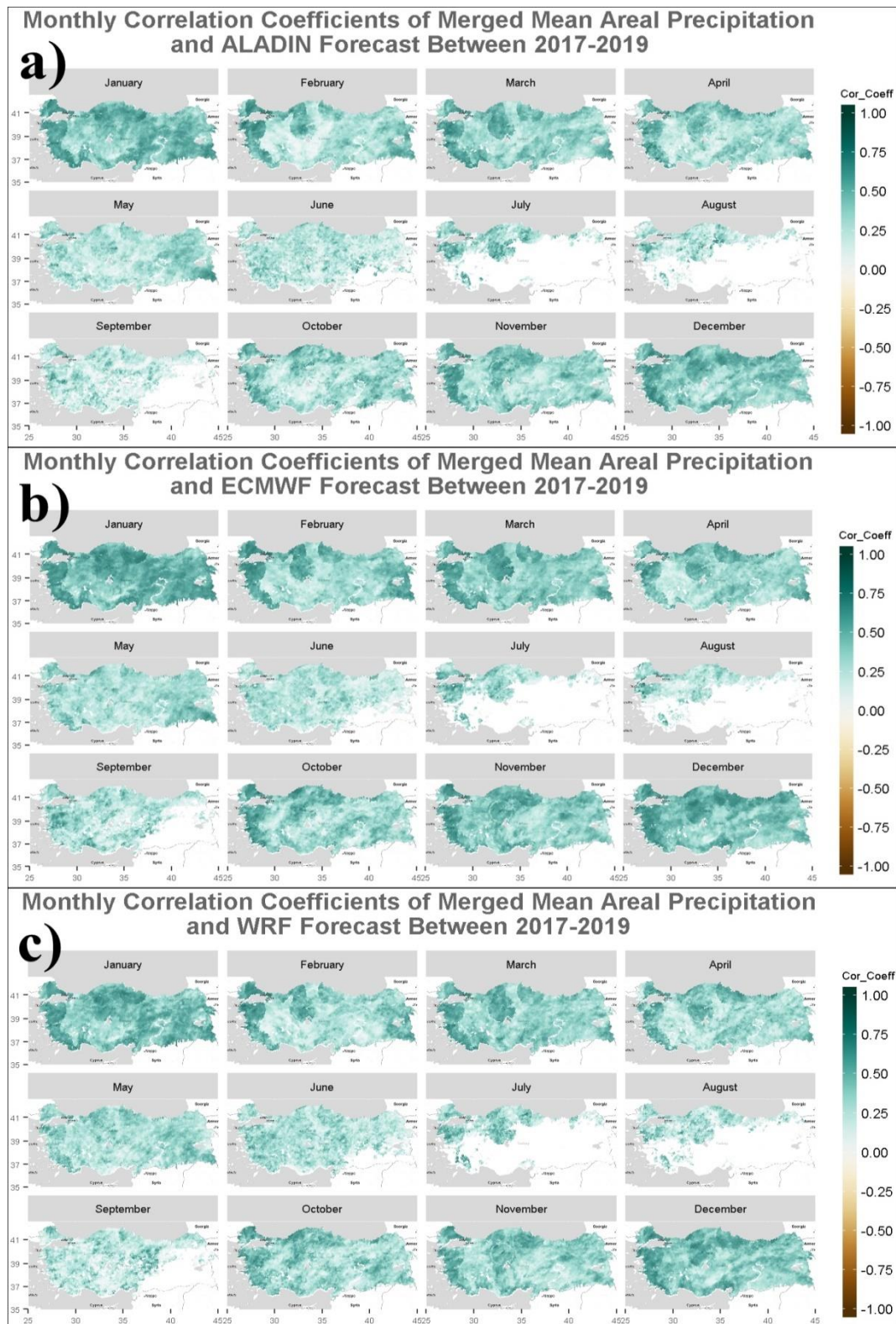


Figure B. 3 Monthly distribution of correlation coefficient values between MAP and ALARO (a), ECMWF (b) and WRF (c) for the period of 2017 and 2019.

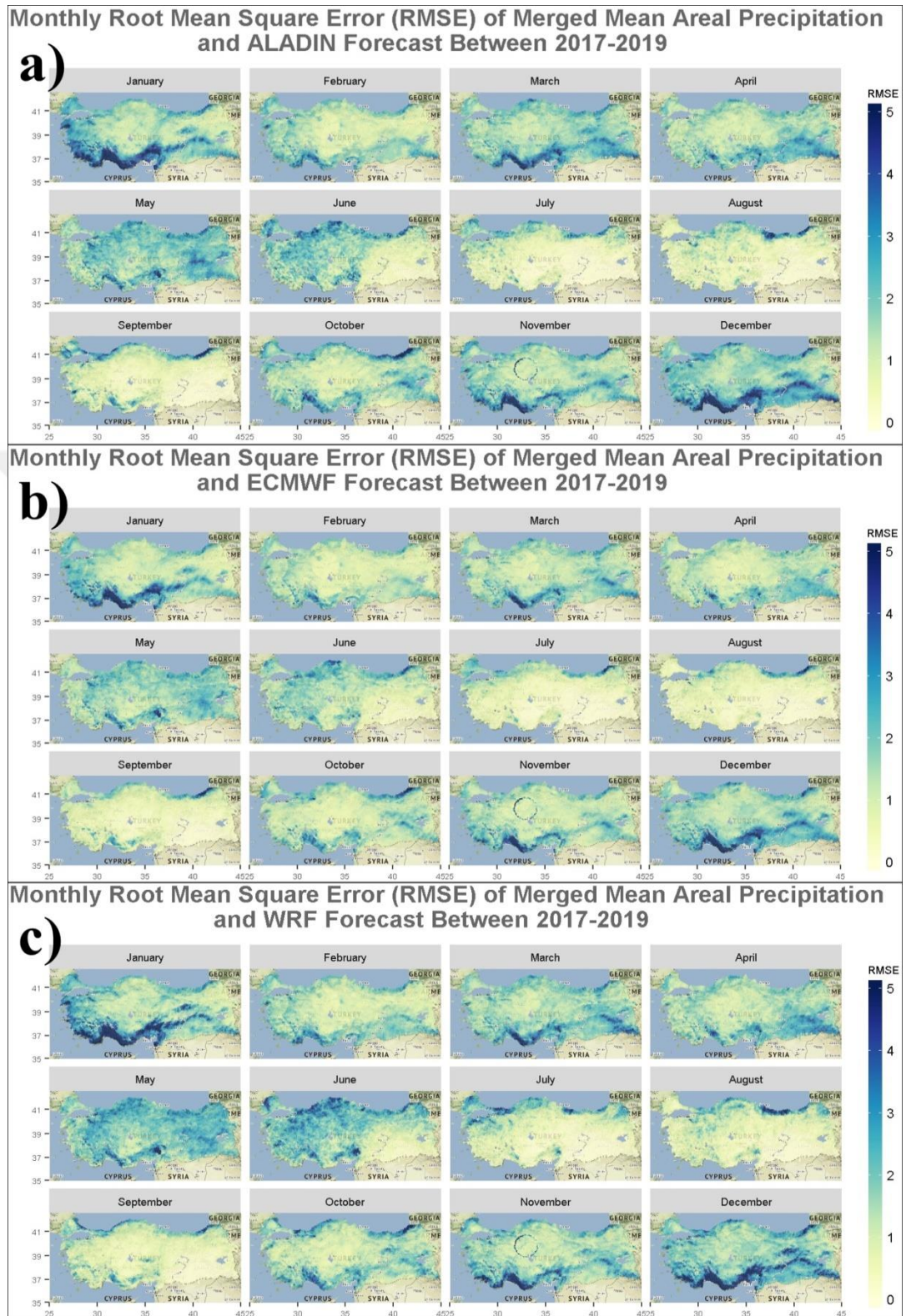


Figure B. 4 Monthly distribution of root mean square error values between MAP and ALARO (a), ECMWF (b) and WRF (c) for the period of 2017 and 2019.

C. Synoptic Charts and Radiosonde Soundings

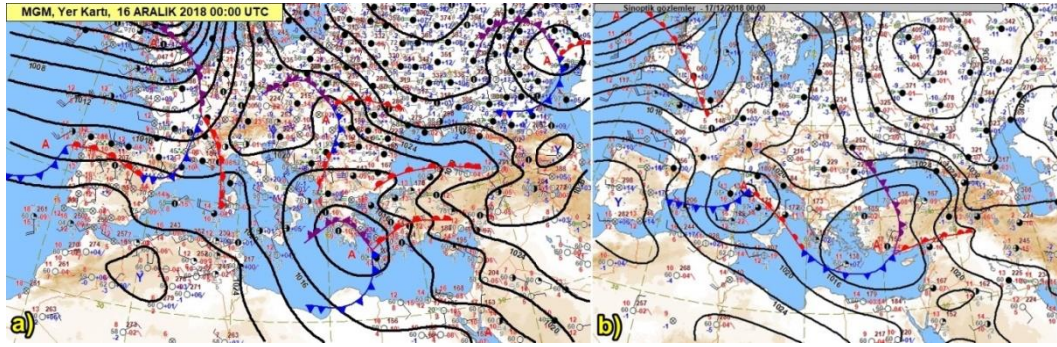


Figure C. 1 Surface analysis for (a) 00:00 UTC 16 December 2018 and (b) 00:00 UTC 17 December 2018.

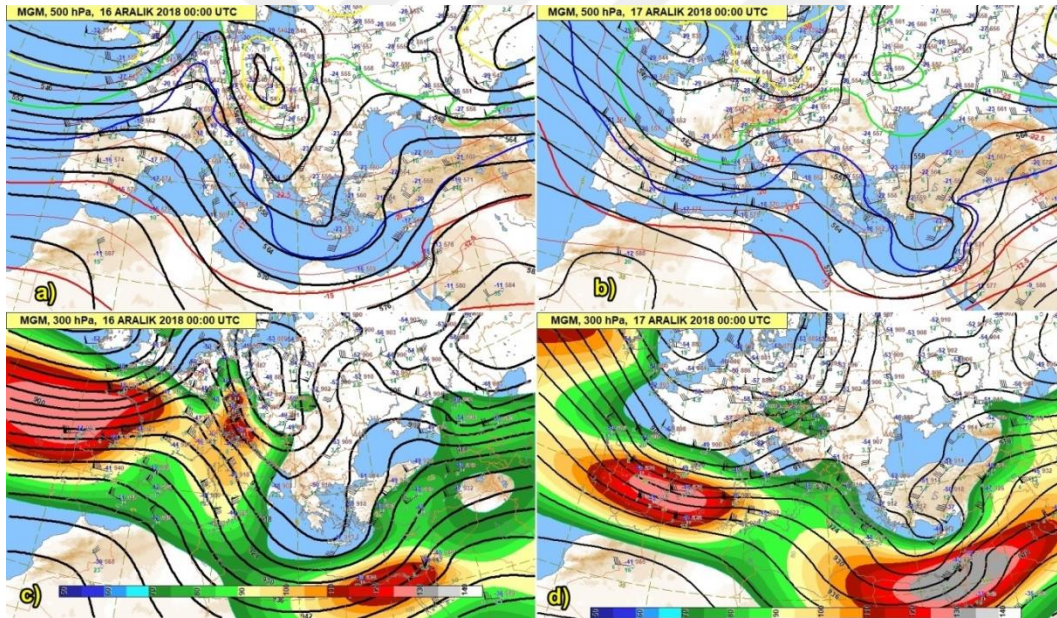


Figure C. 2 The 500-mb analysis for (a) 00:00 UTC 16 December 2018 and (b) 00:00 UTC 17 December 2018, the 300-mb analysis for (c) 00:00 UTC 16 December 2018 and (d) 00:00 UTC 17 December 2018.

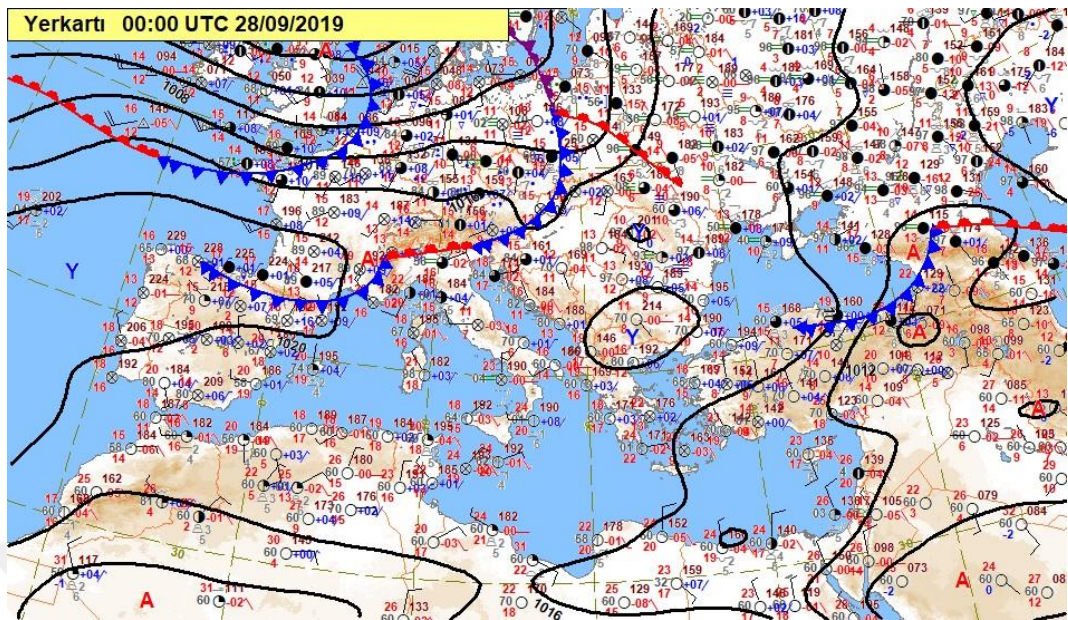


Figure C. 3 Surface chart at 00:00 UTC on 28 September 2019.

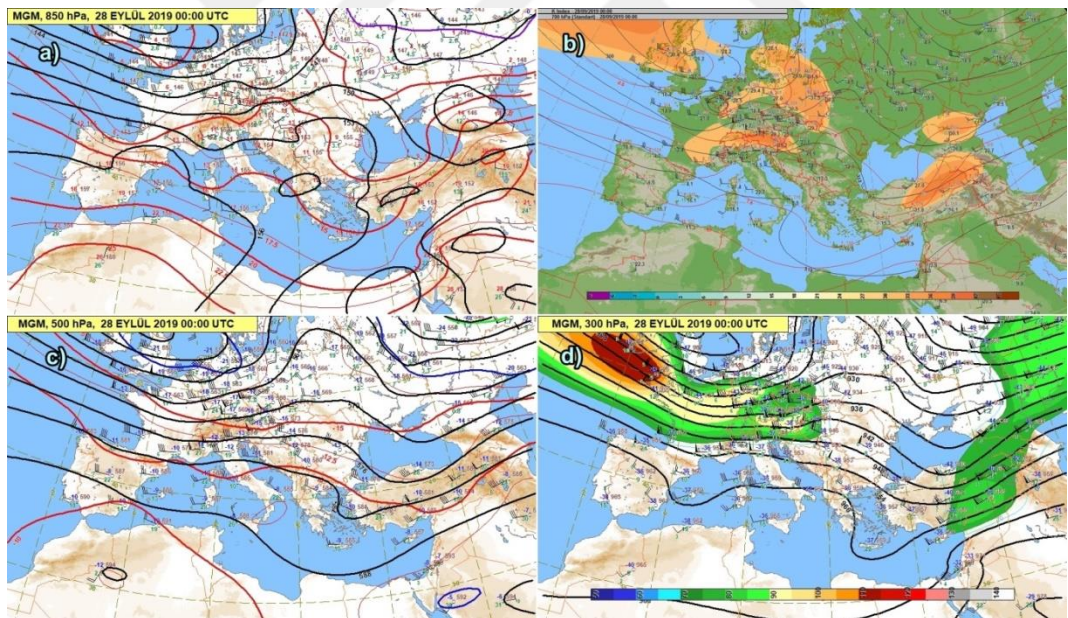


Figure C. 4 Upper level synoptic analyses for 850-mb (a), 700-mb (b), 500-mb (c) and 300-mb (d) at 00:00 UTC on 28 September 2019.

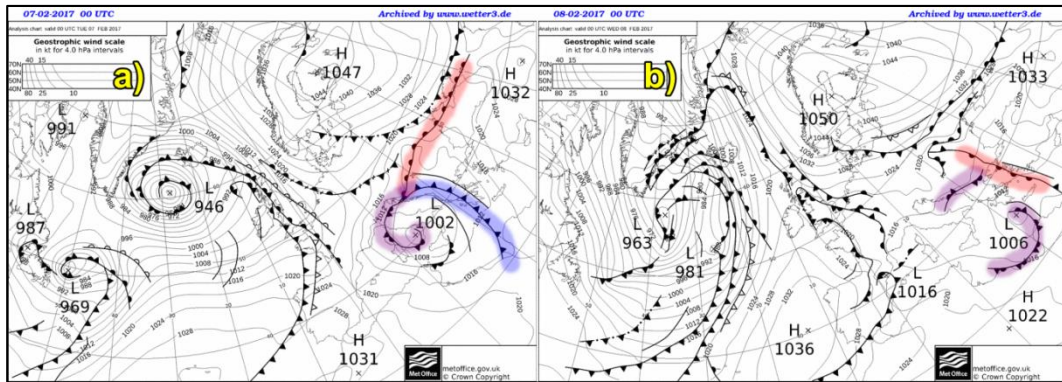


Figure C. 5 Surface analysis for (a) 00:00 UTC 07 February and (b) 00:00 UTC 08 February 2017 (wetter3.de Archive).

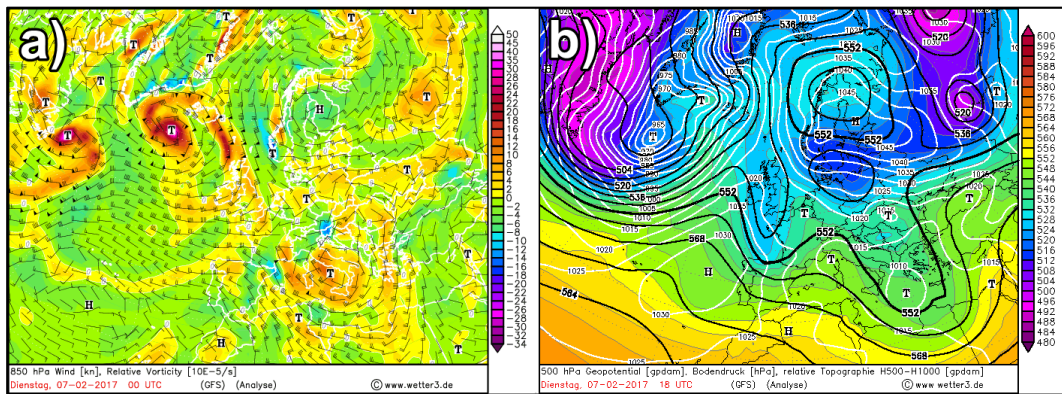


Figure C. 6 The 850-mb analysis for (a) 00:00 UTC 07 February 2017 and 500-mb analysis (b) for 18:00 UTC 07 February 2017 (wetter3.de Archive).

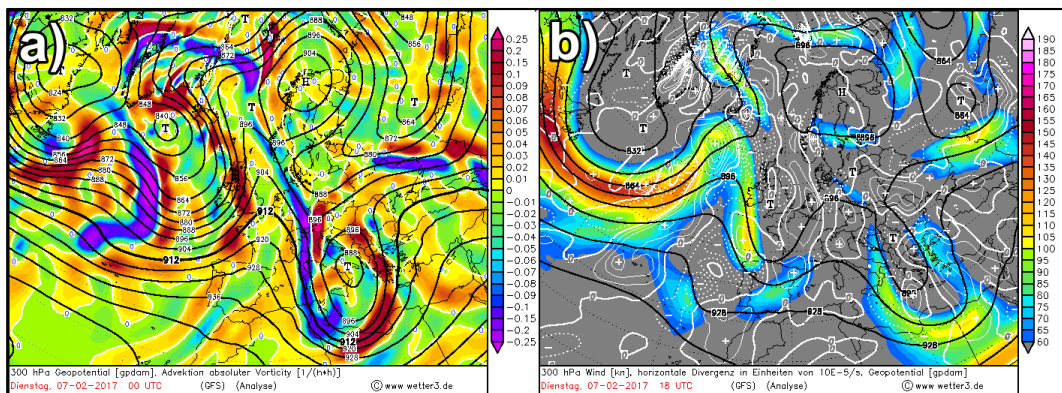


Figure C. 7 The 300-mb analysis for (a) 00:00 UTC 07 February 2017 and 300-mb analysis (b) for 18:00 UTC 07 February 2017 (wetter3.de Archive).

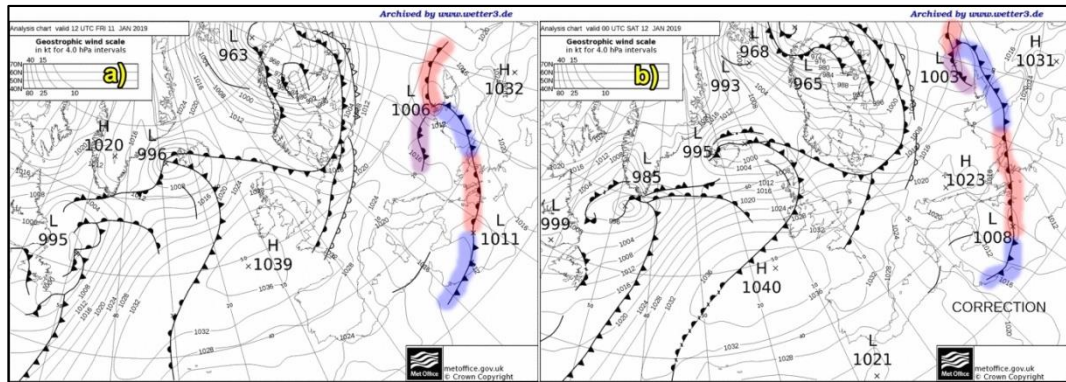


Figure C. 8 Surface analysis for (a) 12:00 UTC 11 January 2019 and (b) 00:00 UTC 12 January 2019 (wetter3.de Archive).

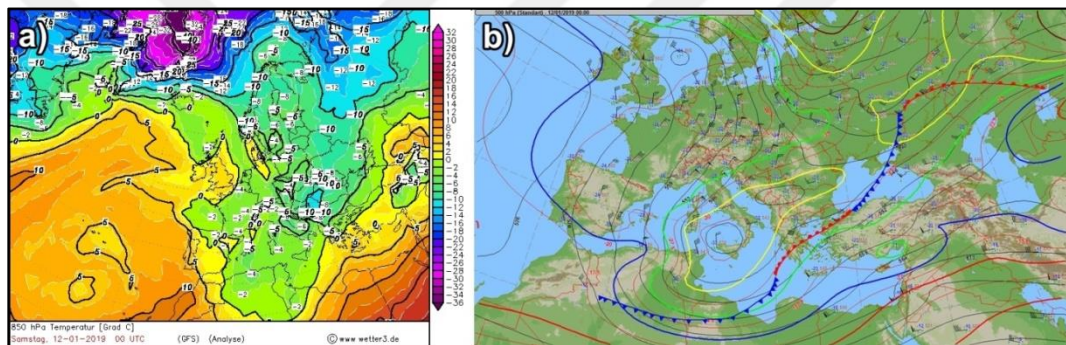


Figure C. 9 The 850-mb analysis (a) and (b) 500-mb chart for 00:00 UTC 12 January 2019 (wetter3.de Archive).

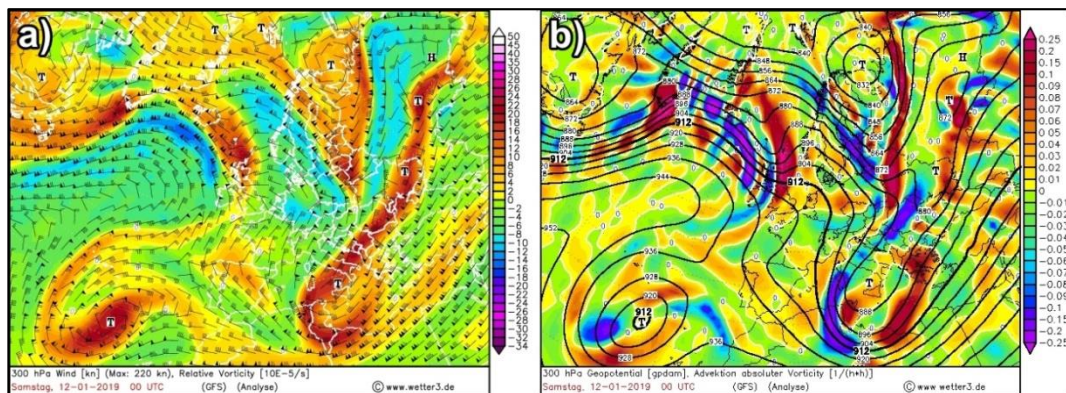


Figure C. 10 The 300-mb charts at 00:00 UTC on 12 January 2019; (a) wind (b) and advection (wetter3.de Archive).

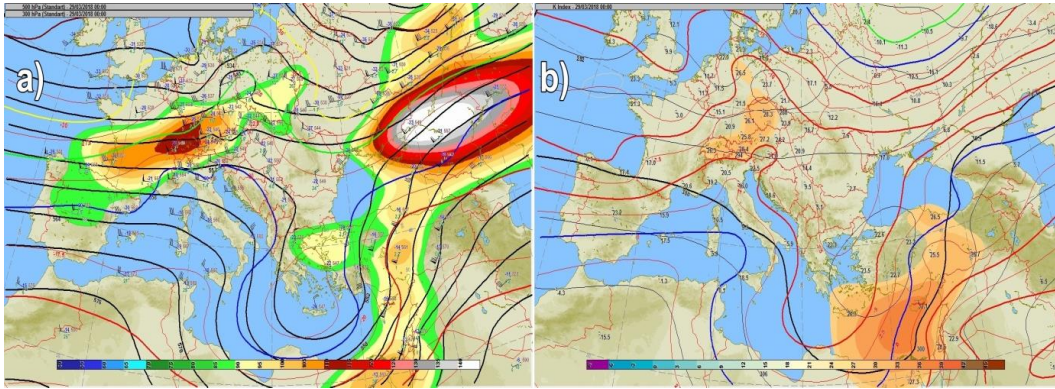


Figure C. 11 The 500-mb analysis (a) and K-index convective instability map (b) for 00:00 UTC 29 March 2018.

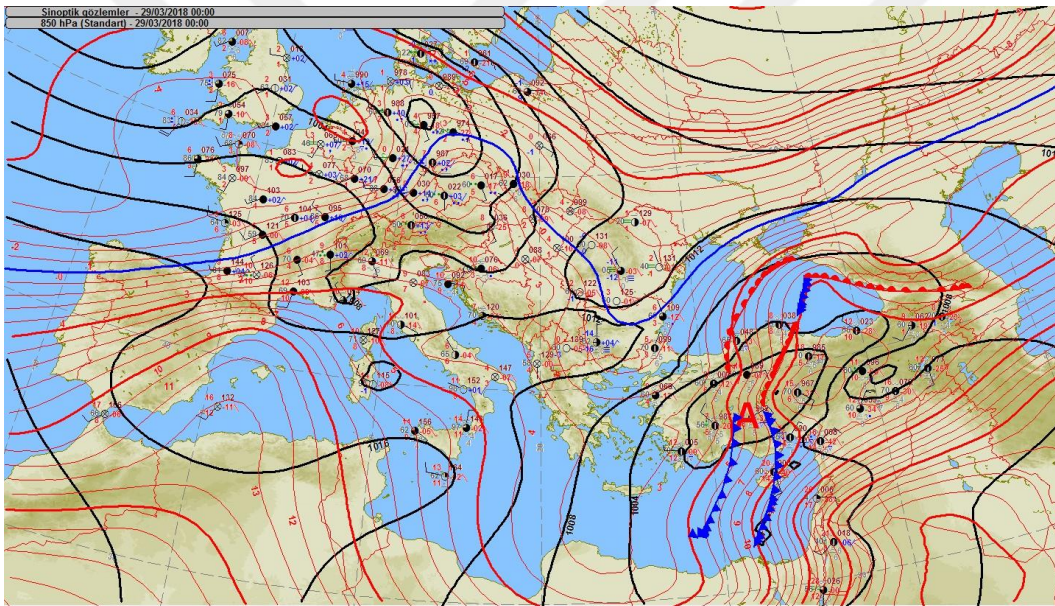


Figure C. 12 Surface and 850-mb chart for 00:00 UTC 29 March 2018.

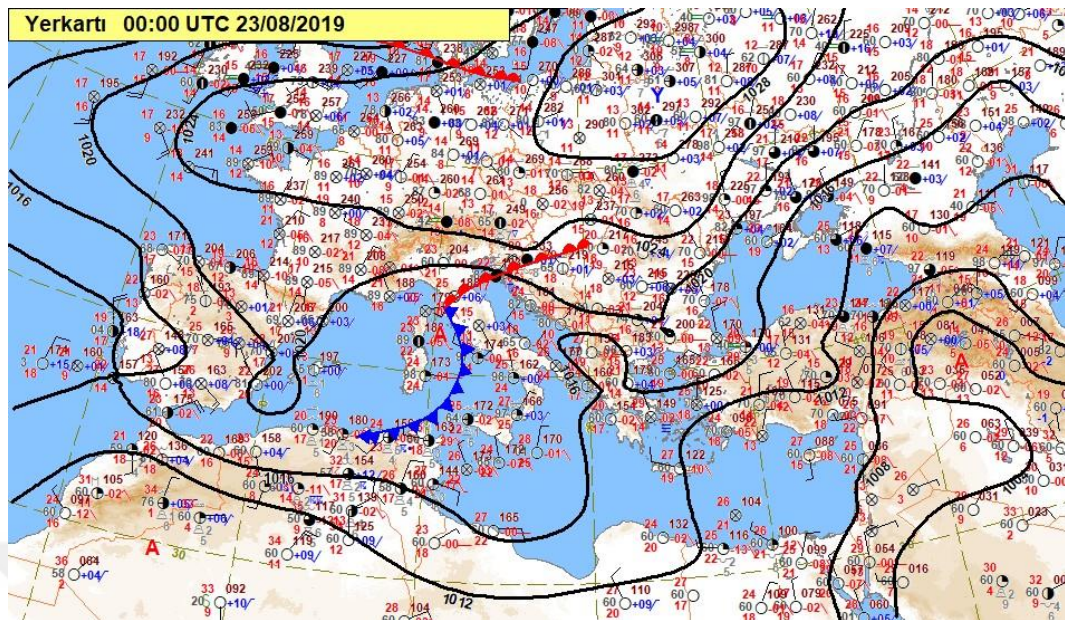


Figure C. 13 Surface chart at 00:00 UTC on 23 August 2019.

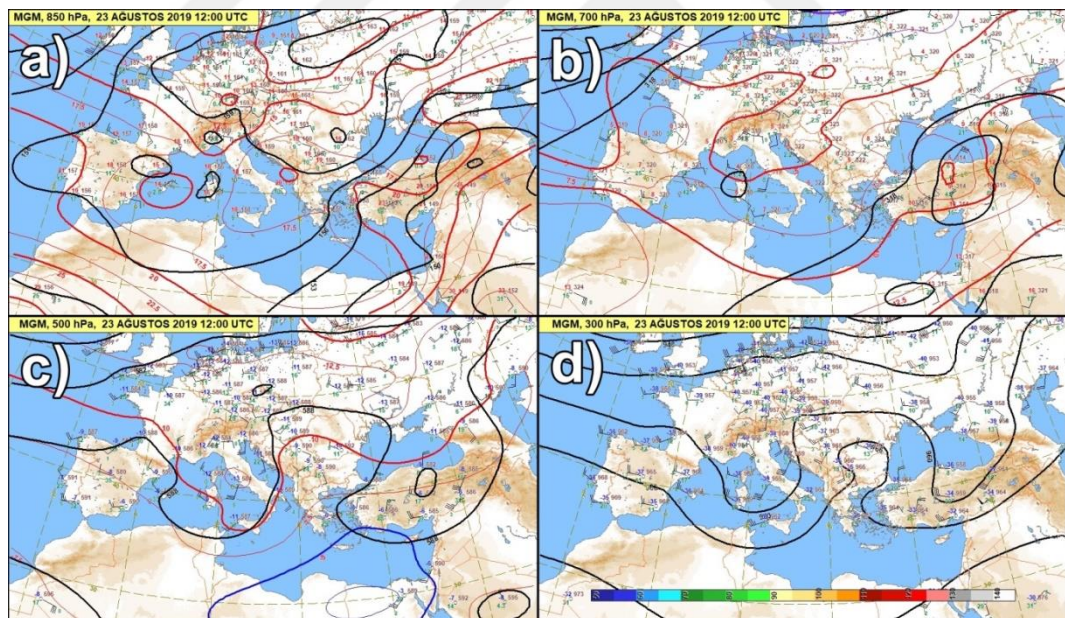


Figure C. 14 850-mb (a), 700-mb (b), 500-mb (c) and 300-mb analyses (d) for 12:00 UTC 23 August 2019.

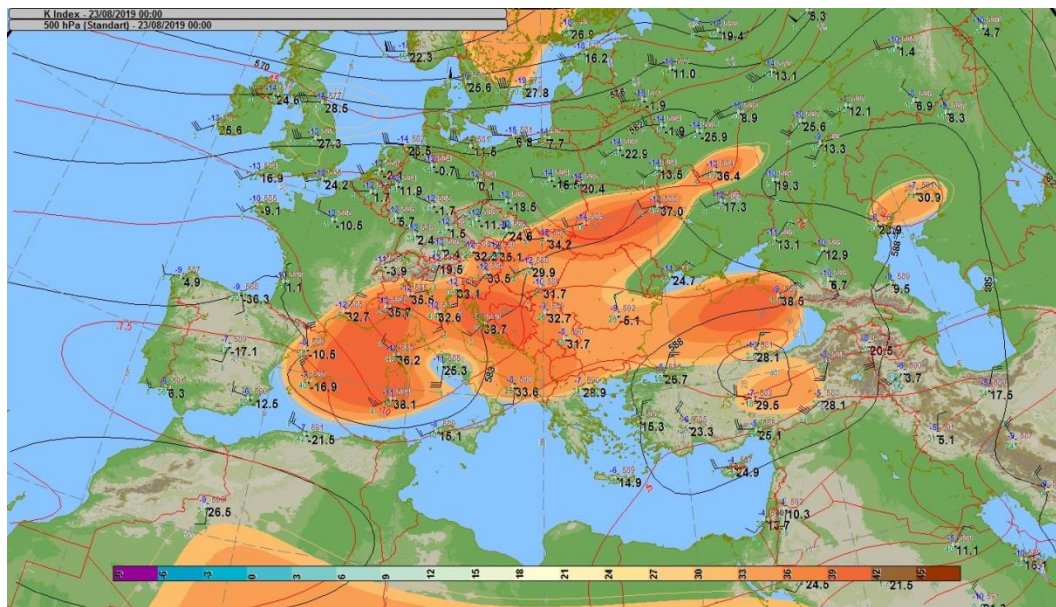


Figure C. 15 500-mb and K index analyses for 00:00 UTC 23 August 2019.

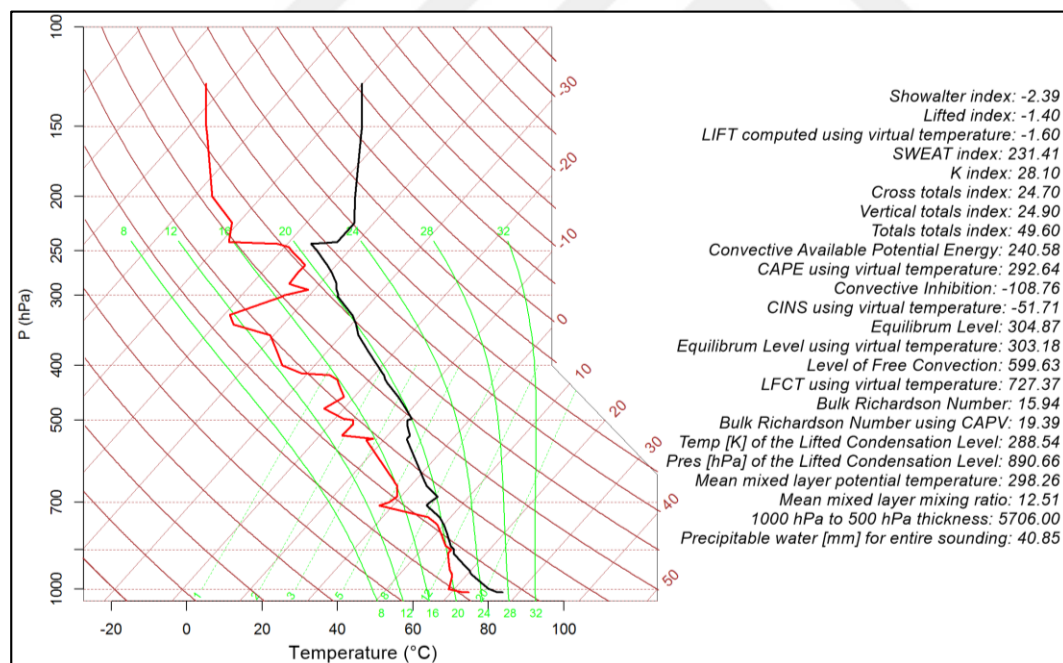


Figure C. 16 Radiosonde sounding and indices for Samsun (17030) at 12:00 UTC on 23 August 2019.

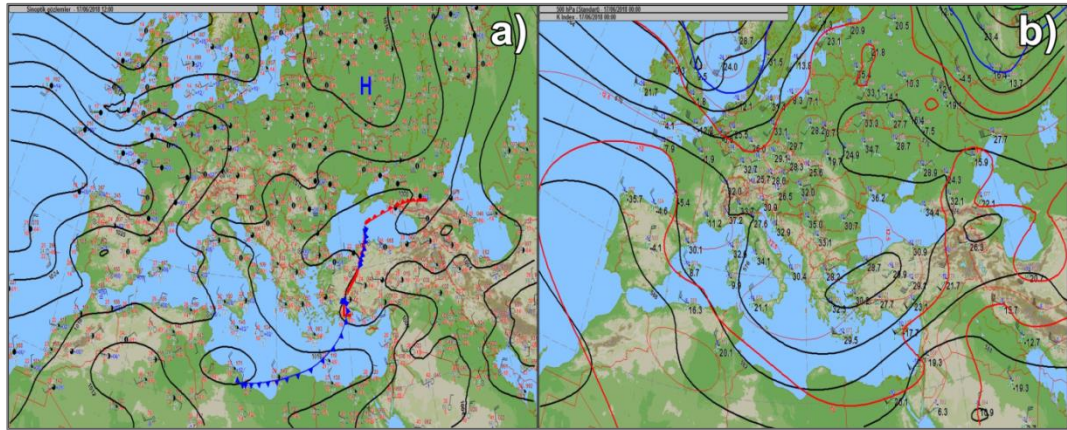


Figure C. 17 Surface and 500-mb analyses for 12:00 UTC (a) and 00:00 UTC (b) 17 June 2018.

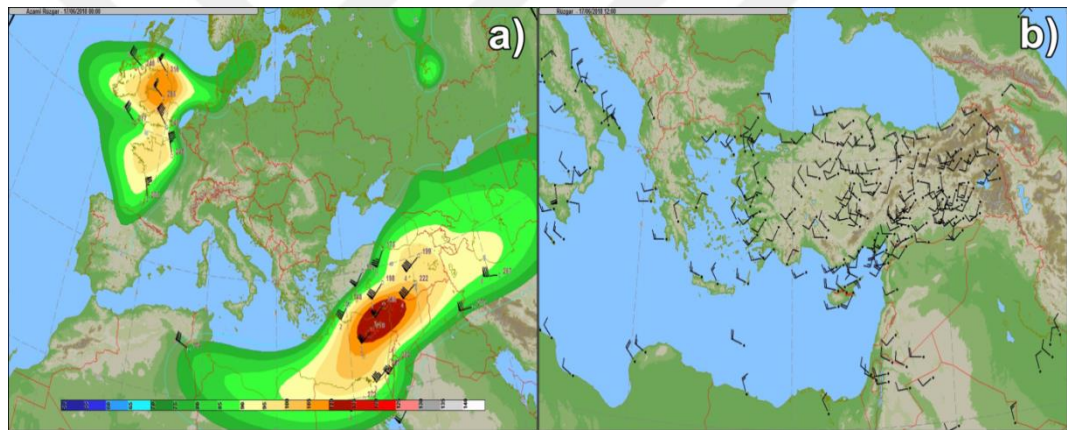


Figure C. 18 300-mb analysis and surface wind directions for 00:00 UTC (a) and 12:00 UTC (b) 17 June 2018.

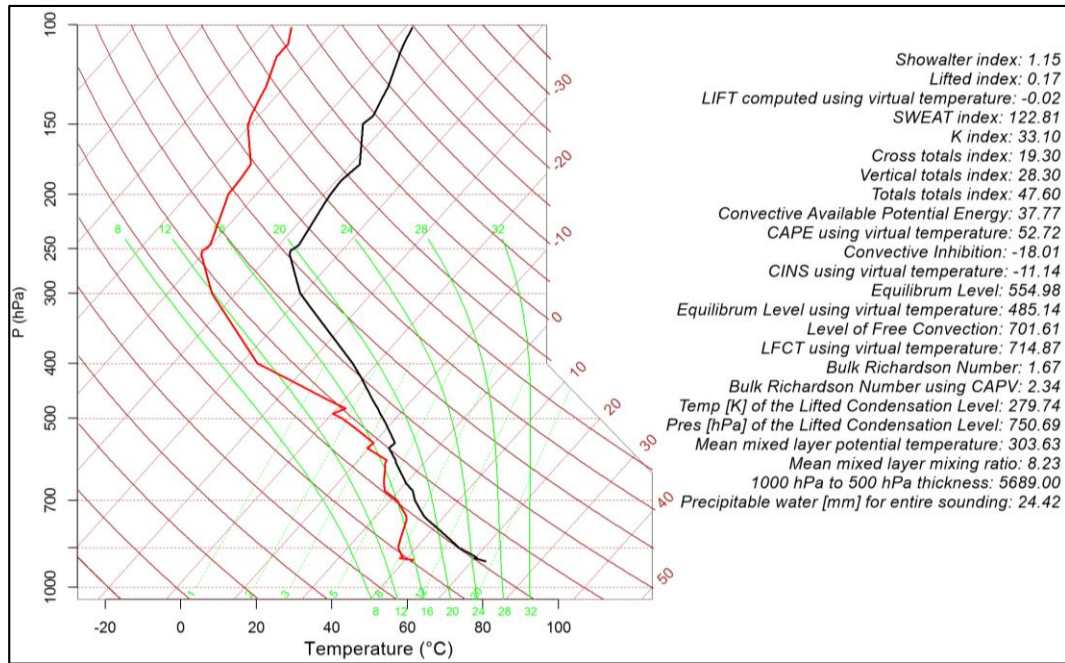


Figure C. 19 Radiosonde sounding and indices for Isparta (17240) at 12:00 UTC on 17 June 2018.

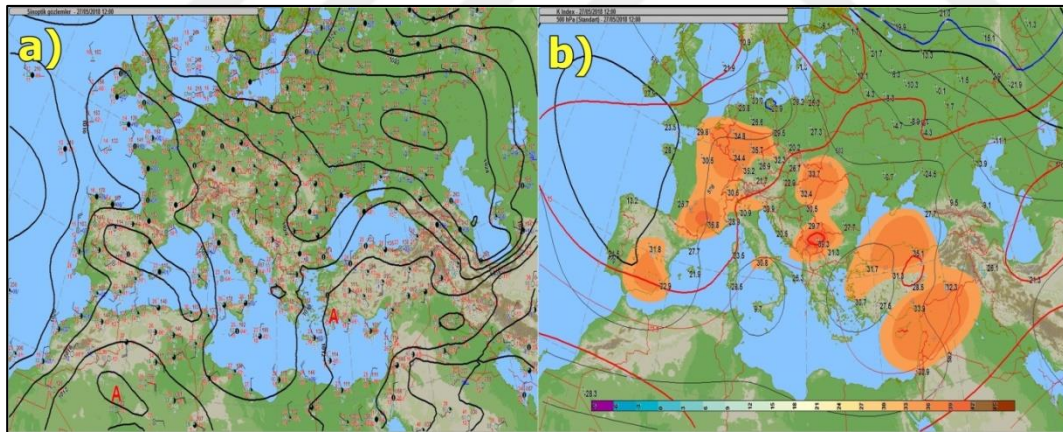


Figure C. 20 Surface (a) and 500-mb (b) analyses for 12:00 UTC 27 May 2018.

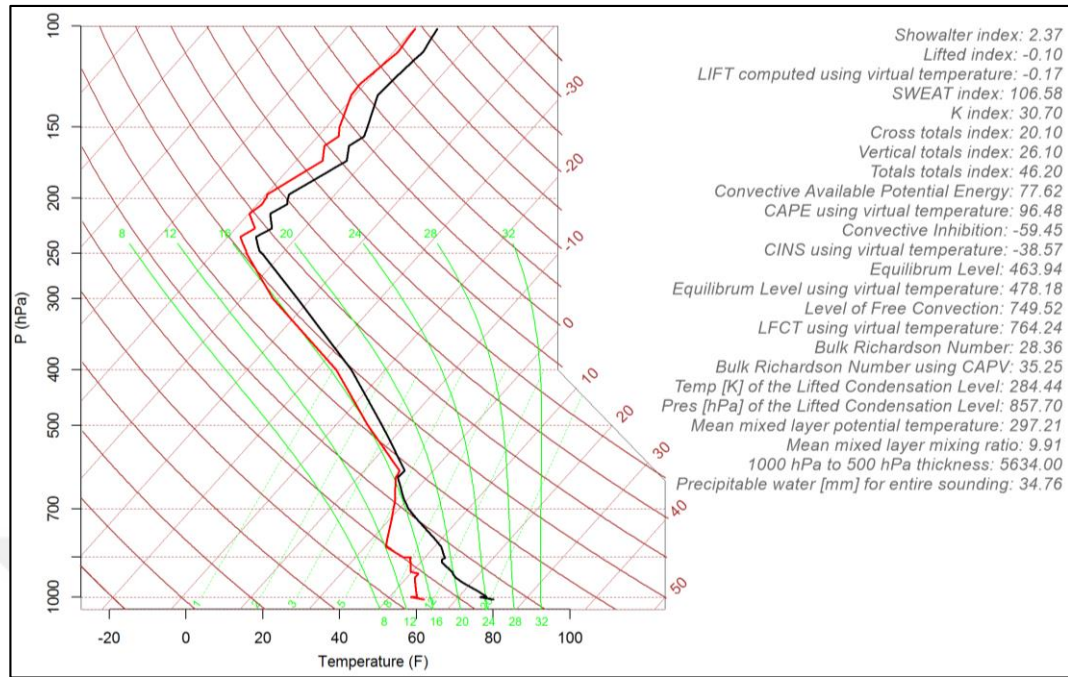


Figure C. 21 Radiosonde sounding and indices for Izmir (17220) at 12:00 UTC on 27 May 2018.

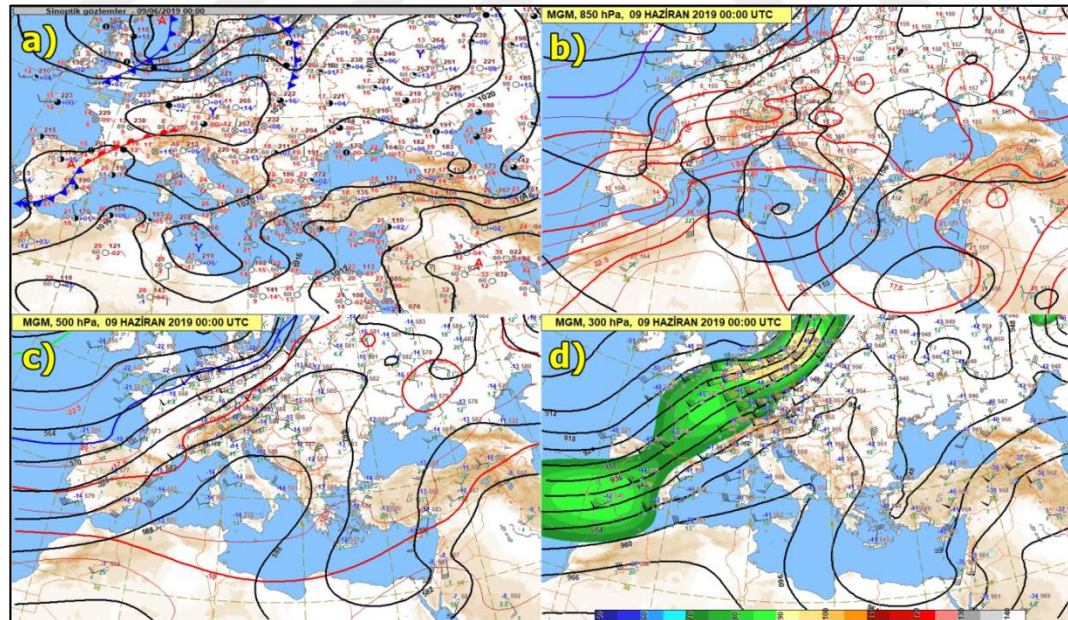


Figure C. 22 Surface (a), 850-mb (b), 500-mb (c) and 300-mb (d) charts for 00:00 UTC 09 June 2019.

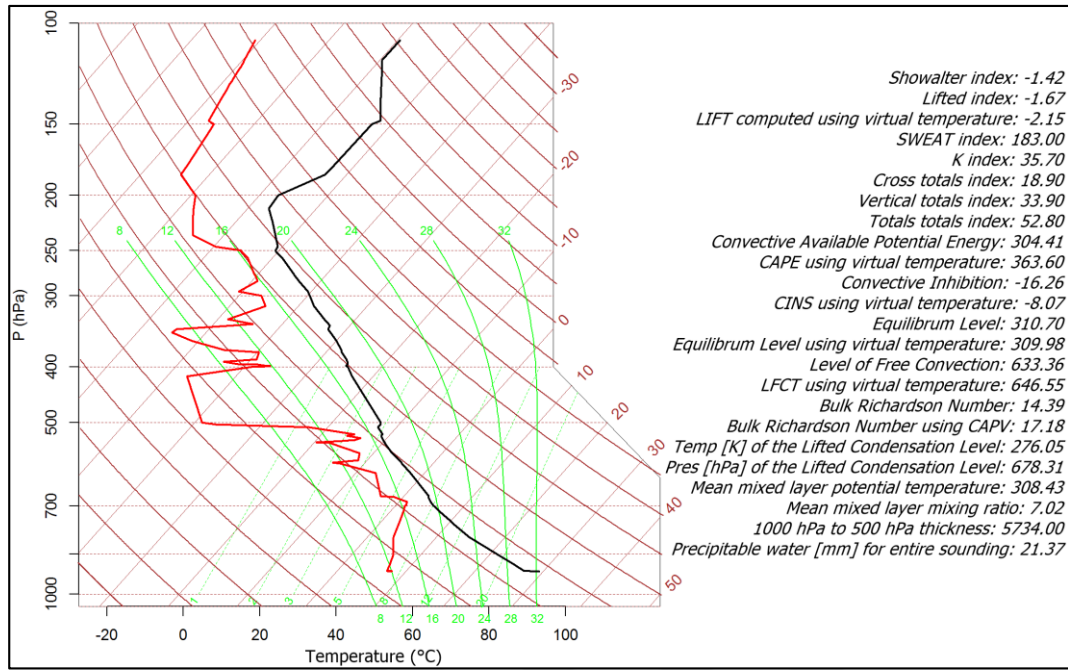


Figure C. 23 Radiosonde sounding and indices for Ankara (17130) at 12:00 UTC on 09 June 2019.

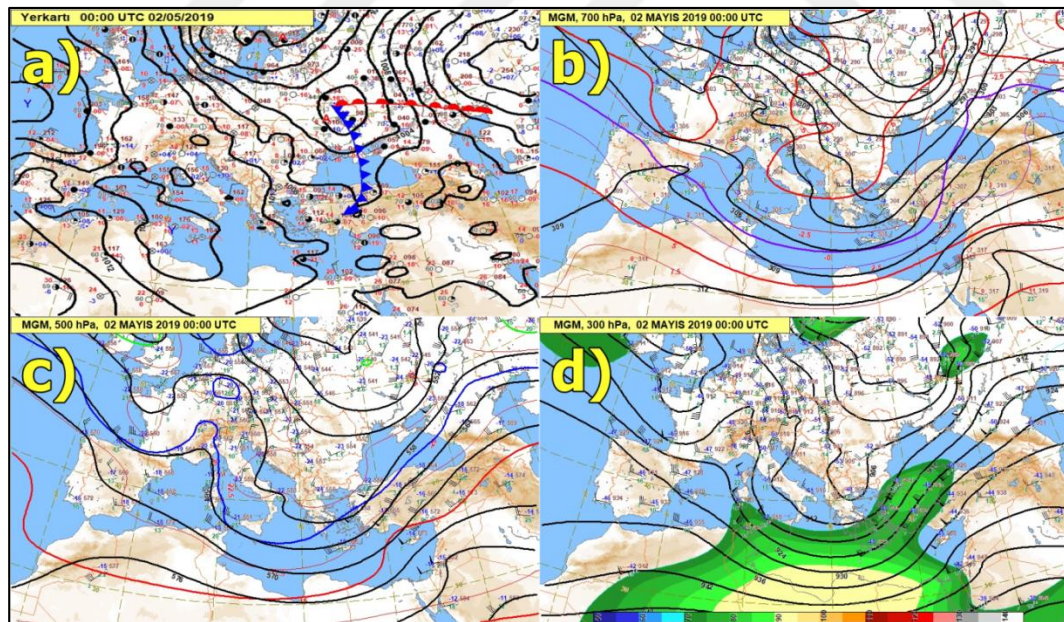


Figure C. 24 Surface (a), 700-mb (b), 500-mb (c) and 300-mb (d) charts for 00:00 UTC 02 May 2019.